EVALUATING THE USE OF STRAW BALES IN ACHIEVING PASSIVE HOUSE CERTIFICATION (PHIUS+ 2015) IN WESTERN CANADA

by

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Abstract

Evaluating the Use of Straw Bales in Achieving Passive House Certification (PHIUS+ 2015) in Western Canada
Master of Building Science, 2018
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Achieving Passive House certification requires superinsulation which can significantly raise the embodied energy and carbon footprint of a project, effectively front-end loading the climate impact, especially where petrochemical foam-based products are used. This research sought to evaluate the use of straw bales - a low embodied energy, carbon sequestering agricultural by-product - to achieve PHIUS+2015 certification. A straw bale wall system was adapted to a single-family detached reference house designed to meet the Passive House standard. The wall system was evaluated for applicability across three Western Canadian cities using WUFI Passive energy simulation software to evaluate compliance; thermal bridging and hygrothermal performance were also evaluated. It was found that the proposed straw bale wall assembly satisfied the PHIUS+ 2015 requirements in all three locations - Saskatoon, Calgary, and Kelowna - with only minor changes required to the reference house design. The annual heating demand and peak heating load, the two targets most sensitive to design changes, were, respectively, 4% and 8.6% below the target in Saskatoon, 63.1% and 21.3% below in Calgary, and 63.1% and 32.6% below in Kelowna. The research also revealed that maintaining a high degree of air tightness is essential for satisfying the requirements. Overall, this research demonstrates that straw bales can be a beneficial component in creating high performance enclosures without exacting a large embodied carbon footprint.

Acknowledgments

I would like to extend my gratitude to Dr. Russell Richman for his guidance and support throughout my studies at Ryerson University, and especially as supervisor for this MRP. I would also like to thank Dr. Mark Gorgolewski for his timely feedback and advice. And to Frank Crawford for supplying the reference house material and for his steadfast support along the way. Thanks to Chris Magwood of the Endeavour Centre whose work and pragmatism has always pushed me to explore new heights, and to Deva Racusin and Brian Fuente for the inspiration and guidance as I sharpened my pencil on this exploration into the world of high performance straw bale building. And thank you to Brian Rippy for his insights on assembly configurations and for the opportunity to build a series of panels with his SCMT class at Okanagan College, providing a proof of concept that left me with big smiles. Lastly, I would like to thank my family and friends for their encouragement, love and support as I embarked on this journey. Much love to you all!

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1.0 Introduction

1.1 Introduction

To secure a safe, reliable and low carbon energy future, it is crucial that there be major improvements to the energy performance of Canada's housing stock. Residential buildings in Canada account for 17% of final energy consumption across all uses (Natural Resources Canada, 2014), and represent 55% of energy used by buildings (Natural Resources Canada, 2016), revealing a significant opportunity for reducing energy consumption and related greenhouse gas emissions through energy conservation measures. Space heating, which makes up 63% of residential energy consumption (Natural Resources Canada, 2017), is of particular consequence when designing 'low energy' housing.

Only recently have specific energy efficiency requirements found their way into local building codes - through the adoption of Section 9.36. of the National Building Code of Canada - but these requirements are minimal by other international precedents, where 'near' or 'at' net-zero energy consumption housing is becoming status quo (Yip & Richman, 2015). Indeed, the National Research Council (2016, June 14) estimates that adopting Section 9.36. will yield energy savings of 10-20% over that of 2009 construction but still a long way off what would be required to reasonably achieve net-zero housing. By some estimates, an 80% reduction in heating energy use is better aligned with meeting the net-zero target (Yip & Richman, 2015), which, in the short term at least, will be achieved by following the 'performance path' permitted by the standard, and likely through one of the voluntary energy performance programs offered in Canada.

One of the most aggressive energy conservation programs is Passivhaus, a voluntary certification scheme that originated in Germany in the early 1990s, and later adopted to the North American context by PHIUS (Passive House Institute US). Certified homes have an annual space heating demand that is upwards of 90% lower than for a conventional house (Passive House Institute US , 2017). This is primarily achieved through superinsulation, air tightness, and thermal bridge-free construction techniques. While the certification is proven in its ability to drastically reduce operational energy demands, setting strict limits on heating demands for instance, some evidence suggests that the extra materials needed to achieve such high performance, especially the high amounts of insulation needed, may exact a high embodied energy cost on a project and thus counter-balancing the operational savings (Stephan, Crawford, & Myttenaere, 2013). Seeing that climate stabilization is a major driver for PHIUS (and for many of the other energy efficiency standards and policies), and the founding pillar of the original Passive House standard, efforts to limit embodied energy are imperative, especially as these energy costs are front loaded on a project, creating an energy and emissions deficit amortized over the life of a project. Even if balanced over time, the scientific community stresses that emission reductions are needed now, not in 20 years. As such, low embodied energy materials, and perhaps those capable of sequestering carbon, will best be able to reduce emissions now and in the future.

One potential insulation material that may satisfy these needs is straw bales - an agricultural by-product that has been used as wall insulation in buildings for more than 125 years. An optimized straw bale wall system will be presented and adapted to a single- family detached reference house designed to meet the Passive House Standard. It will be evaluated for applicability across three Western Canadian cities - Saskatoon, Calgary, and Kelowna - using WUFI Passive energy simulation software. The results will demonstrate the effectiveness of using straw bales in achieving Passive House certification in Western Canada.

1.2 Background

Cereal straw - a byproduct of grain cultivation, including wheat, rye, flax, barley and rice - is a ubiquitous, renewable and low embodied energy resource that, when baled, serves as a useful ‘building block’ with high levels of thermal insulation (a 360mm to 460mm thick plastered straw bale wall has a thermal resistance of approximately RSI-5.28 m^2K/W (14 to 18 inches results in approximately R-30). The atmospheric carbon captured through a plant's lifecycle is locked within its tissues and is sequestered within the walls of a building over the life of the project. These seemingly rudimentary bales produced by a machine that has changed little in 120 years are increasingly being used in novel ways in contemporary architecture worldwide, with projects in the USA, Canada, Europe, Australasia, Japan and China (Magwood, Mack, & Therrien, 2005; Holzhueter, 2010).

Typical 2-string bales are 360mm x 460mm x 889mm to 1016mm, weighing 18 to 23 kg (Figure 1), offering a relatively speedy and low-tech building technique that requires few specialized tools or skills. But unlike most construction materials that are standardized, uniform, and modular by design, packaged in a form that is optimized for easy construction or easily manipulated for flexible arrangement, straw bales are best used intact; cutting, notching, and shaping bales is challenging and time consuming. Well executed designs seek to design around the bale module, maximizing the use of full bales, and thus resulting in a more buildable and efficient design.

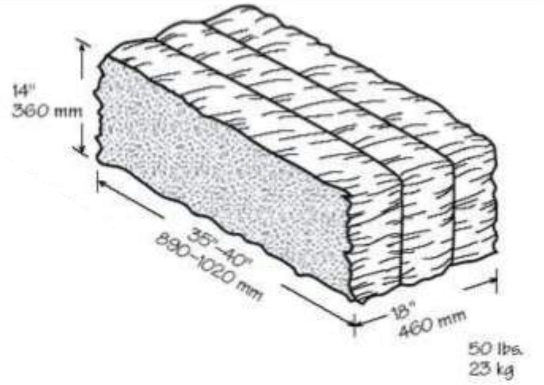

Figure 1: Typical 2-String Bale Dimensions (Wilson, 1995)

Whilst there are many positive attributes associated with using straw bales in buildings, with a growing body of research demonstrating long-term durability where best practices are followed (more of this in Section 2.2), wall thickness is largely dictated by the bale dimensions. This means incremental additions of insulation to achieve thermal insulation values exceeding RSI- 5.28 m^2K/W are not as straightforward as adding several more inches of straw, and adding a second bale width is for the most part impractical. Creating a wall assembly that achieves the R-values recommended by PHIUS (RSI- 6.87 to 11.45 m^2K/W for climate zones 6 and 7, which correspond to the select cities being studied), while still utilizing a typical 2-string straw bale, requires an approach that deviates from the typical straw bale building technique of stacking bales in a single width and plastering the bale face inside and out - what some have labeled a “first-generation” assembly (Graham, 2014).

1.3 Objectives

The objective of this research is to determine how typical 2-string straw bales may be used within above-grade wall assemblies for single family dwellings seeking to achieve Passive House certification (PHIUS+ 2015). Computer simulation, informed by best practices revealed during the literature review, will be used to create an optimized assembly that will then be adapted to a detached single-family reference house in three Western Canadian cities - Saskatoon, Calgary, and Kelowna - to satisfy the Standard.

1.4 Problem Statement and Research Questions

Although the PHIUS+ 2015 standard only focuses on reducing operational energy (Passive House Institute US , 2017), requirements for reducing the environmental and climate impacts associated with building materials and construction processes are on the rise. Architecture 2030, a leader in addressing the climate impact caused by the building industry, has called for zero carbon emissions by 2050 for all new construction, including both operational and embodied carbon (Architecture 2030, 2014). The use of cellulosic building materials, including straw bales, offers an important tool in the path towards zero carbon building. *Yet, at the time of this writing*, *there are no PHIUS+ 2015-certified projects built using straw bales* (L. White, personal communication Nov 9, 2017). This research will enable a clearer understanding of how typical 2-string straw bales may be used to satisfy these rigorous performance standards.

This project seeks to answer the following research questions:

- Are typical 2-string straw bales suitable for creating super-insulated wall assemblies?

- What is the configuration of the straw bale wall assembly and associated details that would satisfy Passive House certification (PHIUS+ 2015) in three Western Canadian cities - Saskatoon, Calgary, and Kelowna?

2.0 Literature Review

2.1 Passive House in North America

The performance-driven Passive House standard (PHI) that originated in Germany under the direction of Dr. Wolfgang Feist during the early 1990's emphasized five basic principles - thermal insulation, Passive House windows, ventilation with heat recovery, airtightness, and a thermal-bridge-free design (Paquin-Bechard, n.d.). Along with a series of recommendations, the PHI standard sets a minimum airtightness target (≤0.6ACH50), and limits primary energy consumption to ≤120 kWh/m^2/year. It also established a strict annual space heating limit of 15 kWh/m^2/year, regardless of where the building is located. Originally PHI partnered with Passive House Institute US (PHIUS) - the group that brought passive house principles to the US - but disagreements ensued over the appropriate approach for North America, where the climate is radically more variable than exists in continental Europe, not to mention the context for which building occurs (Paquin-Bechard, n.d.). PHIUS, working in partnership with the Building Science Corporation and the US Department of Energy, established a new standard with "climate-specific" targets tailored to their locale (Passive House Institute US , 2017). The latest iteration of this climate-specific standard is called PHIUS+ 2015 and its certification requirements are summarized in Table 1 (PHI requirements are included for comparison).

Table 1: Passive House Certification Requirements, adapted from PHIUS (2015).

Criteria	Unit	PHIUS	PHI
Primary Energy	varies	≤ 6200 kWh/person/year*	≤120 kWh/m^2/year
Annual Heating Demand	kWh/m^2	Climate specific** (3.16- 37.9)	15
Annual Cooling Demand	kWh/m^2	Climate specific** (3.16 - 67.6)	15
Peak Heating Load	W/m^2	Climate specific** (2.55 - 17.2)	10

Peak Cooling Load	W/m^2	Climate specific** (1.8 - 8.9)	8
Airtightness	varies	≤0.05 cfm/ft^2 envelope @ 50Pa	≤ 0.6ACH @ 50Pa
Ventilation	% efficiency	53 - 95	≥ 75
	Wh/m^3	0.159 - 1.313	≤ 0.447
Thermal Envelope	m^{2}K/W	~ RSI-4.40 - 14.09	≥ RSI-6.78
	W/mK	~ U-0.069 - U-0.0216	≤ U-0.0450
Thermal Bridge Free	W/mK	Ψ ≤ 0.01	Ψ ≤ 0.01
Windows Installed	W/mK	0.71-0.138	≤ 0.26
SHGC	%	~ 0.27 - 0.61	~ 0.50 - 0.55
Max ΔT Interior Air vs Interior Surface Temperature$^{\Omega}$	°C	≤4.0°C	≤3.0°C$^{\partial}$
Minimum Fresh Air/person	m^3/hr	30.6	30.6

* PHIUS calculates the number of residents as the number of bedrooms plus one.

** The targets for each of the select Western Canadian cities are listed in Section 5.2.4.

$^{\Omega}$ This comfort range is in keeping with ISO 7730, which documents the thermal comfort parameters for human comfort (PASSIPEDIA, 2017).

$^{\partial}$ Passive House Institute, 2016

Since 2011, when PHIUS and PHI parted ways, there has been exponential growth in passive house certifications in the US, with PHIUS-certifications accounting for the bulk of the market share (Figure 2; Frappe-Seneclauze, Heerema, & Wu, 2016). This growth, according to Klingenberg (2017), indicates that the certification protocols and climate-specific targets were successful in removing barriers that hindered earlier adoption.

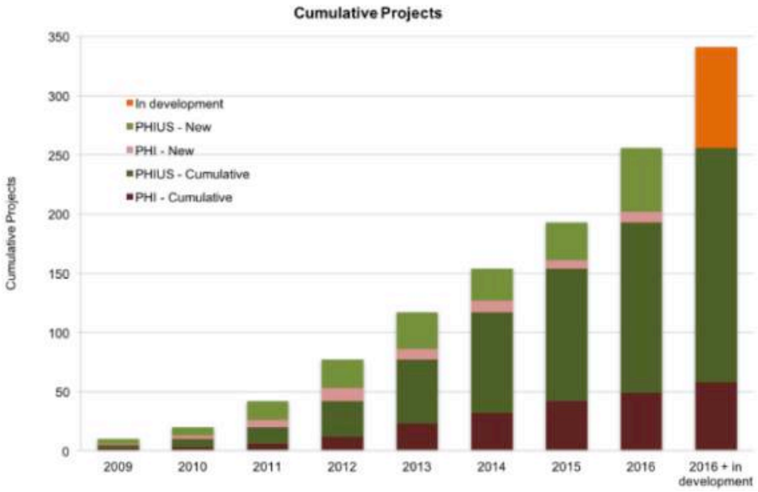

Figure 2: Passive House projects are on the rise and PHIUS-certified projects represent the bulk of the North American market share (adapted from Frappe-Seneclauze, Heerema, & Wu (2016).

2.2 Recent Developments in Straw Bale Construction

The main push for building with straw bales is the perceived environmental benefits. The combination of a low embodied energy/carbon and high insulation value material means that using straw bales can help reduce both embodied and operational energy/carbon by building with them. Offin (2010) found that a house built with a load-bearing straw bale assembly had the least embodied energy of all construction styles. Magwood (2015b) has published similar findings in relation to embodied carbon.

Despite these benefits, Canada does not have provincial or national straw bale building codes, and those straw bale buildings that have been approved have done so on a case-by-case basis (ASRi, 2013). Anecdotal evidence suggests that professional builders have been met with resistance when attempting to obtain warranty insurance for straw bale homes, so those wishing to live in a straw bale home must apply for an owner-builder exemption, which carries its own risks and responsibilities (ASRi, 2013). A lack of standardized best practices, misconceptions regarding fire and seismic safety, and durability concerns, particularly relating to moisture, have been cited as barriers to mainstream adoption of straw bale building (ASRi, 2013; King, 2006; Holzhueter, 2010).

Recently, though, the International Code Council (ICC) officially recognized straw bale construction with its inclusion of Appendix S in the 2015 International Residential Code (IRC) – the basis for the residential building code in virtually every jurisdiction in the United States (The Institutes CPCU Society: Underwriting Interest Group, 2016). This is an important development and is a major step forward in the acknowledgement of straw bales as a suitable building material. Its inclusion in the IRC will hopefully make consumers, builders, lenders, insurers, and inspectors less leery of straw as a building material, thus increasing the number of permitted straw bale projects in the US. One can only hope that this development will raise awareness that will trickle north of the border.

2.2.1 Structure

Straw bales can be used as a structural component in a building - structural load-bearing or structural shear wall - or simply as infill (ASRi, 2013). Variations of these are many and are well described in the Alternatives Solution Resource (ASRi, 2013), as well as in the various current books about straw bale construction (Magwood, 2005; Steen, Steen, & Bainbridge, 1994; Lacinski & Bergeron, 2000). While structural load-bearing assemblies are generally the simplest to build, reduce wood use, and thus have a lower embodied energy and carbon footprint (Offin, 2010), they preclude having a roof during construction making the technique only practical in the driest of climates. Snow and seismic loads require additional structural considerations. For these reasons, infill techniques represent the majority of North American straw bale buildings (Bronsema, 2010).

There are numerous structural details pertaining to straw bale buildings, particularly where straw bales are used as a structural component. Bruce King's "Design of Straw Bale Buildings" (2006) provides a good summary of the current state of the art, covering the load bearing capacity of walls, plaster strengths and reinforcing, earthquake resistance, fire safety measures, and other related topics.

2.2.2 Hygrothermal Properties of Straw Bale Walls

Thermal Performance

The thermal conductivity of straw bales has been well researched over the past 25 years. The type of straw, its moisture content, density and the orientation of the fibres, and other elements such as the type of finish, all impact the overall thermal performance of the assembly. A thorough overview of the history of this research is provided by Bronsema (2010), where it is noted that the quality of the results for the overall thermal performance of an assembly is strongly influenced by the construction technique utilized. Density has a significant influence on conductivity, with higher bale densities generally providing better thermal performance (International Code Council (ICC), 2015). Appendix S of the 2015 IRC, states that "bales shall have a minimum dry density of 6.5 pounds per cubic foot (104 kg/cubic meter). The dry density shall be calculated by subtracting the weight of the moisture in pounds (kilograms) from the actual bale weight and dividing by the volume of the bale in cubic feet (cubic meters)" (International Code Council (ICC), 2015).

While there is a poor correlation between the measured conductivity of straw and the measured R-value of plastered walls (Bronsema, 2010), testing of plastered straw bale walls using a guarded hot-box facility, has led to some recommendations. Andersen (2001) (as cited in Bronsema, 2010) advises using a conductivity for straw of 0.08 W/m-K, a value slightly more conservative than the reported range of 0.06-0.075 W/m-K suggested by Struabe & Burnett (2005). Where best practices are followed, Bronsema (2010) advises using conductivities between 0.060 and 0.070 W/m-K for bales laid on edge (heat flow perpendicular to the grain) and between 0.065 and 0.075 W/m-K for bales laid on flat (heat flow parallel to the grain).

These values, though they are in line with the oft-citied 4.76 m^2K/W to 5.28 m^2K/W given to a plastered straw bale wall (ASRi, 2013; King, 2006; Magwood, Essential Prefab Straw Bale Construction, 2016; Stone, 2003), they are generous compared to thermal resistance values for straw bales included in Appendix S of the 2015 International Residential Code (IRC). In it, the permitted R-values are 1.3 per inch (0.11 W/m-K) for bales laid flat and 2 per inch (0.072 W/m-K) for bales on-edge. This is likely a broad net intended to capture instances where best practices are not followed, but seeing that straw bale construction is now effectively codified, at least in many parts of the US, these values are significant. Given the tremendous experience of those involved in shaping Appendix S, and noting the inherent variability of straw bales as a building material, using these especially conservative values seems prudent, especially in high performance construction where precision matters.

The type of plaster used with the assembly has little bearing on the thermal resistance of the assembly since the R-value of the plaster is generally less than 5 percent of the R-value of the straw bale (Bronsema, 2010).

Air Permeability and Convection

Air spaces that bypass insulation in cavities results in natural convection, which negatively impacts the thermal resistance of an assembly. Filling voids between bales and framing members with loose straw to a density comparable to the bale is essential for maintaining thermal continuity. The importance of this was demonstrated by Andersen (2001), who found that the U-factor increased by more than 10% by not properly dealing with voids within the straw bale assembly being tested, an effect that increases with temperature differences through the straw (as citied in Bronsema, 2010). Similar findings were reported by Rissanen & Viljanen (1998) in their work on the thermal conductivity in flax straw.

Reducing air gaps between the plaster and straw is also important, as this too can contribute to natural convection, thus increasing heat flow. A 1996 test on a straw bale wall system at the Oak Ridge National Labs (ORNL), resulted in R-values one third of what had previously been reported (Stone, 2003). This result was due to the presence of numerous and significant air gaps between the bales and the interior mounted sheetrock and between the bales and the exterior stucco (Stone, 2003). To the testers credit, this was a demonstration for elementary school teachers and not as a rigorous attempt at measuring thermal performance. It does however serve a purpose in demonstrating the need to avoid gaps between bales and the finish used to encase them.

Moisture

Rotting of straw is the largest durability concern for straw bale buildings (Holzhueter, 2010). Reducing high moisture levels in straw from built-in moisture, interior and exterior humidity, driving rain, splash back, ground moisture and plumbing leaks is necessary to prevent decay. The process of decay in cellulosic materials, including straw, is covered in detail by Holzhueter (2010) and Bronsema (2010), and in lesser detail by King (2006).

To deal with built-in moisture, the moisture content of straw bales at the time of installation should not exceed 20% the total weight of the bale (ASRi, 2013;

International Code Council (ICC), 2015). Once moisture content exceeds 20% mold spores may start to grow (ASRi, 2013).

Rain control is crucial to avoid freeze-thaw damage, corrosion and decay, and the ‘Canadian holistic approach’ as described by the three D’s, 1) Deflection, 2) Drainage/Storage/Exclusion, 3) Drying, should guide decisions to mitigate durability and health problems (King, 2006).

Building shape and site design are important considerations, especially as straw bale walls tend to use the storage approach for dealing with moisture (King, 2006). Thus, minimizing wetting is essential. According Gonzales (n.d.), the 3-foot (~1 metre) overhang rule-of-thumb has been used for one-storey buildings, while larger roof overhangs are recommended for taller buildings (as citied in ASRi, 2013). Where there is high exposure, rainscreen designs are possible and desirable. In all cases, adequate drip overhangs and flashing details must be in place to move water away from the walls.

Grade separation and the use of porous surfaces are used to control splashback, and keeping bales a minimum of 203 mm (8 inches) above grade is generally considered the minimum for straw bale walls (King, 2006). A moisture break between the ground (typically the foundation interface) and the wall prevents moisture migration through capillary action.

Air Barriers

Airtightness is important to reduce energy loss and to guard against condensation problems assosciated with uncontrolled movement of moisture-laden air into wall assemblies. Interior plasters generally provide the air barrier to a straw bale wall assembly but they must be continuous to be effective. Where plasters meet dissimilar materials, particularly at intersections with the floor, window and door jambs, ceiling, and framing members, careful detailing is required to ensure there is no air leakage into the wall assembly. Historically, achieving airtightness with straw bale assemblies has been a challenge - a point well described by Racusin, Graham, & McArleton (2011), whereby post-occupancy energy performance evaluations of seven recently built straw bale homes in the northeastern US found substantial air leakage (all projects tested ≥2.5 ACH50), even where secondary air barrier strategies were deployed. This research represents the largest single effort to collect energy performance metrics on straw bale homes in North America to date. Assembly specific strategies for controlling air leakage at critical intersections, including recommendations from the report, are covered in Section 5.3.5.

Vapour Control

Numerous studies have shown that straw bale wall assemblies must have the ability to transfer and release water vapour in order to prevent long-term accumulation of moisture (Gagne, 1997; Jolly, 2000; Holzhueter, 2010; Bronsema, 2010). Managing the moisture balance depends on having air barriers and using vapour control measures that minimize diffusion wetting and that promote drying of incidental moisture. The combination of straw and plaster has significant vapour diffusion resistance and large moisture storage capacity, making conventional ‘vapour barrier’ strategies unnecessary and even detrimental (King, 2006).

A typical 460mm (18 inch) straw bale has a vapour permeance ranging from 110-230 ng/Pa-s-m (~2 to 4 US perms) and evidence suggests the total cumulative permeance of the plaster skins on either face should not be less than 290 ng/Pa-s-m (~5 US perms), including any any surface treatment or sealer, to encourage fast drying (ASRi, 2013). Appendix S of the 2015 International Residential Code (IRC) states that “Class I and II vapour retarders shall not be used on a strawbale wall, nor shall any other material be used that has a vapor permeance rating of less than 3 [US] perms [172 ng/Pa-s-m]…” (International Code Council (ICC), 2015, pp. S-7).

In general, limiting humidity to 80% RH within the assembly will prevent mould growth, though Bronsema (2010) suggests that this static limit imposed for all temperatures is overly conservative, and “does not include time to germination…[and that] small fluctuations above these limits are likely not going to lead to mould growth…” (pg. 56). Keeping below this upper limit is, however, a useful reference point for evaluating the suitability of an assembly in regards to health and long term durability (PHIUS, 2015).

2.3 Case Studies on High Performance Straw Bale Walls

The following case studies provide an overview of how typical 2-string straw bales have been used to build high performance wall assemblies. Common to the projects is an increased emphasis on airtightness, super insulation, and reduced thermal bridging to achieve the increasingly rigorous performance standards such as Passive House.

2.3.1 S-House

As part of the “Building for Tomorrow” subprogram, the Center of Appropriate Technology (GrAT/Gruppe Angepasste Technologie) at the Vienna University of Technology developed a concept house (“S-House”), which sought to meet the strict energy targets of the passive house method using renewable materials. The target was to create a building that used only 10 percent of the resources and energy compared to conventional Austria construction (GrAT, 2004).

Figure 3: S-House (GrAT, 2004)

The wall assembly was made up of an inner wooden plate structure (CLT), wrapped in straw bales on the exterior. The exterior straw bales were then coated with a single coat of clay plaster to seal the bales, thus making the ventilated façade less vulnerable. Custom designed Treeplast screws - made from a lignin based biopolymer and measuring 365mm (14.6 inches) in length - were used to fasten counterlathing to the straw bale wall in order to mount the wooden siding, completing the rainscreen (Figure 4; Wimmer, Hohensinner, & Drack, 2004).

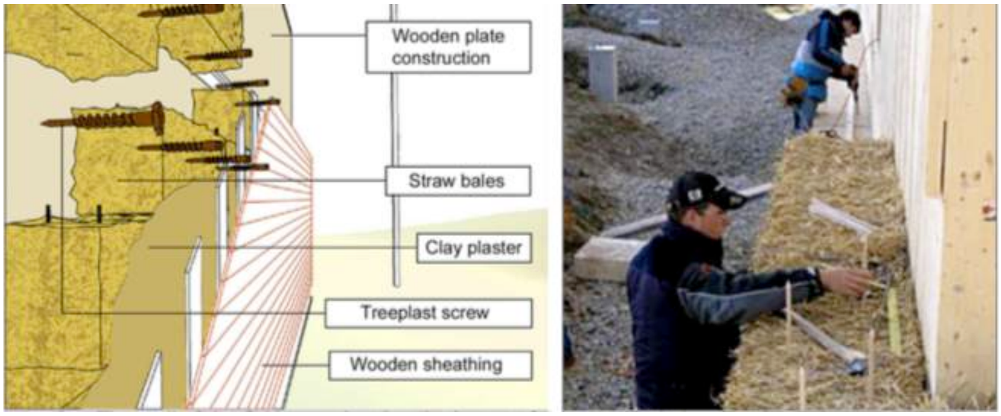

Figure 4: The wall of the S-House showing the layers of the straw bale insulated novel construction in a model and on the building site (adapted from Wimmer, Hohensinner, & Drack (2004)).

The building was fitted with sensors to allow for long-term monitoring of the building components and materials, assessing humidity, temperature, heat flow, and proofing of airtightness. Unfortunately, only several months of data has been made publically available (http://www.s-house.at/BSaktuelleWerte.htm)[1], making it difficult to draw conclusions on the success of this system. It does, however, mimic a "perfect wall" assembly, with the structure inbound of the insulation, which has the added protection of a ventilated rain screen. According to Brian Fuentes, a Colorado-based architect who has used the S-House as inspiration for the straw bale projects he has worked on, including his own home, says the "S-House" represents a high achievement for integrating straw bales into high performance buildings (personal conversation Sept 19, 2017).

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[1] Requests for additional monitoring data for the S-House were unsuccessful.

2.3.2 Modcell

Developed through a collaboration with the Department of Architecture & Civil Engineering at the University of Bath, Modcell strawbale SIPs (structural insulated panels) have gone through rigorous scientific monitoring and testing, culminating in industry standards that show their energy efficiency, fire safety, long term durability, and ability to withstand extreme weather events (University of Bath, 2017). BM TRADA's Q-Mark certification provides assurances of all these qualities and enables developers and homebuyers to obtain insurance and mortgages for straw bale homes and buildings (University of Bath, 2017).

The ModCell Core + panel has received recognition as a 'Certified Passive House Component', meeting the necessary heat transfer coefficient for the building envelope, thermal bridge free design connection details, and airtightness requirements for all components and connection details (ModCell, 2017). A 400mm (16 inch) deep wood frame contains the straw bales and the system is dry lined using breathable sheathing boards - a 15mm (5/8 inch) OSB3 VCL sheathing board on the interior, and a combination 12mm (1/2 inch) external breather board with a 40mm (~1 5/8 inch) wood fibre breather/plaster carrier - and finished with 7-8mm (~1/3 inch) of breathable exterior lime render (Figure 5/Figure 6; ModCell, 2017). The 0.49m thick wall panel has a thermal heat transfer coefficient of 0.122 (W/m^{2}K), which results in a RSI of 8.20 (m^{2}K/W; R-46.54)[2].

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[2] The Modcell thermal resistance claim relies on straw bales with a thermal conductivity in the ballpark of 0.06 W/m-K (noting that their bales are 400mm deep versus 356mm deep for common North American straw bales on edge). This is in line with the recommend thermal conductivity range of 0.060 and 0.070 W/m-K for bales on edge noted in the literature review, and the slightly more generous than the 0.0721 W/m-K given to straw bales used in this research.

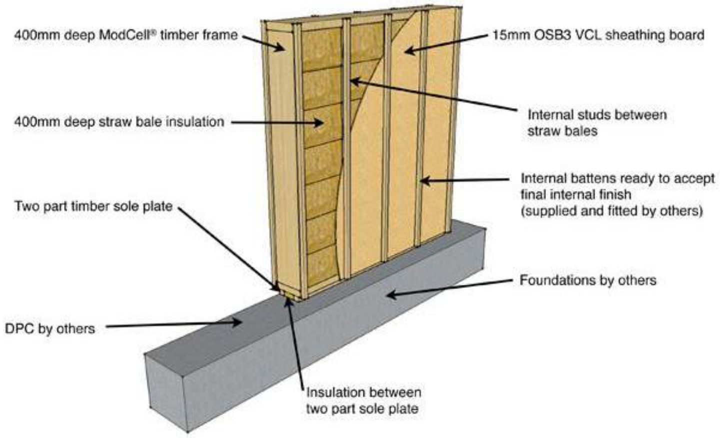

Figure 5: ModCell Core + Internal View (adapted from (ModCell, 2017)

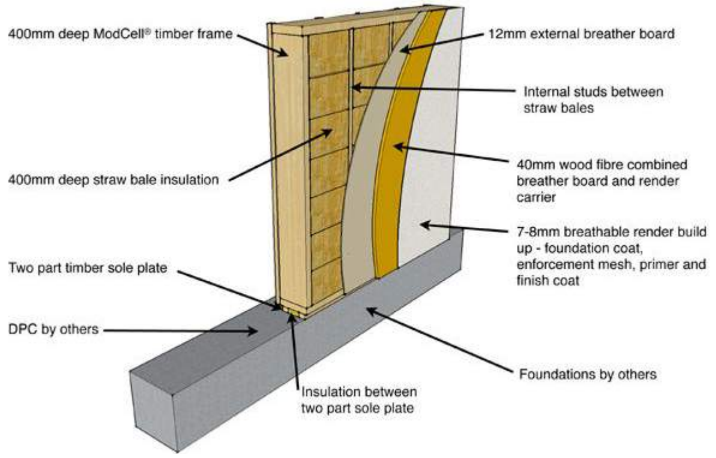

Figure 6: ModCell Core + External View (adapted from (ModCell, 2017)

ModCell Core + has been developed with 26 compliant construction details including basement, wall and rood intersections, ceiling, partition and window details that can be used across Europe (ModCell, 2017). Modcell panels have been used in dozens of projects across Europe, including in schools/secondary institutions, business complexes, retail/commercial spaces, community projects and residential dwellings.

2.3.3 StrawCell

StrawCell - a portmanteau that merges straw bales with dense packed cellulose - is a concept developed by New Frameworks of Vermont. The assembly affixes a typical 2-string bale to an externally framed wall that is dense packed with cellulose (Graham, 2014). Its development came about after an energy audit of seven straw bale homes initiated by the group, which showed some consistent problem areas. *StrawCell* sought to create better straw wall details to promote greater airtightness, accommodate modifications for increased energy performance (e.g. increased R-value), and to make construction easier and more affordable (Graham, 2014).

The layers of the assembly from exterior to interior include (Figure 7):

- Exterior siding over a ventilated rain screen;
- WRB over 13mm (½ inch) insulated sheathing;
- 2x6 exterior load bearing wall insulated with dense packed cellulose;
- Straw bale on edge secured to 2x framing and plastered on the interior face (New Frameworks, 2013).

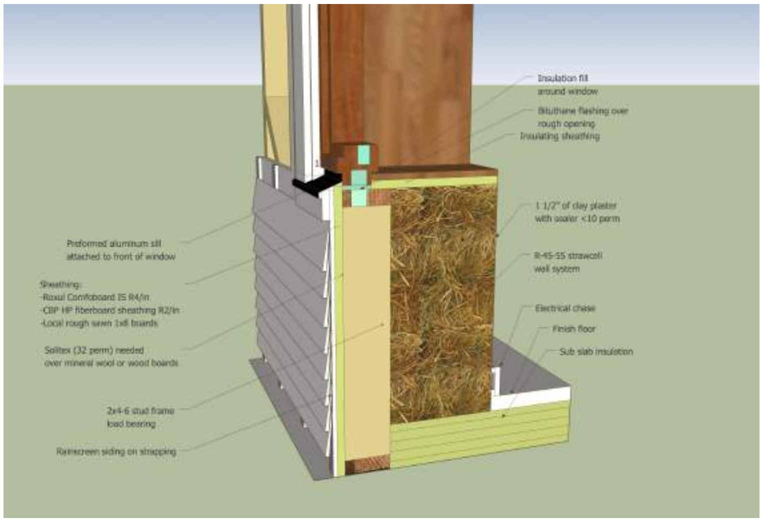

Figure 7: The StrawCell Wall Assembly (New Frameworks, 2013).

Some of the distinguishing features of this system include:

- No exterior plaster, which eliminates a time-consuming and weather sensitive step (this has the added benefit of extending the building season for working with straw bales, which is often limited to warm months);
- Straw bales are placed to the interior of the frame, making them less susceptible to weather during construction;
- 13mm (½ inch) vertical lath is used on the inside face of the bales to sandwich the bales to the framed wall. This creates stability in the unplastered wall so that

the bale strings can be cut to reduce time associated with stuffing the voids between bales;
- Interior structural elements are eliminated, thus creating fewer interruptions that can interfere with the interior plaster air barrier;
- Windows and doors are finished in the same way as typical construction;
- The additional depth of insulation makes achieving increasing standards for superinsulated structures (e.g. Passivhaus) possible;
- Increased flexibility for siding options to fit with the local building vernacular (New Frameworks, 2013).

Overall, adding 140mm of dense packed cellulose to the straw bale wall adds an additional RSI-3.79 m^2K/W, resulting in a total RSI-9.07 m^2K/W for the entire assembly. This represents a 70% increase in thermal resistance over a typical single-width plastered straw bale wall. Additionally, the cellulose blown against the face of the bales deals with any voids resulting from the irregularity of the bale surface, and thus creates a flat, thermally connected surface for which subsequent layers can be affixed.

2.3.4 Zero House

The Zero House was a joint project between The Endeavour Centre and Ryerson University's Department of Architectural Science and centered around five main concepts: 1) zero net energy use, 2) zero carbon footprint, 3) zero toxins, 4) zero construction waste, 5) zero cost premium over conventional construction (Alter, 2017). The demonstration unit was designed not as a sand alone house, but as a unit that could be assembled into a larger housing development (Alter, 2017). The entire building was prefabricated and modular, and included a variety of assembly configurations used to showcase the range of options for achieving these goals.

Two of the walls included straw bales in a prefabricated panel (Figure 8) using two different insulation boards - one wood fibre-based, the other mycelium-based - on the exterior face of the panel to boost the R-value of the assembly. The interior was finished with ReWall EssentialBoard - a structural sheathing product made from 100% recycled beverage containers. The RSI values of these assemblies were 6.87 m^2K/W and 7.22 m^2K/W respectively (Endeavour Centre, 2017).

Figure 8: Straw SIP used in Zero House (Endeavour Centre, 2017).

The water vapor transmission of the interior structural sheathing product (<57.2135 ng/Pa-s-m (1 US perm), which constitutes a Class I vapor retarder) does not satisfy best practice, and fails to comply with the recommendations in Appendix S of the 2015 International Residential Code (IRC). Despite this, the design team was comfortable with assembly after a hygrothermal analysis done by the Ryerson Architectural Science students involved with the project showed no signs of elevated moisture (C. Magwood, personal communication Dec 17, 2017). This suggests that assemblies that deviate from best practice may indeed yield acceptable results but must be assessed on a case by case basis to avoid issues related to durability, health and performance.

2.4 Literature Review Conclusion

Passive Houses have set a high bar for energy performance, long-term durability, and human health and comfort. The Standard represents where most building/energy codes are headed (Yip & Richman, 2015), and the performance targets align with the conservation goals promoted by organizations such as Architecture 2030, at least with regards to operational energy savings. Limiting embodied carbon emissions in buildings is also needed and straw bales have many qualities that make them well suited to high performance construction, while also sequestering carbon and locking it up over the life of the project. However, the successful use of straw bales in high performance building requires that best practices be followed. Choosing bales with the desired density and ensuring that voids are filled to reduce natural convection is necessary to achieve thermal performance in line with published values, while managing moisture is largely a matter of good design and proper implementation, especially with regards to ensuring adequate airtightness and controlling rain exposure. Using dry bales and keeping them dry during the construction process is necessary to avoid microbial decay. The case studies above demonstrate novel ways of combining straw bales with compatible off-the-shelf building materials to satisfy increasingly stringent energy performance standards, though the development of these hybrid assemblies is still very much in its infancy. Just as the StrawCell assembly was developed to address the specific needs of those building in the cold and wet climate of the Northeastern USA, it is only natural that other configurations will come about to meet the unique needs of other regions, whether to satisfy local code requirements, to achieve certain performance targets, to make use of locally available materials and/or trade skills, or to deal with weather and climate variables. High performance straw bale assemblies specific to Western Canada have received little focus and this research seeks to address this gap by defining and evaluating a high performance straw bale wall assembly that is regionally relevant and climate appropriate, and specific to achieving PHIUS+ 2015 in the three select cities.

3.0 Research Approach

A reference house previously certified by the Canadian Passive House Institute (CanPHI) in 2015 was used to test the impact of a straw bale wall assembly developed to satisfy the various compliance thresholds needed to achieve PHIUS+ 2015 certification for the select cities. A complete description of the reference house is presented in Section 4.0.

A whole building energy model was created using WUFI Passive - a software program used to determine the operating energy consumption in accordance with the Standard. Early assessments comparing predicted modeled performance with actual usage from measured data shows that the PHIUS+ 2015 algorithms and assumptions appear accurate, though this work has largely been restricted to multifamily dwellings (Klingenberg, 2017). It is anticipated that as projects become more numerous, and as more measured data is collected, similar assessments will be conducted on differing building archetypes, creating more measured data feedback loops in an effort to hone the accuracy of the modeling tools (Klingenberg, 2017).

The model was populated using the parameters from the Passive House Planning Package (PHPP) submitted with the original PHI certified project (the full PHPP is included in Appendix I). Three models - one for each of the select cities - were created and simulations were run using PHIUS approved climate data for each location. As the performance requirements are unique to each location, and because protocols for achieving compliance differ between the two Standards, minor adjustments were made to each model to achieve compliance with the PHIUS+ 2015 standard. An overview of the whole building energy modeling process is provided in Section 5.2.

Once compliance was achieved for each of the select locations, the ‘as-designed’ above-grade walls were then substituted with a straw bale wall assembly that maintained compliance. Defining an appropriate straw bale assembly was accomplished through an iterative process, adjusting the assembly as necessary to satisfy the targets set by the Standard for each location, and informed by the best practices revealed during the literature review. An overview of this assembly is provided in Section 5.3.

Where modifications were made to the original design to accommodate the straw bale wall assemblies, thermal bridge analysis was carried out. An overview of thermal bridge free construction is provided in Section 5.3.5 and the results of the thermal bridge analysis are given in Section 6.2.

Finally, the hygrothermal performance of each straw bale wall assembly used to achieve PHIUS+ 2015 compliance for each of the select cities was conducted using WUFI Plus. A full overview of this process is covered in Section 6.3. The research approach is summarized in a flow chart in Figure 9 below.

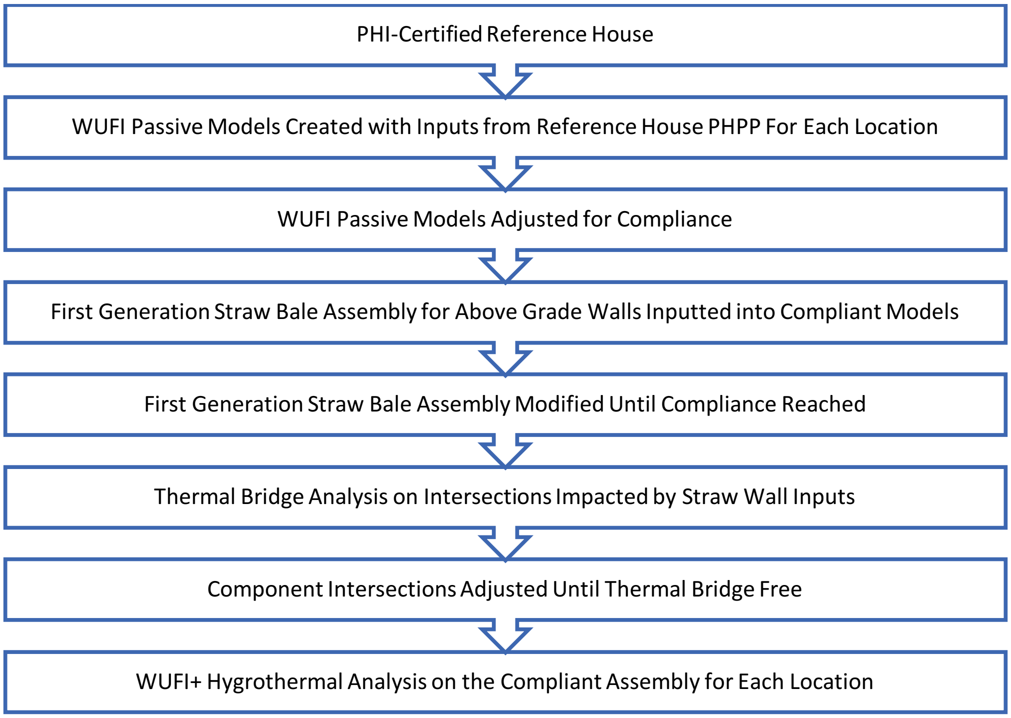

Figure 9: Research Approach

4.0 Reference Building Design

4.1 Building Typology

The reference building is a single-family detached (SFD) house with a basement suite built in Calgary, Alberta and certified by the Canadian Passive House Institute (CanPHI) in 2015 (Figure 10). This home was chosen for three primary reasons. Firstly, since this is a certified Passive House, the integrity of the design - orientation, floor plan layout, windows and components, and mechanical systems - could be maintained while simply allowing for the wall assembly to be modified to measure the impact on performance. Secondly, SFDs represent over half of the residential dwelling units in Canada and over 67% of total built floor area (Natural Resources Canada, 2014). It also represents the primary typology for which straw bales are used in construction (ASRi, 2013). Thirdly, the inclusion of a secondary suite in the home represents an additional technical challenge for achieving the Standard but the prevalence of secondary suites in Canada is on the rise and this trend is projected to continue (Canada Mortgage and Housing Corporation, 2017).

Figure 10: Reference House (Passive House Canada, 2017)

4.2 Reference House Description

4.2.1 Building Geometry and Orientation

The reference house has a treated floor area of 256.4 m^2 (2759.9 ft^2), with a 104.6 m^2 (1,125.8 ft^2) basement suite and the remaining 1,634.1 ft^2 (151.8 m^2) divided between the main floor and loft area. The building geometry is compact, with a minimal footprint. The front of the house orients south-southwest at 196 degrees. The architectural drawings of the basement and main floor plans are shown in Figure 11. Site plan, sections and elevations of the reference home have been included in Appendix II.

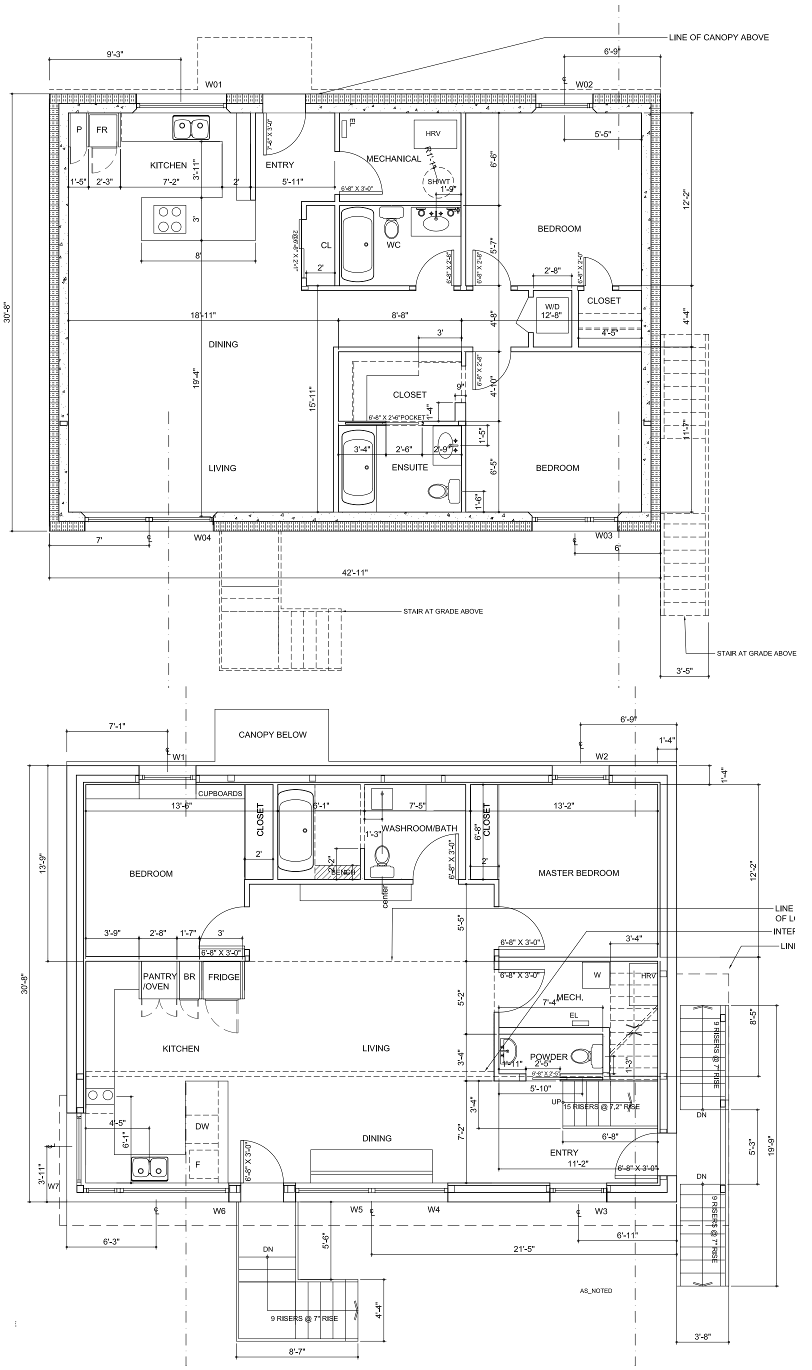

Figure 11: Basement (upper) and Main Floor (lower) Floor Plans (adapted from LVDesign, 2014).

4.2.2 Suitability for Straw Bale Integration

Overall, the reference house design is not ideally suited for straw bales. It’s sloping roofline, for example, would require that the straw bales be modified and fitted to the shape rather than the shape conforming to the bale. Furthermore, fitting bales above the structural beam supporting the clerestory would prove challenging. As was discussed in the literature review, designing around a bale module is the most effective path to creating a high performance enclosure. Eliminating complex shapes during the design phase is essential for maintaining thermal continuity and air tightness, while also improving buildability. These points will be further discussed in Section 5.3.

4.2.3 Building Envelope

The basement slab and walls are traditional concrete wrapped in 203mm (8 inches) of EPS foam, with the concrete slab exposed to provide accessible thermal mass. The main level and loft walls are 38x140mm (2x6 inch) framing with additional exterior rock wool insulation. The roof assembly consists of a 406mm (16 inch) TJI with blown-in fibreglass, with an additional 38x38mm (2x2) insulated service cavity behind the interior gypsum wall board. The reference building envelope sections are presented in Figure 12 and assembly thermal properties are summarized in Table 2.

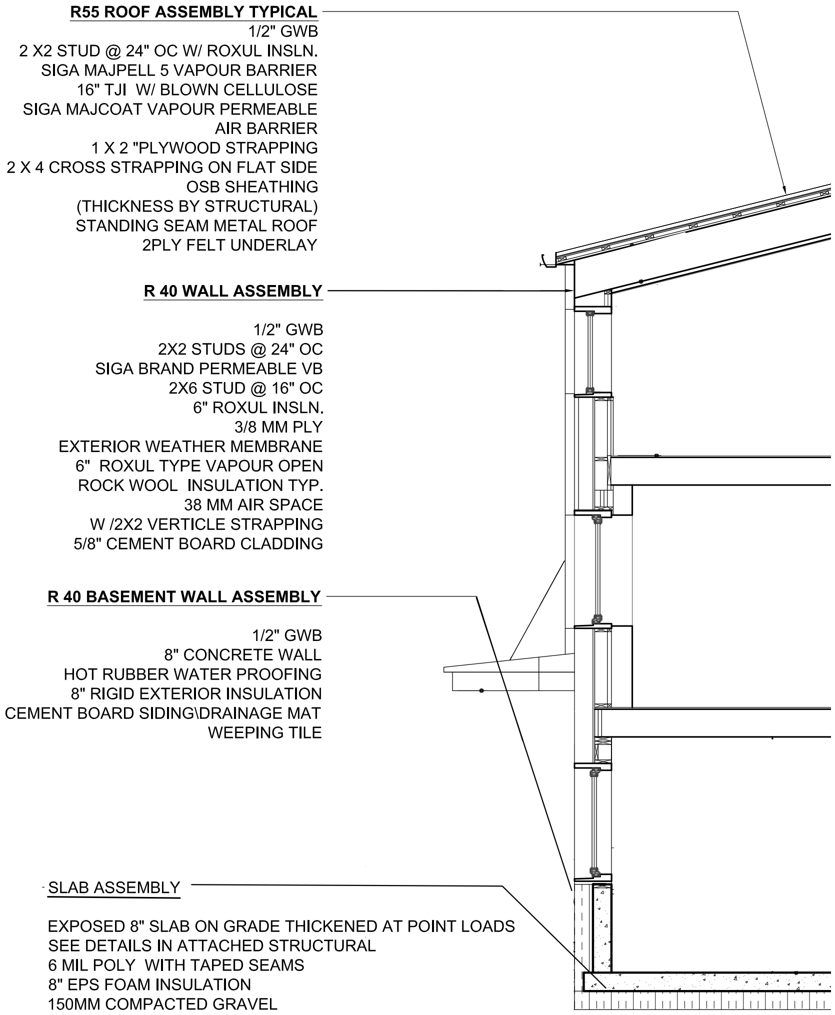

Figure 12: Reference House Section (adapted from LVDesign, 2014).

Table 2: RSI Values of Reference House Assemblies

Assembly Type	Insulation Type	RSI-value (m^2K/W) from WUFI Passive*	RSI-value (m^2K/W) from PHPP
Basement Wall	EPS	6.37	6.42
Slab	EPS	6.31	6.39
Above Grade Wall	Mineral Wool	8.03	7.70
Roof	Blown-in Fibreglass & Mineral Wool	10.54	10.36
* These RSI values are from WUFI Passive using the assembly configuration noted in the architectural plans and thermal conductance values noted in the PHPP. The differences in values are the result of rounding between metric and imperial inputs and their conversion within WUFI Passive.			

4.2.4 Glazing Size and Orientation

PHI-certified triple-glazed windows were used throughout. The window frames are PVC with PU-foam insulation in the air chambers. A warm edge spacer is used and the sealed units are filled with Krypton gas. South and west-facing windows have a high solar heat gain coefficient (SHGC), while north-facing windows have a low SHGC. There are no east-facing windows. A summary of the window properties specified for the reference building is provide in Table 3. The total window area is 39.4 m^2 (28.3 m^2 glazed area).

Table 3: Window Performance Data

Window Number	Façade	Frame Type	Total U-value* (W/m^2-K)	SHGC (-)
1	South	Fixed	0.76	0.5185
2	South	Tilt & Turn	0.77	0.5185
3	South	Casement	0.77	0.5185
4	South	Fixed	0.84	0.5185
5	South	Tilt & Turn	0.83	0.5185
6	South	Fixed	0.77	0.5185
7, 8	South	Fixed	0.75	0.5185
9	South	Tilt & Turn	0.82	0.5185
10, 11	South	Fixed	0.80	0.5185
12, 13	South	Fixed	0.62	0.5185
14, 15	South	Awning	0.81	0.5185
16, 17	North	Tilt & Turn	0.76	0.4165
18	North	Fixed	0.76	0.4165
19	North	Tilt & Turn	0.77	0.4165
20	North	Fixed	0.71	0.4165
21	North	Fixed	0.70	0.4165
22	North	Casement	0.76	0.4165
23	West	Fixed	0.81	0.5185

* Total U-value represents weighted centre-of-glass and frame U-value, including the Ψ_{Spacer} & $\Psi_{Installation.}$

4.2.5 Doors

There is a total of three exterior doors. Two (one north-facing, another east-facing) are solid 3 hinge fiberglass PU-insulated doors with a single deadbolt. The U-Value for each of these doors is 0.80 W/m^{2}K. The remaining door (south-facing) contains a 1.5 m^2 PHI-certified triple-glazed unit with U-Value of 0.82 W/m^{2}K and a SHGC of 0.5185. A warm edge spacer is used and the sealed units are filled with Krypton gas.

4.2.6 Ventilation System

Two separate ERVs were installed to provide ventilation in each dwelling unit - one in the basement suite, another for the upper levels. It is a certified component by PHI, and is rated for air flow rates of 60 to 150m^3/h (Zehnder, n.d.). Each unit has an effective heat recovery efficiency of 89.4% and an electric efficiency of 0.42 Wh/m^3. The units allow for air flow balancing and has frost protection for the heat exchanger with continuous fresh air supply down to -15°C (outdoor air).

4.2.7 Heating, Cooling and Domestic Hot Water (DHW)

Solar thermal flat plate collectors, covering 11m^2, provide an estimated 74% of DHW needs. A condensing gas boiler with an 80% efficiency (at constant operation) feeds hydronic coils in the supply air streams for additional space heating and makes up the balance of DHW needs.

4.2.8 Thermal Bridges

No thermal bridging data was inputted into the PHPP, suggesting that a thermal bridge analysis was not completed or the values were not significant enough to require inclusion.

4.2.9 Air Tightness

An air change rate of 0.3 1/h was used for calculation purposes. This value also aligns with the verified pressurization test result as reported in the PHPP.

5.0 Reference Building Simulations

5.1 Chosen Geographic Locations

Geographic locations were selected to reflect three relatively different climates in Western Canada (Table 4), each with good access to a straw resource and in locations with a population of over 100,000 people, whereby sustained population growth is anticipated to carry into the future (Statistics Canada, 2017). The three locations selected were Saskatoon, Calgary, and Kelowna.

Table 4: Subject Location Selection Criteria

Location	Climate Factors*		Annual Precipitation (mm)**	Distance from Straw (km)$^{\Omega}$
	Heating Degree Days (HDD)	Cooling Degree Days (CDD)		
Saskatoon, SK	5785.6	101.5	353.7	<25
Calgary, AB	4967.9	45.7	418.8	<50
Kelowna, BC	3554.5	218.8	386.9	<100

* Adapted from Canada Weather Stats (2017) and represent an average of the 1992 to 2016 weather data.
** From weatherbase.com
$^{\Omega}$ Based on the author's experience obtaining straw in these areas.

5.2 Whole Building Energy Model

5.2.1 Whole Building Energy Modeling Software

WUFI Passive 3.1 was used to create a whole building energy model using the design and parameters of the reference house described in Section 4.2. Fraunhofer Institute for Building Physics collaborated with PHIUS and Owens Corning to develop a software tool that is suited to the varying climate zones found in North America (PHIUS, 2017). Climate-specific performance targets are entered into the software, along with PHIUS-approved climate data, allowing for buildings to be easily evaluated for compliance with the PHIUS+ 2015 Passive Building Standard.

5.2.2 Weather Data

Climate data may be entered manually or loaded into the WUFI Passive software in a pre-formatted file type, though all climate data must be approved by PHIUS for each project (PHIUS, 2017). The climate files for the select cities were acquired from PHIUS in an XLS format and loaded directly into WUFI Passive without modification.

5.2.3 WUFI Passive Modeling Procedure & Assumptions

A 3-D model was created in SketchUp based on the architectural plans and imported into WUFI Passive. The model was then populated with the parameters from the Passive House Planning Package (PHPP) submitted with the original project. The inputted floor area value was adjusted to reflect the fact that PHIUS+ and PHI calculate living space differently. While PHI calculates Treated Floor Area (TFA) - the living or useful floor area within the thermal envelope, PHIUS calculates the Conditioned Floor Area (iCFA) - the interior (drywall-to-drywall) floor area within the conditioned space with at least seven feet ceiling height (Passive House Institute US , 2017). The calculation method has implications for the performance targets, which are largely measured on a per unit of floor area basis. The calculated areas for the reference house based on the two calculation methods are shown in Table 5.

Table 5: Floor Area Calculation Methods

Certification Standard	Measurement Method	Area
CanPHI	Treated Floor Area (TFA)	256.4 m^2 (2759.9 ft^2)
PHIUS+ 2015	Internal Conditioned Floor Area (iCFA)	245.7 m^2 (2644.6 ft^2)

PHIUS and PHI also calculate the number of occupants differently. The calculation method and the calculated number of residents for the reference house based on each standard is shown in Table 6.

Table 6: Number of Residents Calculation Method

Certification Standard	Measurement Method	# of Occupants
CanPHI	35m^2/person	7.3
PHIUS+ 2015	# of bedrooms + 1*	6
* This is calculated per dwelling unit. In the case of the reference house, there are 2 units, each with 2 bedrooms.		

5.2.4 WUFI Passive Simulations

Using the parameters outlined in Section 4, and accounting for any changes owing to PHIUS requirements (see Section 5.2.3), a model was created for each location to determine compliance with the PHIUS+ 2015 Passive Building Standard using PHIUS-approved climate data and the climate-specific performance targets. The performance targets for each location are listed in Table 7.

Table 7: PHIUS Climate-Specific Targets for Select Locations

Location	Zone	Annual Heating Demand (kWh/m^{2}a)	Annual Cooling Demand (kWh/m^{2}a)	Peak Heating Load (W/m^2)	Peak Cooling Load (W/m^2)
Saskatoon, SK	7A	28.39	3.15	19.24	11.67
Calgary, AB	7A	27.13	3.15	19.24	10.41
Kelowna, BC	6	21.77	3.15	15.77	11.99
Additional targets: Source Energy Demand: ≤6200 kWh/yr/person Airtightness: ≤0.05 cfm/ft^2 envelope* @ 50 Pa * gross envelope area external of the thermal boundary					

5.2.5 WUFI Passive Results and Discussion

The ‘as-designed’ reference home complied with 4 of 5 of the climate-specific targets in all three locations. The annual cooling demand, however, was exceeded in all instances, surpassing the limit by a factor of 2.96 in Calgary, 3.49 in Saskatoon, and 4.78 in Kelowna. These results of this initial analysis are displayed in Table 8.

Table 8: As-Designed Outputs and Targets for Select Cities

Location	Annual Heating Demand (kWh/m^{2}a)		Annual Cooling Demand (kWh/m^{2}a)		Peak Heating Load (W/m^2)		Peak Cooling Load (W/m^2)		Source Energy Demand (kWh/person-yr)	
	Output	Target	Output	Target	Output	Target	Output	Target	Output	Target
Saskatoon, SK	20.11	28.39	10.96	3.15	16.2	19.24	8.11	11.67	6,082	6,200
Calgary, AB	11.27	27.13	9.29	3.15	13.27	19.24	6.33	10.41	5,729	6,200
Kelowna, BC	8.86	21.77	15.01	3.15	11.04	15.77	9.02	11.99	5,727	6,200

The inflated annual cooling demand is the result of greater internal heat gains in the WUFI Passive model compared to the PHPP outputs. While the PHPP contained specific interior lighting and consumer electronic loads, PHIUS+ requires the use of default reference quantities for these variables, one for PHIUS+ Interior Lighting, another for PHIUS+MELs (miscellaneous electric loads, including televisions and plug loads. These loads are much greater, resulting in significantly larger internal heat gains, which translate into higher annual cooling demands. To remedy this, each model was adjusted for compliance.

Three primary adjustments were made to achieve compliance, though not all three were needed in all locations. This was an iterative process, beginning with the 'low-hanging-fruit'. These included:

1) Increasing natural night ventilation, a cooling strategy called 'night flushing' that allows cool night air to carry away heat absorbed by the building during the day (Griffin, 2010), from 0.02 [1/h] used in the PHPP calculations to the default value of 0.3 [1/h] in the WUFI Passive software. This was applied to all three locations, and put Calgary in compliance with the Standard.
2) Increasing the percentage of high efficiency lighting from the 0% used in the PHPP calculations to 100% in the WUFI Passive software. This was applied to Saskatoon and Kelowna and had a measured impact in the correct direction but it was not sufficient to achieve compliance in either location.
3) Changing the south and west-facing windows from high SHGC models to low SHGC models. This change was applied to Saskatoon and Kelowna and resulted in both locations achieving compliance.

The results of these changes are listed in Table 9.

Table 9: Outputs (showing compliance) and Targets for Select Cities

Location	Annual Heating Demand (kWh/m^{2}a)		Annual Cooling Demand (kWh/m^{2}a)		Peak Heating Load (W/m^2)		Peak Cooling Load (W/m^2)		Source Energy Demand (kWh/person-yr)	
	Adjusted Output	Target	Adjusted Output	Target	Adjusted Output	Target	Adjusted Output	Target	Adjusted Output	Target
Saskatoon, SK	23.36	28.39	2.73	3.15	16.58	19.24	5.97	11.67	5,409	6,200
Calgary, AB	11.57	27.13	2.19	3.15	13.54	19.24	3.93	10.41	5,674	6,200
Kelowna, BC	11.95	21.77	3.06	3.15	11.21	15.77	5.73	11.99	4,997	6,200

While these changes negatively impacted the annual heating demand, overall it reduced total annual energy demand (heating & cooling) in all 3 locations; reducing it by 19% in Saskatoon, 49% in Calgary, and 59% in Kelowna.

With each of the models now compliant with the PHIUS+ 2015 Passive Building Standard, a straw bale wall assembly was fitted to the model for all above grade walls. The assembly is defined in the proceeding section.

5.3 Developing the Straw Bale Wall Assembly

5.3.1 Assessment Criteria

As the case studies revealed, there are multiple opportunities for achieving a high-performing building envelope with straw bales. To achieve Passive House certification, the wall assembly must satisfy four primary criteria, including:

1) Adequate thermal resistance;
2) Climate appropriate construction such that mold and moisture risks are minimized;
3) Thermal bridge free construction;
4) Air tightness.

The recommended assembly will need to satisfy these primary criteria - verified in WUFI Passive (see Section 6.1) - while also addressing some practical considerations - buildability, cost, reduced maintenance, and the overarching goal of reduced embodied carbon. These secondary criteria provide a lens by which to evaluate the materials/methods needed to satisfy the primary criteria.

Of particular importance is the buildability of the assembly, especially as conventional trades are unlikely to be familiar with straw bale construction. High performance construction, especially where air tight enclosures are required, already face challenges from the trades (Magwood, 2012b); introducing an unfamiliar material only adds to this challenge. Simplifying the assembly as much as possible to match standard practice is necessary to increase the likelihood of achieving the primary criteria required to meet the Standard. And though straw bale SIPs, such as those used by ModCell, have been used successfully in projects achieving Passive House certification (in Europe), the intention of this evaluation is to recommend a site-built (and not prefabricated) assembly that follows the convention of how the majority of houses are constructed in North America. This assessment will begin by looking at buildability.

5.3.2 Buildability

According to Erb (2014), “a wall built according to standard practices is the most buildable wall because standard practice is “easy” in the sense that it is well-understood by all involved” (pg. 15). While most of the trades are unlikely to be familiar with straw bales, aligning the rest of the assembly with standard practices, where practical, is likely to improve the buildability. It’s also worth noting that Passive House assemblies are considered less buildable in North America because they deviate from code-minimum construction methods and require more time, material, and care to build (Erb, 2014). Additional training and supervision is likely for any Passive House project in North America, not just those involving straw bale. An ideal assembly, then, is one that maximizes both buildability and the overall performance potential.

With straw bale, the framing method impacts the performance potential to a large degree, influencing: 1) thermal bridging, 2) windows and door installation, including where they may be mounted within the wall plane, 3) ease of installing bales and the tightness of the overall wall (more voids and areas stuffed with loose straw results in greater heat transfer); and 4) opportunities for affixing additional components - air sealing products, sheathing and insulating boards, cabinets, or strapping for a rainscreen[3]. There are no fewer than a dozen framing methods for straw bale construction (Magwood, 2015a), but not all are well suited to the goals of an idealized assembly. Balicki (2014) provides an overview of many of the most common framing methods used in Passive House construction - exterior insulation, double stud, Larsen truss, vertical TJI, all of which suit themselves to straw bale construction, and have indeed been used in straw bale projects, though not with an equivalent efficiency.

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[3] Rainscreen assemblies are increasingly common on straw bale wall assemblies and deal with one of the greatest susceptibilities of straw - the potential for microbial decay from wind-driven rain. Rainscreens also reduce maintenance and allow for a variety of siding options.

Getting most of a straw bale to the exterior of the structure involves one of two options, 1) embedding the frame within the bales - which requires notching and stuffing around the framing (impacting the integrity of the wall); mid-wall framing makes for difficult attachment of additional building components; 2) placing the bales to the exterior of the frame (similar to the S-House in Section 2.3.1) - but this generally involves additional footings - one for the structure, another to carry the bale loads - adding cost and complexity. Roof loads are also difficult, as overhangs must be cantilevered far from the structure. While it does approximate an ideal assembly, mimicking the “perfect wall”, whereby most of the insulation is exterior of the frame, the use of straw bales to do so adds complexity and neither of the aforementioned designs could be regarded as particularly ‘buildable’.

Of the remaining three - double stud, Larsen truss, vertical TJI - one stands out as the most buildable. Erb (2014), who assessed the framing methods described by Balicki (2014) for buildability, reported that double stud framing “is very similar to standard practice”, scoring it in the “strong buildability” category alongside exterior insulation (Figure 13). It’s also the framing method most commonly used with dense packed cellulose, a wall assembly becoming increasingly common (Magwood, 2015a). This framing method provides a thermal break between the framing members and simplifies the install of additional components mentioned previously, which, as the following sections will demonstrate, increase the performance potential needed to achieve compliance.

Figure 13: Double stud framing used with straw bale (Endeavour Centre).

5.3.3 Adequate Thermal Resistance

The *PHIUS+ 2015 Certification Guidebook* (Passive House Institute US , 2017) provides R-Value Guidelines for the various building assemblies - wall, ceiling, slab - based on the designated climate zone. The recommended RSI ranges for walls in each of the select cities is listed in Table 10.

Table 10: Wall RSI Ranges for Select Cities, adapted from (PHIUS, 2017).

Location	Zone	RSI Ranges (m^2K/W)*
Saskatoon, SK	7A	8.63 - 11.45
Calgary, AB	7A	8.63 - 11.45
Kelowna, BC	6	6.87 - 8.98
* Actual values will vary by project.		

These guidelines offer a soft target but the R-value is specific to each project and is influenced by such things as the surface to volume ratio of the house, its orientation and microclimate, the number occupants, and all the other components and mechanical systems that influence the design and operation of the project. WUFI-Passive is used to balance these variables, allowing the modeler to ‘turn the dials’ on the design and system components to achieve compliance. As such, the RSI ranges may deviate from the recommendations depending on the overall building design and modeled occupant behaviour. But seeing that a typical, “first generation”, straw bale wall assembly has an RSI of 5.28 (m^2K/W), which falls 30% to 117% below the recommendations, additional insulation is likely needed to achieve adequate thermal resistance for compliance. The literature review (Section 2) identified some of the opportunities to increase thermal resistance of straw bale assemblies, notably the use of insulation placed to the exterior of the bales. Insulated sheathing products (e.g. Sonoclimat Eco4), non-structural insulation boards (e.g. Roxul Comfortboard), or dense pack cellulose abutting the bales (e.g. StrawCell) can be used to increase the thermal resistance of the assembly. Table 11 notes the thermal conductivity of several insulation products that may be used in conjunction with straw bales.

Table 11: Summary of Insulations to be Used with Straw Bale

	Typical Thickness (mm)	λ (W/mK)
SonoClimate Eco4	38	0.0534
Roxul Comfortboard	32, 38, 51, 63.5, 76	0.0361
Dense Pack Cellulose (3.5 lbs/ft^3)	variable	0.0361

The right material to be used in a straw bale assembly is not necessarily the one with the greatest R-value. Choosing components that serve multiple functions within an assembly is a worthwhile goal, as it is the overall quality of the assembly that is important in high performance enclosures. For example, insulated sheathing may satisfy structural needs and serve as a secondary air barrier, while the framing needed for dense pack cellulose may serve as the structural component for the building. Understanding the ancillary benefits of a product will help guide the decision-making process.

5.3.4 Climate appropriate construction

Appendix B of the *PHIUS+ 2015 Certification Guidebook* provides moisture control guidelines that, if followed, generally lead to a “green light” for the assembly. They list four above-grade wall assemblies that capture most of the possible enclosure configurations, which include:

a) Framed assemblies with all or most of the insulation inside of the sheathing and between the framing members,

b) Framed assemblies with some insulation outboard of the framing and some insulation between the framing members,

c) Assemblies with all or most of the insulation outboard of the structure (framed or solid), and

d) Assemblies with insulation comprised only of air-impermeable and Class II vapor control insulation between, within, or outside of the structure.

Each of these configurations comes with a list of zone-specific criteria that must be met for the assembly to be deemed “appropriate”. Assembly configuration ‘c’ is noted as being “the simplest and most robust wall to design with respect to vapour control” (Passive House Institute US , 2017, p. 76), and most closely approximates the perfect wall concept. As was already discussed in Section 5.3.2, this is difficult to achieve with straw bales. In many cases, configuration ‘b’ is the most suitable to high-performance straw bale assemblies, with some insulation value external to the framing or structure. For zones 6 to 8, which captures most of Canada, the “[insulated] sheathing-to-cavity R-value ratio” ranges from >0.50 to >0.70 (Passive House Institute US , 2017, p. 78), which is not only difficult but unnecessary for straw bale assemblies. WUFI analysis has shown that when best practices are followed, super insulated vapour-open straw bale assemblies manage moisture to within acceptable tolerances for maintaining a healthy wall assembly (ModCell, 2017).

5.3.5 Thermal Bridge Free Construction

One of the “hard requirements” for PHIUS+ 2015 certification is avoiding significant thermal bridges to reduce heat loss and to avoid mold growth on interior surfaces made susceptible by low temperatures associated with thermal bridging. The thermal bridge coefficient (Psi-value) “represents the difference between the thermally interrupted component and the uninterrupted component that is assumed for the balance” (PASSIPEDIA, 2016). Thermal bridges occur where insulation is non-continuous, often at transition areas between dissimilar materials. These areas are to be modeled in THERM and if the thermal bridge is significant enough (Psi ≥ 0.01 W/mK) it must be accounted for in the WUFI Passive software. Additionally, compliance requires that the maximum temperature difference between the interior air and the interior surface temperature not be more than 4.0°C (PHIUS, 2015).

As was discussed in Section 5.3.2, the framing system chosen for the assembly has a large impact on thermal bridging. Some framing systems are inherently better suited to reduced thermal bridging than others. For example, a double stud wall is naturally thermally broken, whereas a wall framed with a TJI is not. The framing system also has implications for window and door installation, and for the mounting of insulated sheathing products that may reduce thermal bridging at vulnerable intersections.

It is typically at the transition areas from one assembly to another (e.g. foundation to wall connection) where insulation continuity is difficult to maintain (Figure 14), and where thermal bridges are most pronounced. Choosing a framing system that allows for the inclusion of an adequate amount of insulation at these transition areas is important for a thermal bridge free design.

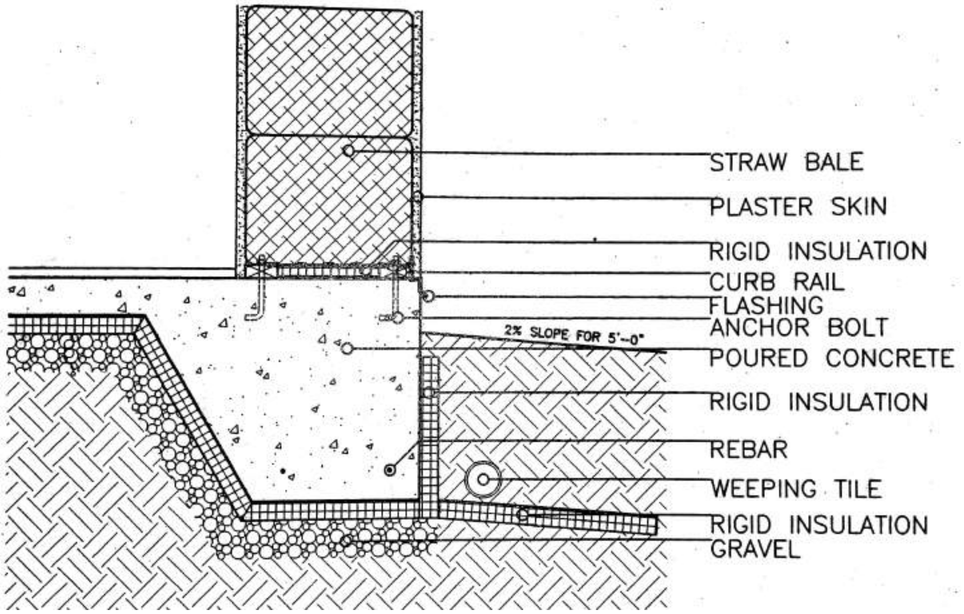

Figure 14: A Typical Straw Bale to Foundation Detail Where Insulation is Not Continuous (Magwood & Walker, 2001).

Aligning the insulation planes is also important to reduce thermal bridging. In the case of the reference house, the 'as designed' above grade walls have externally mounted insulation that extends in the same plane as the externally mounted EPS insulation on the basement walls. To carry the loads of the straw bale assembly through the foundation using a typical thermally broken base plate, it requires offsetting the above grade walls from the basement walls, forcing the isotherms to fall out of plane, and creating a thermal bridge (Figure 15). Even when a solid baseplate is used to canteliver the bales over the EPS insulation, and adding significantly more insulated sheathing and overinsulation at the basepate, an undesirable thermal bridge is created (Figure 16).

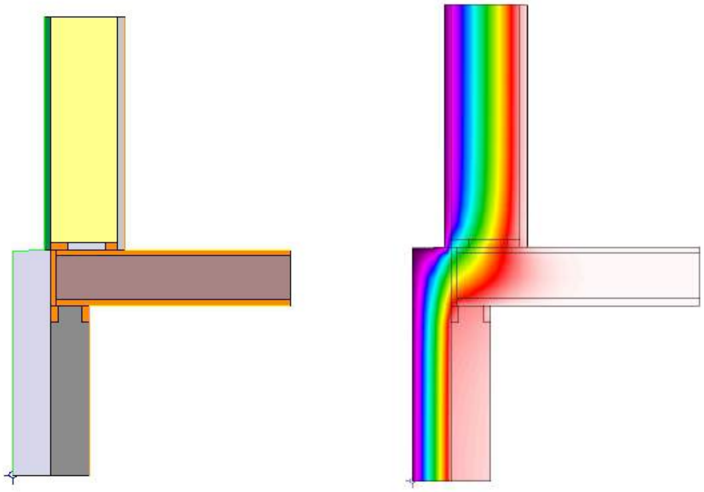

Figure 15: Straw bale assembly (with typical thermally broken base-plate) mounted on 'as designed' reference house foundation, showing distortion of the isotherms. Psi=0.100 W/mK. The lowest interior surface temperature was 4.9°C.

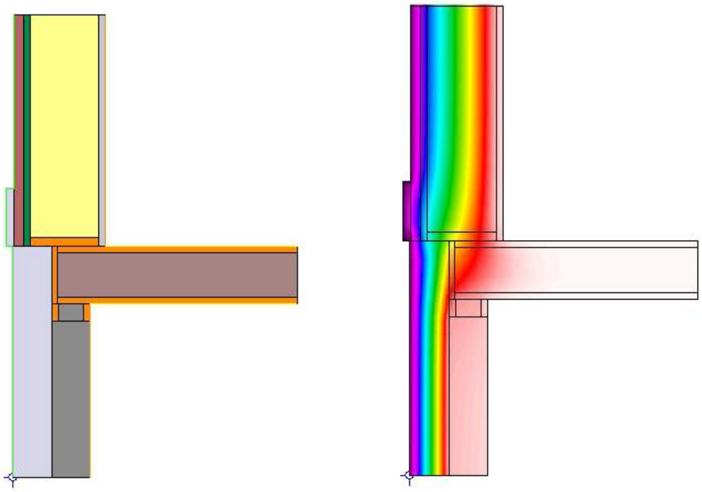

Figure 16: A solid base-plate allows the straw bale wall to cantilever over the EPS insulation but even with additional insulation and overinsulation at the connection point, an undesirable thermal bridge is created. Psi=0.049 W/mK. The lowest interior surface temperature was 11.8°C.

Choosing a foundation system that better suites the insulation profile of a straw bale is desirable to reduce the need for overinsulation and to improve buildability. Switching the ‘as designed’ foundation to an ICF (insulated concrete form) foundation results in a straightening of the isotherms and mitigates the thermal bridge, even with a simpler straw bale wall assembly (Figure 17). The thickness of the EPS insulation and concrete was maintained between the ‘as-designed’ wall and the substituted ICF foundation and, therefore, the thermal resistance was maintained at an RSI of 6.73 m^2K/W as noted in Table 2.

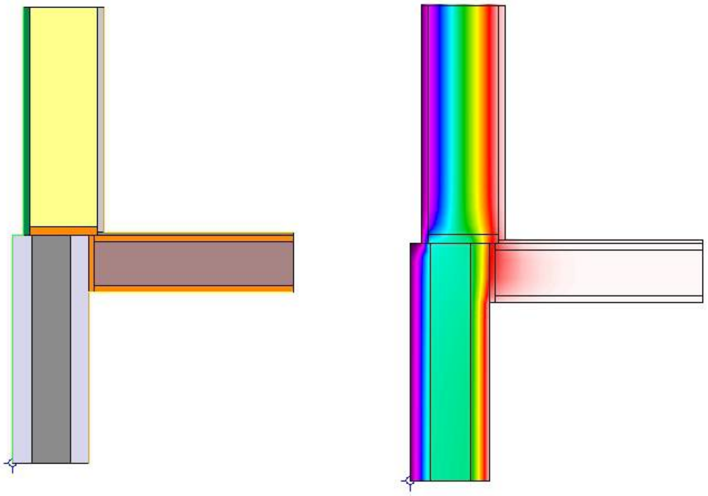

Figure 17: Using an ICF foundation allows the use of a simpler straw bale wall assembly without thermal bridging at the interface. Psi=0.0097 W/mK. The lowest interior surface temperature was 16.5°C.

5.3.6 Air Tightness

Achieving air tight assemblies with straw bales can pose a challenge. While plasters provide an air barrier, they must be continuous to be effective. Where plasters meet dissimilar materials, particularly at intersections with the floor, window and door jambs, ceiling, and framing members, careful detailing is required to ensure there is no air leakage into the wall assembly. Overlapping plasters with adjoining wood is one strategy to achieve air tightness. A variation of this is to use an ‘air fin’, which is typically a piece of drywall, tar paper, house wrap or homasote with added mesh to provide an adherent surface for the plaster (Figure 18). The air fin is then placed behind the framing or fixed to the framing with tape or acoustic sealant over which plaster is applied, effectively continuing the plaster without interruption. It is worth noting that the effectiveness of these non-commercial, ‘homemade’ air fins has been shown to be inconsistent, with some resulting in bonding issues that result in unwanted air leakage (Magwood, 2012a). A better solution for this detailing is to use the increasingly available off the shelf fleece air barrier tapes designed to hold plaster, thus making airtight construction much easier and effective (Figure 19).

Figure 18: Tar paper/diamond lath air fin at window buck (Frey, 2014).

Figure 19: CONTEGA FC tape ready to accept stucco over straw bale (475 High Performance Building Supply, 2014).

Another strategy is to use sheet materials to provide the air barrier. Care must be taken to choose products that maintain the “vapour-open” profile required to keep a straw bale wall assembly healthy. Sheet products that may be used include gypsum wall board (interior use only), wood fibre sheathing - a compressed wood fibre board with a wax-based binder - and magnesium oxide board (permeability ratings can vary widely depending on the manufacturer, so confirming the permeability is essential). Manufactured wood sheathing (plywood and oriented strand board (OSB)) does not have the necessary water vapour permeability to be used with straw bale wall assemblies (Magwood, 2016).

The major benefit of using sheet products is that they provide a solid backing for supporting air sealing tapes, making the air sealing process more robust and increases installation efficiency. And as was discussed in Section 2.2.2, care must be taken to fill out any voids between the bale face and the sheet material, as these voids allow for natural convection that lower the insulating ability.

5.3.7 Proposed Assembly

The proposed assembly (Figure 20) came about through an iterative process, beginning with simulations using a 'first-generation' wall assembly to establish a reference point (the results are summarized in Section 6.1.1), and adjusted as necessary to satisfy the targets set by the Standard for each location, and further informed by the best practices and case studies described in the literature review. The assessment criteria are listed in Section 5.3.1.

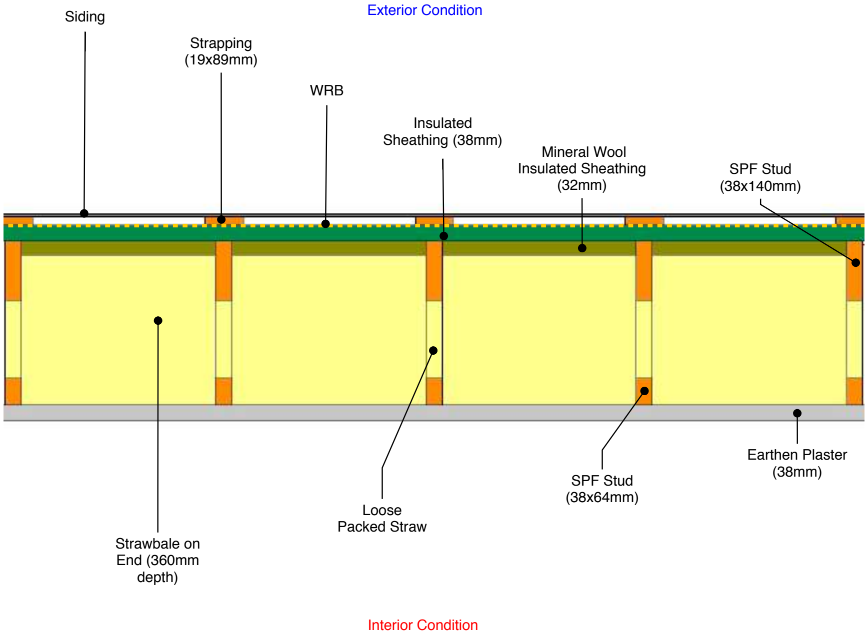

Figure 20: Proposed assembly. The RSI is 6.722 (m^2K/W) and the total thickness is 0.52 metres.

The assembly (Figure 21) consists of a double stud wall - 38x140mm (2x6 inch) outer stud and 38x64mm (2x3 inch) inner stud - built on 495mm centers (19.5 inches). This allows full bales to be used, placed on end, with the 360mm (14 inch) dimension creating the thickness of the wall - a configuration has the straw fibres running perpendicular to heat flow, and thus a higher R-value per inch. The base plate is 387mm wide (15.25 inches), with doubled up top plates to connect the wall to the roof bearing assembly. The exterior 38x140mm stud is offset from the exterior-most bale face by 32mm (1.25 inches) to accommodate the mineral wool insulated sheathing (e.g. Roxul Comfortboard) that will add to the R-value of the assembly, while also compressing into any voids that may be present on the bale face (thus reducing convective heat transfer)[4]. Outboard of the framing and the mineral wool insulated sheathing is 38mm (1.5 inches) of insulated sheathing (e.g. SonoClimat Eco4) to provide additional structural support and a solid backing for the mounting of the air-tight water resistant barrier (WRB; Solitex Mento+) which will be taped with a compatible air-tight product (e.g. Tescon Vana by Pro Clima). 19x89mm (1x4 inches) vertical strapping will be mounted outboard of the WRB and the assembly will be finished with siding (e.g. Hardiboard). The interior bales will be finished with 38mm (1.5 inches) of earthen plaster (2 - 3 coats as per convention), and detailed with a felt-based air sealing tape (e.g. Contega PV by Pro Clima) designed for plasters. This tape is affixed to the adjoining interface and floated into the plaster to create an air-tight seal.

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[4] The primary purpose of the mineral wool insulated sheathing is to reduce natural convection that has been found to occur between the bale face and sheet materials. The easy to handle mineral wool insulated sheathing (which typically comes in 600x1200mm sheets) is flexible enough to facilitate easy filling of voids behind the material as it is installed, thus eliminating voids that cause natural convection. It has the added benefit of adding additional thermal resistance and provides a solution that eliminates all wet construction from the exterior of the assembly, increasing the construction window for building with straw bales.
An alternative to this, especially where installation is not temperature sensitive (e.g. during months where freezing is not a risk), is to replace the mineral wool insulated sheathing with a coat of earthen plaster. The offset framing allows the plaster to be screeded across the framing faces to create a flat surface for which to affix the outboard insulated wood fibre sheathing. In this instance, if additional thermal resistance was required, the mineral wool insulated sheathing could be moved outbound of the WRB.

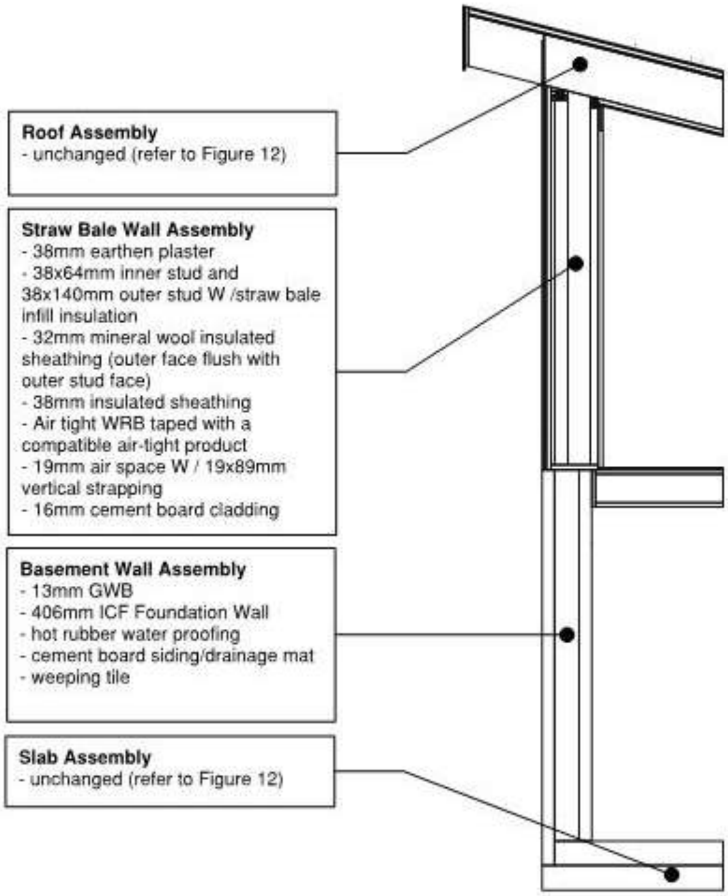

Figure 21: Full section of proposed assembly.

The total R-value of the assembly is 6.72 m^2K/W (from 8.05 m^2K/W). The final thickness, including the vented rainscreen is 0.52 metres (from 0.41 metres for the ‘as designed’ wall assembly) - a 26% increase in thickness. The impact this has on floor area (iCFA) is discussed below. The results generated from substituting the ‘as-designed’ walls for the reference house with the proposed straw bale assembly are detailed in the results section that follows.

6.0 Results and Discussion

6.1 WUFI Passive Results

6.1.1 ‘First-Generation’ Assembly

A typical ‘first-generation’ wall assembly comprised of a single width of bales on end with the interior and exterior bale faces plastered with 38mm of an earthen (clay-based) plaster was inputted to the PHIUS+ 2015-compliant models for each of the select cities. The assembly has a total R-value of 5.01 m^{2}K/W. It’s worth noting that the plaster type has negligible effect on the thermal resistance of the assembly, so any plaster system - clay-lime, lime, cement-lime - could have been used for this analysis. The physical properties of the components used in the simulations for the first-generation straw bale assembly are listed in Table 12.

Table 12: Material properties of components used in the first-generation straw bale assembly.

Material	Thickness (mm)	Density (kg/m^3)	Conductivity (W/mK)	Heat Capacity (J/kgK)	Solar Absorptance (-)
Straw bale (on edge) $^{\Omega}$	355.7	110	0.0721	1350	-
Earthen plaster $^{\Omega}$	38.1	1400	0.6	850	0.9
$^{\Omega}$ From Bronsema (2010).					

To assess the sensitivity of air leakage on the model, two sets of simulations were generated. The first simulation applied the 0.3 1/h air change rate (which corresponds to 0.0225 cfm/ft^2 within the WUFI Passive model) used in the reference house PHPP model, while in the second simulation the air leakage rate was increased to 0.05 cfm/ft^2 - a value that represents the maximum air leakage rate allowed for certification. For these simulations, the iCFA was kept the same as the reference house, thus suggesting the slight increase in wall thickness (0.43m from 0.41m) would be ‘pushed’ to the exterior. A summary of the results for the five primary compliance criteria are listed in Table 13.

Table 13: WUFI Passive output showing impact of a 'first-generation' straw bale assembly adapted to reference house for select cities (compared to the 'as designed' and PHIUS+ 2015 targets). Targets that are not satisfied are highlighted.

Saskatoon							
Metric	Target	'As designed' - adjusted for compliance		First Generation Straw bale (0.0225 cfm/ft^2 AC)		First Generation Straw bale (0.05 cfm/ft^2 AC)	
		Output	% Below Target	Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	28.39	23.36	21.5	32.1	-11.6	35.93	-21.0
Annual Cooling Demand (kWh/m^{2}a)	3.15	2.73	15.4	2.05	53.7	2.05	53.7
Peak Heating Load (W/ m^2)	19.24	16.58	16.0	19.52	-1.4	23.14	-16.9
Peak Cooling Load (W/ m^2)	11.67	5.97	95.5	4.46	161.7	4.4	165.2
Source Energy Demand (kWh/person•yr)	6,200	5409	14.6	5796	7.0	5952	4.2
Calgary							
Metric	Target	'As designed' - adjusted for compliance		First Generation Straw bale (0.0225 cfm/ft^2 AC)		First Generation Straw bale (0.05 cfm/ft^2 AC)	
		Output	% Below Target	Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	27.13	11.57	134.5	16.63	63.1	19.52	39.0
Annual Cooling Demand (kWh/m^{2}a)	3.15	2.19	43.8	2.16	45.8	2.17	45.2
Peak Heating Load (W/ m^2)	19.24	13.54	42.1	15.86	21.3	19.06	0.9
Peak Cooling Load (W/ m^2)	10.41	3.93	164.9	2.86	264.0	2.73	281.3
Source Energy Demand (kWh/person•yr)	6200	5674	9.3	5892	5.2	5987	3.6
Kelowna							
Metric	Target	'As designed' - adjusted for compliance		First Generation Straw bale (0.0225 cfm/ft^2 AC)		First Generation Straw bale (0.05 cfm/ft^2 AC)	
		Output	% Below Target	Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	21.77	11.95	82.2	16.29	33.6	18.67	16.6
Annual Cooling Demand (kWh/m^{2}a)	3.15	3.06	2.9	2.96	6.4	2.96	6.4
Peak Heating Load (W/ m^2)	15.77	11.21	40.7	13.1	20.4	15.51	1.7
Peak Cooling Load (W/ m^2)	11.99	5.73	109.2	5.2	130.6	5.17	131.9
Source Energy Demand (kWh/person•yr)	6200	4987	24.3	5204	19.1	5287	17.3

The results show that, with the exception of Saskatoon, the straw bale wall assembly satisfied all of the PHIUS+ 2015 primary certification criteria, even with the air leakage rate increased to the maximum permitted by the Standard (which is still a fraction of what is common of standard building practice). The decreased thermal resistance of the assembly had a negative impact on the annual heating demand and peak heating load in all locations; it did however have a beneficial impact on the annual cooling demand and peak cooling load in all locations. The source energy demand was little changed and complied in all locations. Regarding the Saskatoon model, the straw bale assembly was inadequate for meeting the annual heating demand and peak heating load, exceeding the target by 11.6% and 1.4% respectively. Increasing the air leakage rate to the maximum allowable limit resulted in poorer performance, with the target being exceeded by 21% for the annual heating demand and 16.9% for peak heating load.

It needs to be said that while these outputs comply with the primary certification criteria for Calgary and Kelowna, and provide a useful reference point for building from, a 'first-generation' straw bale assembly is not well suited to achieving the other criteria outlined in Section 5.3 necessary to achieve compliance. Air tightness and thermal bridge free construction are two matters that are not well suited to such a simplified system, thus necessitating an evolution toward a hybrid system that combines the desirable qualities of straw bale (e.g. thermal resistance, low embodied carbon, aesthetics) with complimentary materials to create an assembly suited to high performance enclosures. The next section summarizes the results of the proposed assembly.

6.1.2 Proposed Assembly

The proposed wall assembly was inputted to the PHIUS+ 2015-compliant models for each of the select cities. The physical properties of the straw bale and earthen plaster are taken from above, while the additional components used in the proposed assembly are listed in Table 14.

Table 14: Material properties of the additional components used in the proposed straw bale assembly.

Material	Thickness (mm)	Density (kg/m^3)	Conductivity (W/mK)	Heat Capacity (J/kgK)	Solar Absorptance (-)
SonoClimat Eco 4*	38.1	264.3	0.0534	1400	-
Roxul Comfortboard**	31.8	128.1	0.0361	850	-
* Highlighted values are from the SonoClimate Eco 4 technical data sheet obtained at mslfibre.com. The heat capacity was obtained from the default wood fibre insulation board in the WUFI+ materials database. ** Highlighted values are from the Roxul Comfortboard technical data sheet obtained at http://www.roxul.com/products/roxul-comfortboard-80/. The heat capacity was obtained from the default Roxul ComfortBoard in the WUFI+ materials database.					

Seeing that the proposed wall assembly is considerably thicker than the 'as designed' wall assembly (0.52m from 0.41 m), two sets of simulations were performed to assess the sensitivity of the increased wall thickness on the models. In the first scenario, the additional wall thickness is 'pushed' to the exterior, maintaining the same iCFA as the reference house model. The second scenario maintains the plane of the basement walls with that of the above grade walls, thus reducing the iCFA from 245.7m^2 to 236.7m^2. Both were modeled with an air change rate of 0.0225 cfm/ft^2 (which corresponds to the 0.3 1/h air change rate achieved by the reference house). Because the PHIUS+ 2015 targets are measured on a per-unit of area basis, a smaller iCFA results in an energy intensity penalty, thus negatively impacting the results. This is a consideration that must be balanced during the design phase. A summary of the results for the five primary compliance criteria are listed in Table 15.

Table 15: WUFI Passive output showing impact of the proposed straw bale assembly adapted to reference house for two iCFA scenarios for the select cities (compared to the 'as designed' and PHIUS+ 2015 targets). Targets that are not satisfied are highlighted. Simulations were based on a 0.0225 cfm.ft^2 air leakage rate.

Saskatoon							
Metric	Target	'As designed' - adjusted for compliance		Straw bale (iCFA = 236.7m^2)		Straw bale (iCFA = 245.7m^2)	
		Output	% Below Target	Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	28.39	23.36	21.5	28.59	-0.7	28.59	-0.7
Annual Cooling Demand (kWh/m^{2}a)	3.15	2.73	15.4	2.16	45.8	2.16	45.8
Peak Heating Load (W/m^2)	19.24	16.58	16.0	18.45	4.3	18.45	4.3
Peak Cooling Load (W/m^2)	11.67	5.97	95.5	4.59	154.2	4.59	154.2
Source Energy Demand (kWh/person•yr)	6,200	5409	14.6	5563	11.5	5563	11.5

Calgary							
Metric	Target	‘As designed’ - adjusted for compliance		Straw bale (iCFA = 236.7m^2)		Straw bale (iCFA = 245.7m^2)	
		Output	% Below Target	Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	27.13	11.57	134.5	13.89	95.3	13.07	107.6
Annual Cooling Demand (kWh/m^{2}a)	3.15	2.19	43.8	2.30	37.0	2.12	48.6
Peak Heating Load (W/m^2)	19.24	13.54	42.1	14.85	29.6	14.25	35.0
Peak Cooling Load (W/m^2)	10.41	3.93	164.9	3.01	245.8	2.95	252.9
Source Energy Demand (kWh/person•yr)	6200	5674	9.3	5718	8.4	5781	7.2
Kelowna							
Metric	Target	‘As designed’ - adjusted for compliance		Straw bale (iCFA = 236.7m^2)		Straw bale (iCFA = 245.7m^2)	
		Output	% Below Target	Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	21.77	11.95	82.2	14.08	54.6	13.35	63.1
Annual Cooling Demand (kWh/m^{2}a)	3.15	3.06	2.9	3.12	1.0	2.91	8.2
Peak Heating Load (W/m^2)	15.77	11.21	40.7	12.41	27.1	11.89	32.6
Peak Cooling Load (W/m^2)	11.99	5.73	109.2	5.36	123.7	5.2	130.6
Source Energy Demand (kWh/person•yr)	6200	4987	24.3	5064	22.4	5109	21.4

As was mentioned above, reducing the iCFA had a negative impact on performance and pushed the Annual Heating Demand for Saskatoon slightly above the target (from 27.3 kWh/m^{2}a to 28.59 kWh/m^{2}a, and 0.7% above the target). All other targets were satisfied in Saskatoon with the reduced iCFA. Calgary and Kelowna satisfied the targets under both scenarios. Where the iCFA was maintained, adapting the proposed straw bale assembly to the above grade walls of the reference house satisfied the five primary performance targets for all 3 locations (the full WUFI Passive reports for each location are included in Appendix IV). This remainder of the discussion will centre on these models (where the iCFA = 245.7m^2), as it provides an apples-to-apples comparison to the reference house.

The compliance achieved in the above simulations is also based on the thermal resistance across a clear section of wall. To determine if there is penalty to the thermal resistance owning to thermal bridging at the connections between the proposed assembly and the existing components, further analysis is required. This is examined in Section 6.2.

The results also show that even with the same assembly, there is not a linear relationship between the climate-specific PHIUS targets and the modeled outputs. For example, Saskatoon complies within 4% of the annual heating demand target, while Calgary, with only a slightly smaller annual heating demand target (27.13 versus 28.39 kWh/m^{2}a), achieves it by a margin of 63.1%[5]. Kelowna achieves its annual heating demand target by 63.1%. This non-linear relationship suggests that performing a whole house model is necessary to determine the suitability of various components, walls included, in determining the overall performance of a building. Inferring an assembly's R-value for a corresponding climate zone is not likely to give dependable results.

As was noted above, it was also assumed that the airtightness achieved with the wall assembly in the reference house was maintained with the proposed straw bale wall assembly. The proposed assembly was designed to offer ample opportunities for air sealing, including some redundancy. For example, the use of exterior mounted insulated sheathing mounted behind an airtight membrane provides a good measure of initial air tightness, while the earthen plaster used in conjunction with air sealing tape at vulnerable intersections provides redundancy on the interior. To test the sensitivity of air tightness on the overall performance of the building, additional simulations for two variations (0.04 cfm/ft^2 & 0.05 cfm/ft^2) were conducted. The results are summarized in Table 16.

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[5] The similar annual heating demand permitted under PHIUS+ 2015 for Saskatoon and Calgary is curious, as Saskatoon is a much colder climate (see Table 4), though both locations are similar in other respects - wind speed (https://www.currentresults.com/Weather/Canada/Cities/wind-annual-average.php) and mean daily insolation values (http://www.nrcan.gc.ca/18366). This disparity is perhaps something PHIUS needs to address.

Table 16: WUFI Passive output showing impact of changing airtightness on overall performance (compared to the PHIUS+ 2015 targets). Targets that are not satisfied are highlighted.

Saskatoon							
Metric	Target	Straw bale (airtightness = 0.0225 cfm/ft^2)		Straw bale (airtightness = 0.04 cfm/ft^2)		Straw bale (airtightness = 0.05 cfm/ft^2)	
		Output	% Below Target	Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	28.39	27.3	4.0	29.68	-4.3	31.05	-8.6
Annual Cooling Demand (kWh/m^{2}a)	3.15	2	57.5	2	57.5	2	57.5
Peak Heating Load (W/m^2)	19.24	17.71	8.6	20.01	-3.8	21.32	-9.8
Peak Cooling Load (W/m^2)	11.67	4.45	162.2	4.42	164.0	4.4	165.2
Source Energy Demand (kWh/person•yr)	6,200	5605	10.6	5699	8.8	5753	7.8
Calgary							
Metric	Target	Straw bale (airtightness = 0.0225 cfm/ft^2)		Straw bale (airtightness = 0.04 cfm/ft^2)		Straw bale (airtightness = 0.05 cfm/ft^2)	
		Output	% Below Target	Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	27.13	16.63	63.1	18.45	47.0	19.52	39.0
Annual Cooling Demand (kWh/m^{2}a)	3.15	2.16	45.8	2.16	45.8	2.17	45.2
Peak Heating Load (W/m^2)	19.24	15.86	21.3	17.90	7.5	19.06	0.9
Peak Cooling Load (W/m^2)	10.41	2.86	264.0	2.78	274.5	2.73	281.3
Source Energy Demand (kWh/person•yr)	6200	5892	5.2	5952	4.2	5987	3.6
Kelowna							
Metric	Target	Straw bale (airtightness = 0.0225 cfm/ft^2)		Straw bale (airtightness = 0.04 cfm/ft^2)		Straw bale (airtightness = 0.05 cfm/ft^2)	
		Output	% Below Target	Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	21.77	13.35	63.1	14.79	47.2	15.62	39.4
Annual Cooling Demand (kWh/m^{2}a)	3.15	2.91	8.2	2.91	8.2	2.91	8.2
Peak Heating Load (W/m^2)	15.77	11.89	32.6	13.43	17.4	14.3	10.3
Peak Cooling Load (W/m^2)	11.99	5.2	130.6	5.18	131.5	5.17	131.9
Source Energy Demand (kWh/person•yr)	6200	5109	21.4	5154	20.3	5181	19.7

These results reveal the scale of impact that airtightness has on overall performance, most notably impacting the performance during the heating season. While Calgary and Kelowna could buffer the impact of a leakier building, the Saskatoon model could not, with the annual heating demand and peak heating load exceeding the target at both intervals. This again speaks to the need to develop an assembly that lends itself to airtight construction. With the Saskatoon model edging so close to its performance targets, if an extremely high degree of airtightness could not be assured (e.g. ~0.0225 cfm/ft^2) it may be necessary to add additional outboard insulation to buffer the effects of increased air leakage.

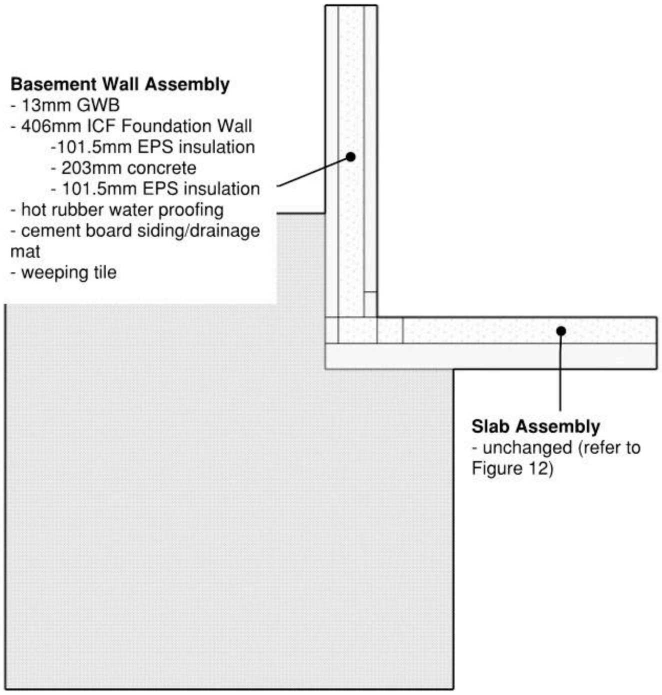
6.2 Thermal Bridge Analysis

6.2.1 THERM Software

THERM is a 2-dimensional heat-transfer modeling program developed at Lawrence Berkeley National Laboratory (LBNL). It also practitioners to model 2-dimensional heat transfer effects in building components where thermal bridges are of concern, allowing a precise evaluation of a component's energy efficiency. It also provides local temperature patterns that could lead to condensation, moisture damage, and/or structural concerns. THERM is also commonly used with the Berkeley Lab WINDOW program to determine window product U-factors and SHGCs.

6.2.2 Thermal Bridge Simulations

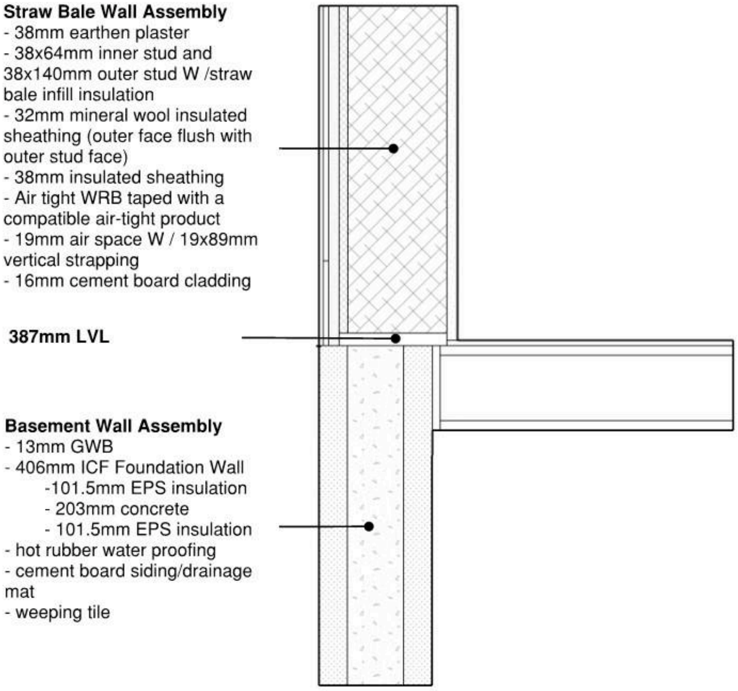
Five intersections were identified for thermal bridge analysis: the basement wall to slab (Figure 22), basement wall to above grade straw bale wall (Figure 23), corners between two walls (Figure 24), and two connections of the straw bale wall to the roof - one for the obtuse connection (Figure 25) and another for the acute connection (Figure 26). Each of these 'typical' building envelope connection details was created and simulated in THERM.



Basement Wall Assembly
- 13mm GWB
- 406mm ICF Foundation Wall
    - -101.5mm EPS insulation
    - - 203mm concrete
    - - 101.5mm EPS insulation
- hot rubber water proofing
- cement board siding/drainage mat
- weeping tile

Slab Assembly
- unchanged (refer to Figure 12)

Figure 22: Basement wall to slab connection.

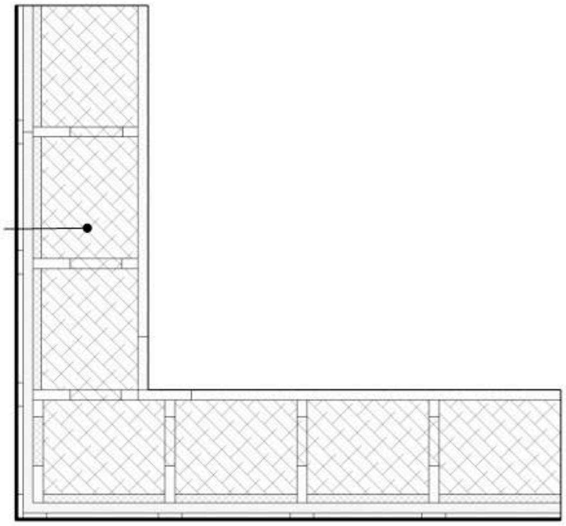


Straw Bale Wall Assembly
- 38mm earthen plaster
- 38x64mm inner stud and 38x140mm outer stud W /straw bale infill insulation
- 32mm mineral wool insulated sheathing (outer face flush with outer stud face)
- 38mm insulated sheathing
- Air tight WRB taped with a compatible air-tight product
- 19mm air space W / 19x89mm vertical strapping
- 16mm cement board cladding

387mm LVL

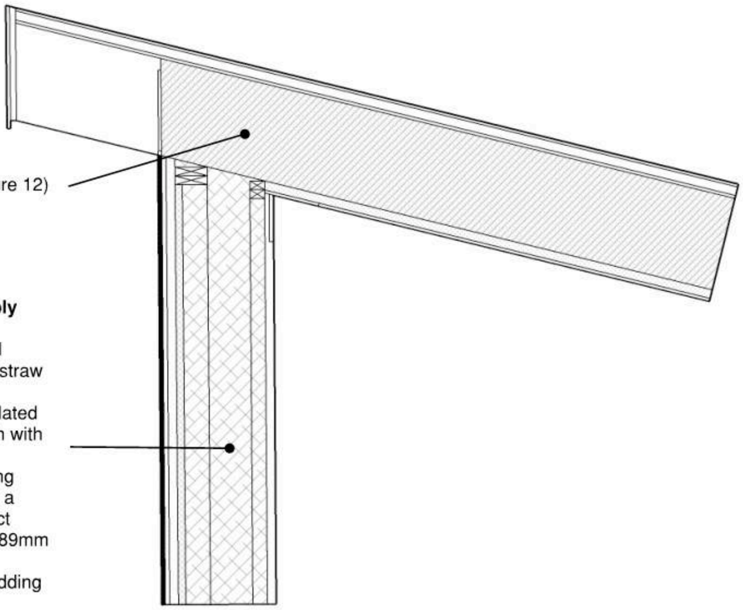
Basement Wall Assembly
- 13mm GWB
- 406mm ICF Foundation Wall
    - -101.5mm EPS insulation
    - - 203mm concrete
    - - 101.5mm EPS insulation
- hot rubber water proofing
- cement board siding/drainage mat
- weeping tile

Figure 23: Basement wall to above grade straw bale wall connection.



Straw Bale Wall Assembly
- 38mm earthen plaster
- 38x64mm inner stud and 38x140mm outer stud W /straw bale infill insulation
- 32mm mineral wool insulated sheathing (outer face flush with outer stud face)
- 38mm insulated sheathing
- Air tight WRB taped with a compatible air-tight product
- 19mm air space W / 19x89mm vertical strapping
- 16mm cement board cladding

Figure 24: Corner between two walls connection.



Roof Assembly
- unchanged (refer to Figure 12)

Straw Bale Wall Assembly
- 38mm earthen plaster
- 38x64mm inner stud and 38x140mm outer stud W /straw bale infill insulation
- 32mm mineral wool insulated sheathing (outer face flush with outer stud face)
- 38mm insulated sheathing
- Air tight WRB taped with a compatible air-tight product
- 19mm air space W / 19x89mm vertical strapping
- 16mm cement board cladding

Figure 25: Straw bale wall to the roof - obtuse connection.

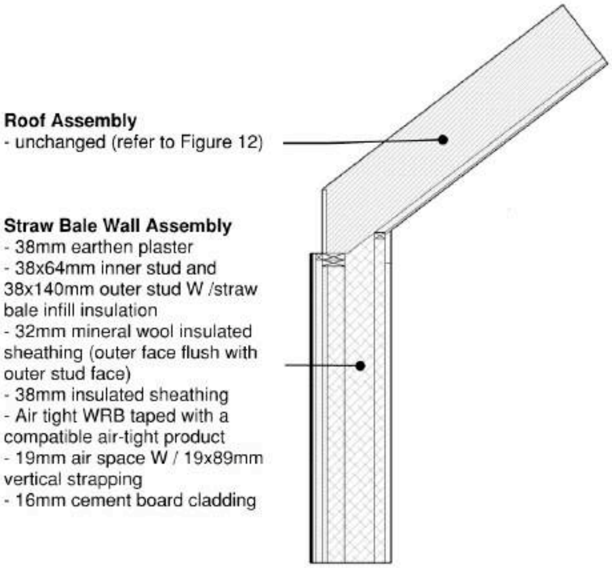


Figure 26: Straw bale wall to the roof - acute connection.

It was assumed that windows would be installed in a similar manner to the reference house, with 2 inches of ridged insulation installed on the head and sill prior to mounting the window frame (Figure 27). A $\Psi_{\text{Installation}}$ of 0.040 (W/mk) was assumed for all windows and reflected in the total window u-value reported in Table 3.

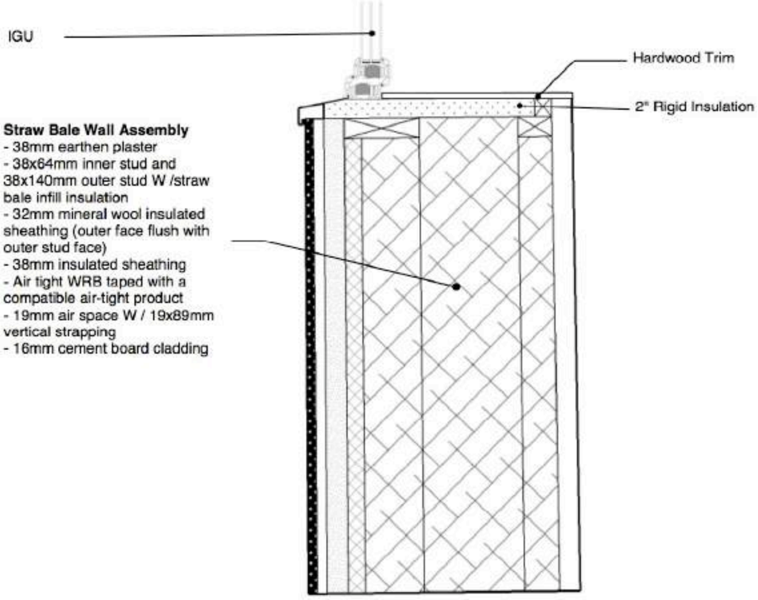


Figure 27: Head and Sill Window Detail (adapted from LVDesign, 2014).

Assessing the thermal bridge across a component requires that boundary conditions be defined. The boundary conditions were supplied by PHIUS and are represented in Table 17.

Table 17: PHIUS Boundary Conditions

Boundary Condition	Temperature (°C)	Convective Coefficient (W/m^2K)*
Exterior	-10	2.555 (vented) 25 (exposed)
Ground	5	567821
Interior	20	7.5 (vertical surfaces); 5.88 (horizontal surfaces); 5.0 (horizontal and vertical surfaces at corners).
* Coefficients are taken from the PHIUS-supplied *boundary condition & generic spacer importer.*		

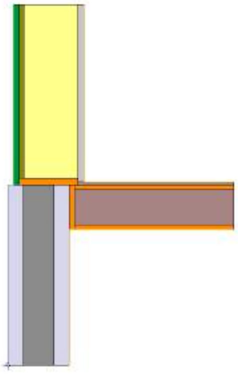
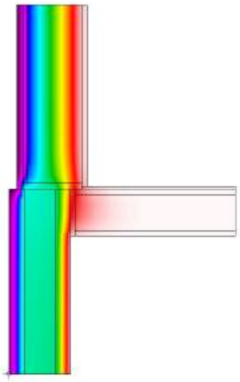
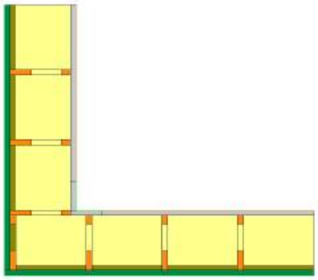
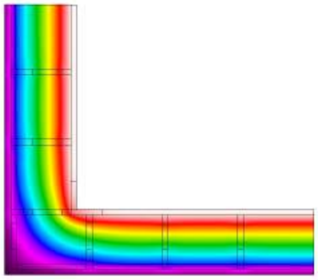
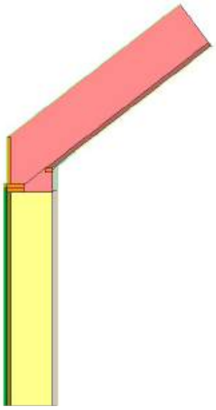
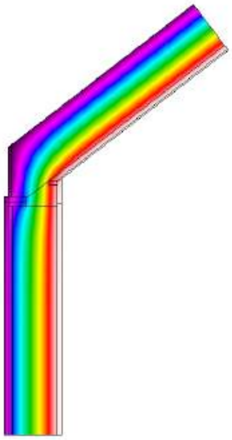
All results had an error of less than 9% across 15 iterations. U-value tags were applied to interior and exterior building envelope components. The linear thermal bridge heat loss coefficients are summarized below in Table 18.

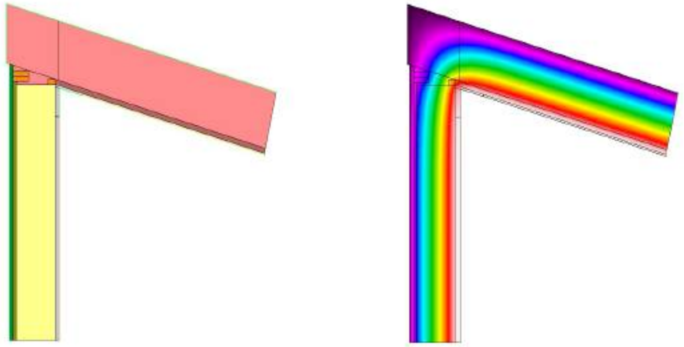
Table 18: Calculated Thermal Bridges for Proposed Assembly.

Interface	Thermal Bridge Type	Calculated Psi Factor (W/mK)	Thermal Bridge Free Connection Achieved? (Psi ≥ 0.01 W/mK)
Basement wall to slab	Perimeter	0.0123	No*
Basement wall to above grade wall	Perimeter	0.0097	Yes
Corner between above grade walls	Ambient	- 0.0696	Yes
Top of wall to roof bearing assembly (obtuse angle)	Perimeter	- 0.1649	Yes
Top of wall to roof bearing assembly (acute angle)	Perimeter	- 0.0336	Yes
* This thermal bridge was not included in the WUFI Passive assessment owing to its negligible size and insignificant effect on the model.			

The thermal bridge analysis indicates that the proposed assembly does not result in thermal bridging as defined by PHIUS (Psi ≥ 0.01 W/mK). Outputs from the THERM analysis are visually represented in Table 19 below; the lowest resulting surface temperature is also noted to show compliance with the PHIUS' minimum interior surface temperature criteria for thermally-bridged construction details.

Table 19: THERM Model Outputs at Interfaces, including Psi-Value and Lowest Interior Surface Temperature for each 'typical' connection.

Psi = 0.0097 W/mK; 16.5°C	 
Psi = - 0.0696 W/mK; 17.8°C	 
Psi = - 0.1649 W/mK; 18.0°C	 

Psi = - 0.0336 W/mK; 18.9°C	

As was discussed in Section 5.3.4, the basement walls were changed to ICFs to better align the insulation plane created with the proposed assembly and to increase buildability. This configuration resulted in a small thermal bridge where the ICF basement wall meets the slab (psi = 0.0123 W/mK; Figure 28). The lowest minimum interior surface temperature is 16.2°C, which complies with PHIUS' criteria for thermally-bridged construction details. This thermal bridge was omitted from the WUFI Passive simulations for the 3 select cities owing to its negligible size.

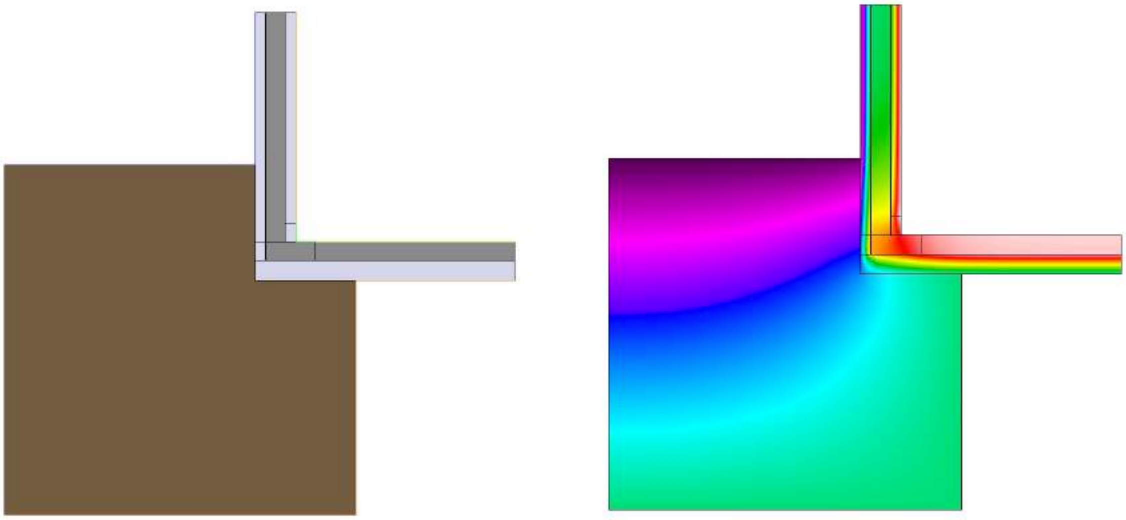


Figure 28: Thermal Bridge Analysis at Foundation. A small thermal bridge (psi = 0.0123 W/mK) exists at the interface between the slab and the ICF basement walls. The lowest interior surface temperature was 16.2°C.

6.3 Hygrothermal Analysis

When the zone-specific criteria set out in Appendix B of the *PHIUS+ 2015 Certification Guidebook* (Passive House Institute US , 2017) are not met, a hygrothermal analysis (WUFI) is required to demonstrate that the proposed assembly manages moisture within an accepted range. Since the proposed assembly deviates from the zone-specific criteria moisture control guidelines established by PHIUS, namely that the insulated sheathing-to-cavity ratio be 0.5 to 0.7 for climate zones 6 and 7/8 respectively, hygrothermal analysis was conducted on the proposed straw bale assembly.

6.3.1 WUFI Plus

WUFI Plus is a simulation tool developed to compute dynamic heat and moisture transfer in a one-dimensional assembly. Its capabilities include modeling heat and moisture transfer through multilayered assemblies using user defined exterior and interior conditions, including temperature, relative humidity, driving rain, and solar radiation. According to Bronsema (2010):

> Heat transfer is calculated through thermal conduction, enthalpy of moisture movement and phase changes, solar radiation and nighttime radiation. Surface film coefficients are used to calculate heat loss to the surroundings in a manner that is similar to the conduction equations, these films can be constant or wind dependent. Moisture movement is broken into two compounds: vapor and liquid. The vapor movement is computed by vapor diffusion as well as solution diffusion. Liquid transport is characterized by capillary conduction and surface diffusion (p. 152).

WUFI simulations are accurate in predicting hygrothermal behavior in building enclosures so long as robust climate data is used, and the correct physical and boundary conditions are supplied (Straube & Schumacher (2003) as cited in Bronsema, 2010).

6.3.2 WUFI Plus Simulations

Hygrothermal simulations were run for the proposed straw bale assembly in each of the three select cities. Hourly weather files (.wac format) were obtained for each location and used for the analysis.

Material properties were created using technical data sheets from the manufactures. Where specific properties were not provided, defaults found in the material database for similar materials were used. The properties most crucial for accurate hygrothermal analysis are listed in Table 20.

Table 20: Material Properties Used in WUFI Plus Analysis.

Material	Thickness (mm)	Density (Kg/m^3)	Conductivity (W/mK)	Diffusion Resistance Factor (-)	Heat Capacity (J/kgK)	Porosity (-)
Solitex Mento Plus WRB[∂]	0.6	130	0.17	83	2300	0.001
SonoClimat Eco 4*	38.1	264.3	0.0534	3.3	1400	0.999
Roxul Comfortboard**	31.8	128.1	0.0361	1.1	850	0.95
Straw bale (on edge)[Ω]	355.7	110	0.0721	1.7	1350	0.95
Earthen plaster[Ω]	38.1	1400	0.6	5	850	0.24

[∂] Highlighted values are from the Solitex Mento Plus technical data sheet obtained at https://www.foursevenfive.ca/wp-content/uploads/2015/09/SolitexMentoPlusSpec.pdf. The density, heat capacity, and porosity were obtained from the default water resistive barrier in the WUFI+ materials database.
* Highlighted values are from the SonoClimate Eco 4 technical data sheet obtained at mslfibre.com. The heat capacity and porosity were obtained from the default wood fibre insulation board in the WUFI+ materials database.
** Highlighted values are from the SonoClimate Eco 4 technical data sheet obtained at http://www.roxul.com/products/roxul-comfortboard-80/. The heat capacity and porosity were obtained from the default Roxul ComfortBoard in the WUFI+ materials database.
[Ω] Highlighted values from Bronsema (2010).

Following ASHRAE 160P (Section 4.6.1 - Rain Penetration), the default value for water penetration through the exterior surface was set at 1% of the water reaching the exterior face of the water resistive barrier (PHIUS, 2015). Again, following the PHIUS (2015) guideline, an air change rate of 50 [1/h] was applied to the vented cavity using the actual thickness of the ventilation cavity (19mm).

The average relative humidity corresponding to five points of interest within the wall - the 38mm wood fibre insulated sheathing (immediately behind the WRB), the 32mm mineral wool insulated sheathing inbound of it, the outer 108mm of straw bale (bound by the outbound 38x140mm stud), the inner 63.5mm of straw bale (bound by the inbound 38x63.5mm stud), and the 38mm of interior earthen plaster - are plotted across a 5 year period for each of the select cities (Figure 29).

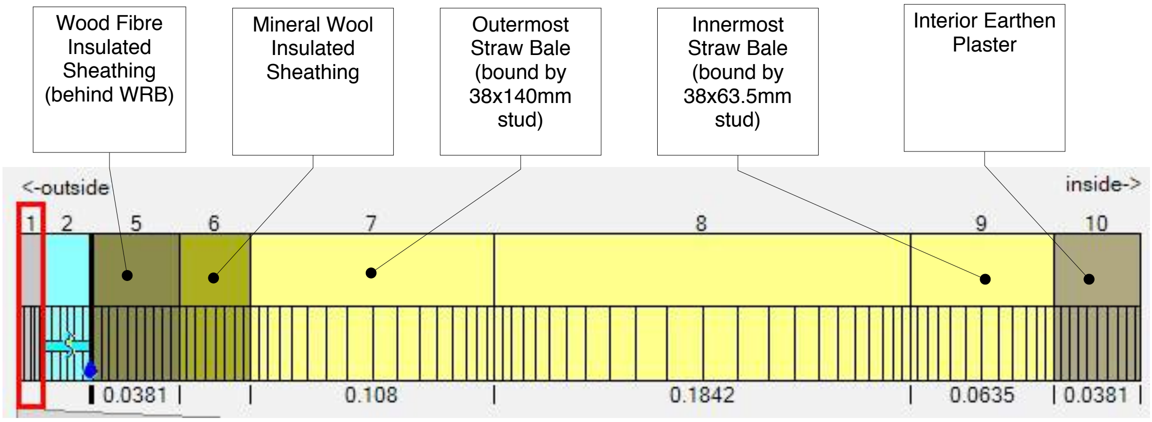


Figure 29: Wall Section Showing Points of Interest for Hygrothermal Analysis

Plots corresponding to the NE orientation are given (this orientation shows the most severe increase in RH in the outermost layer) - Saskatoon is represented in Figure 30; Calgary in Figure 31: and Kelowna in Figure 32. The plots corresponding to the other orientations - NW, SW, SE - are shown in Appendix IV.

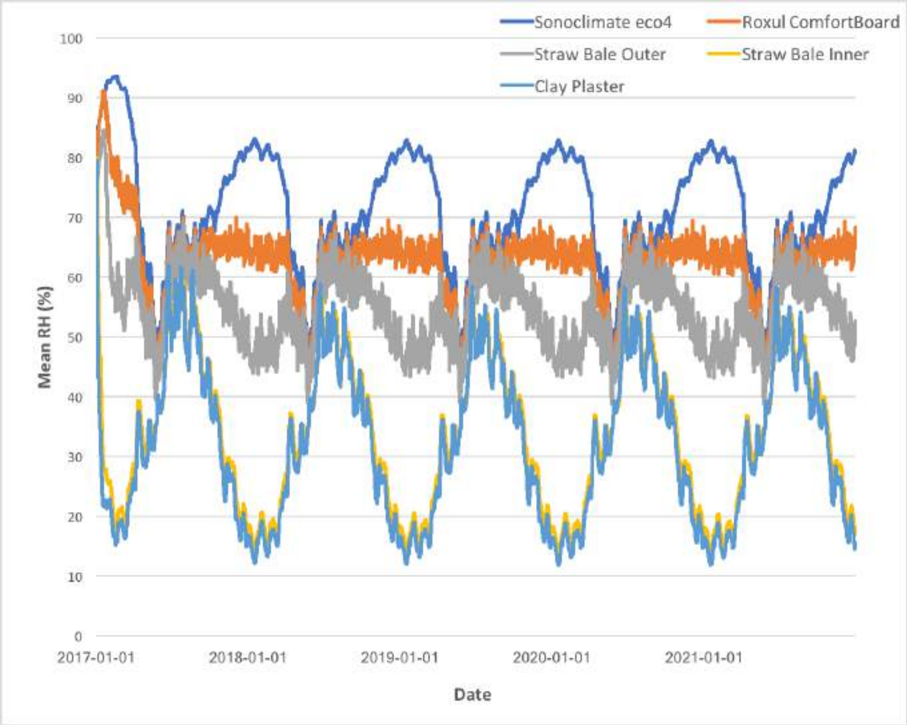


Figure 30: Mean RH (%) of NE Wall in Saskatoon

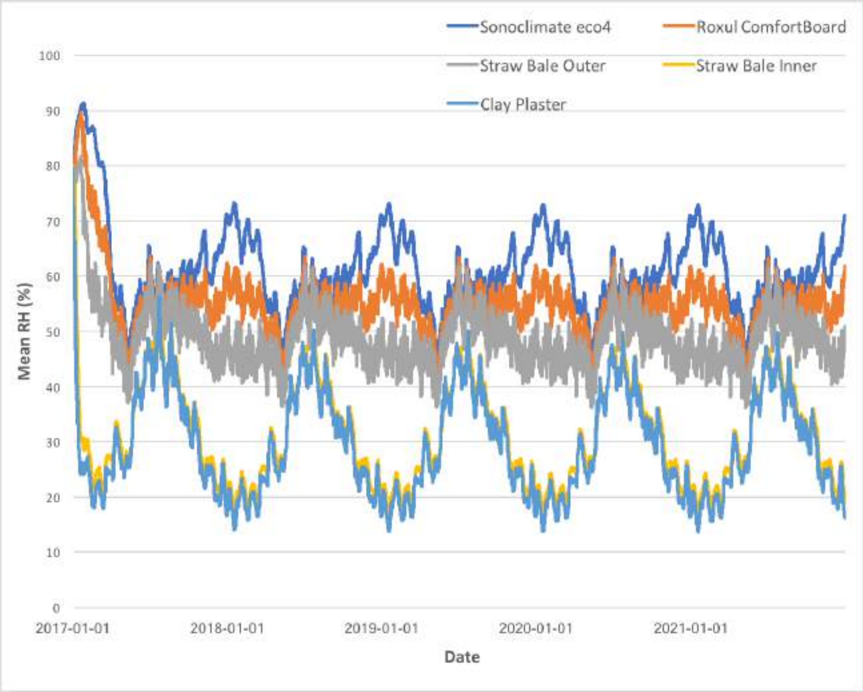


Figure 31: Mean RH (%) of NE Wall in Calgary

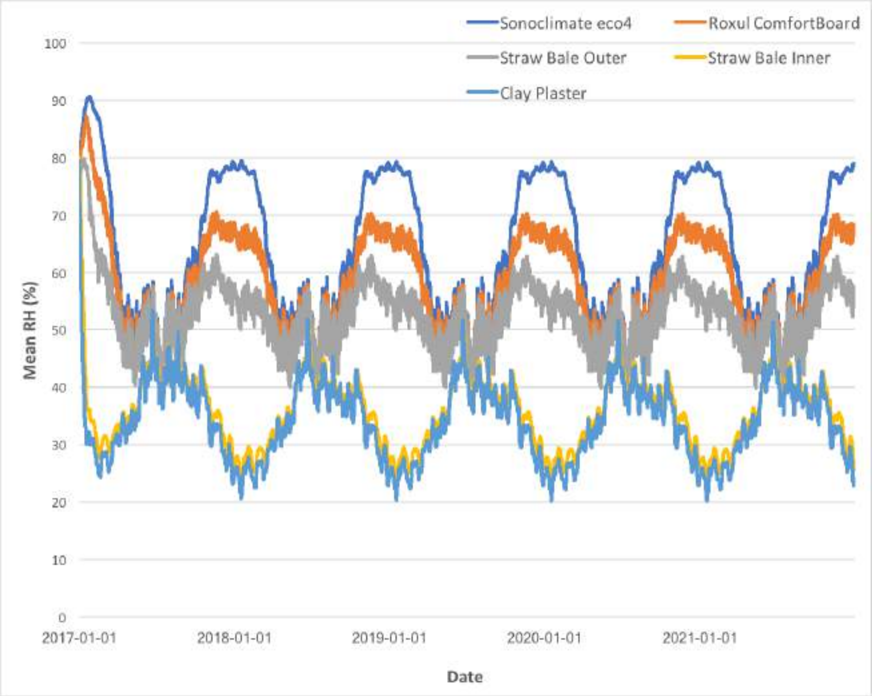


Figure 32: Mean RH (%) of NE Wall in Kelowna

These plots show a clear pattern of seasonal wetting and drying, with no noticeable increase in RH over that time. The wall assembly in Calgary and Kelowna show seasonal cycling within safe limits (<80% RH) for all layers over the 5 year period. In Saskatoon, the insulated sheathing (e.g. Sonoclimat Eco4) shows elevated RH during winter months but there is strong drying as temperatures begin to increase. ASHRAE Standard160P states that in order to minimize the conditions for mould growth the: "30-day running average surface RH<80% when the 30-day running average surface temperature is between 5C and 40C (p.12)." The data were assessed using these criteria for the NE wall in a typical year (2018). It was found that the conditions for mould growth defined by ASHRAE Standard 160P were not present, suggesting the proposed straw bale wall assembly is not at risk in the Saskatoon climate. Temperature and RH for the insulated sheathing layer are plotted together for the Saskatoon in Figure 33. Again, the NE wall is shown as it represents the most extreme case.

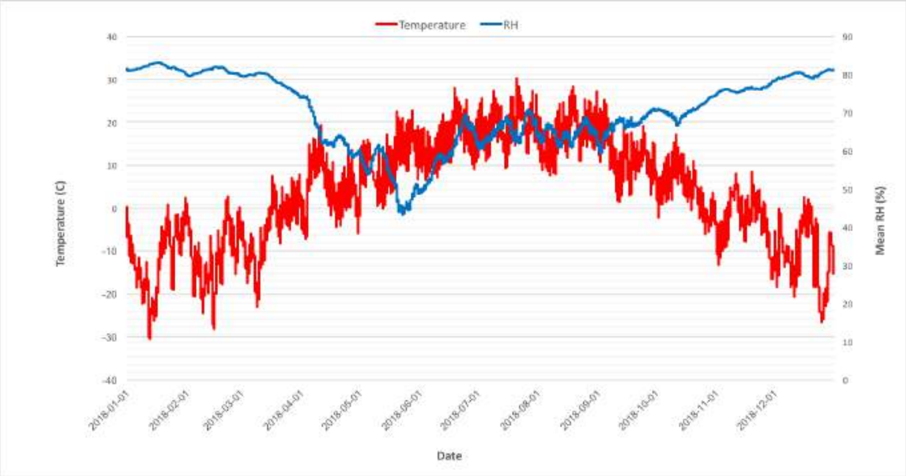


Figure 33: Temperature and RH profile of the Insulated Sheathing Layer on NE Wall in Saskatoon

6.4 Summary

The results show that the proposed assembly is capable of meeting the PHIUS+ 2015 certification criteria in each of the 3 select cities. Achieving a high degree of airtightness (as was achieved with the reference house) is, however, necessary to satisfy the targets. Seeing that straw bale buildings have historically struggled to achieve extremely high degrees of air tightness, it would be prudent to model with an air change rate closer to the maximum permitted under the Standard. This is especially true of locations, Saskatoon for instance, where the performance targets are narrowly satisfied even with an assumed air change rate far below that permitted under the Standard. This allows the designer to turn the dials in other areas (e.g. adding more outboard insulation to the straw bale wall assembly) to ensure the performance targets are satisfied.

The inclusion of a secondary suite skews the results by increasing the total occupancy by one[6], and this has implications for the target criteria, increasing the heating demand and load, as well as the source energy demand (cooling demand and load decrease owing to fewer occupants and associated internal gains; see Appendix V for full results). Occupancy needs to be considered early in the design process, as the number of occupants has a significant impact on the overall performance of the home.

---

[6] Recall, PHIUS+ 2015 calculates the occupancy at # of bedrooms +1. In the case of the reference house, there are 2 units, each with 2 bedrooms, resulting in 6 occupants. Removing the basement suite results in 5 occupants.

The proposed assembly takes inspiration from the case studies, particularly the pre-fabricated straw bale panels that have successfully been used in passive house projects, using complimentary materials to maintain thermal continuity and air tightness, and to add additional thermal resistance necessary for compliance. While these high performance straw bale assemblies may be seen as a vast departure from the rather elegant and uncomplicated plastered bale wall that early practitioners used to good effect, for straw bale building to remain relevant the systems must evolve to meet new code and performance requirements, and to satisfy occupant expectations relating to durability and aesthetics.

7.0 Conclusions

Though straw bales have not been used in a PHIUS+ 2015-certified project to date, the results of the analysis indicate that straw bales can be a beneficial component in satisfying the requirements of the Standard in Western Canada. The literature review identified the qualities of straw bales required to assure reliable performance from the material, while also highlighting the key characteristics of complementary materials need to create a superinsulated straw bale assembly. These material qualities are necessary to achieve thermal performance, as well as to mitigate any issues relating to excessive moisture within the assembly. Deficiencies related to thermal bridging and air tightness are minimized by following one of the main guiding principles of Passive House design, namely simple form. Designing around a bale module is the most effective path to maintaining the integrity of the thermal envelope, and minimizing transitions reduces thermal bridging and reduces the air control detailing necessary for air tight construction. Merging thoughtful design with material compatibility allows straw bales to be used in creating building enclosures capable of achieving the Passive House standard, while also minimizing the embodied carbon of the enclosure.

8.0 Future Work

With the theoretical groundwork in place, there remains a need to test straw bale buildings that are specifically designed with the goal of achieving Passive House standards, particularly in regards to achieving the air tightness goals set out by the standards. There remains ample opportunity to evaluate alternate assembly configurations using straw bales, and associated components, within high performance enclosures, including both modular (and pre-fabricated) and site-built assemblies. There will no doubt be adherents to the more traditional straw bale assemblies that employ both interior and exterior plasters. As such, evaluating the performance of different plaster compositions (e.g. clay, lime, cement-lime), particularly their effect on the moisture characteristics of advanced straw bale assemblies, is worthy of investigation.

Appendix I: PHPP for Reference House

Version 1.0

BRIEF INSTRUCTIONS

Place your mouse here to see the PHPP help.

If no help appears when the mouse passes over cell B5, you can activate it by going into the Worksheet Menu Bar/Tools/Options/View, and under "Comments", select "Comment Indicator Only".

Passive House Verification: Meaning of Field Formats

Example	Field Format	Meaning
78.8	Courier, blue, bold on yellow background	Input Field: Please enter the required value here
6619	Arial, black, standard on white background	Calculation field; please do not change
78.8	Courier New, purple, bold on white background	Field with references to another sheet - should not be changed.
126.0	Arial, black, large & bold on green background	**Important result**

Passive House Planning: Worksheet Directory

Worksheet Name	Function	Brief Description	Required for the c
Verification	Building Data; Summary of Results	Building description, selection of the calculation method, summary of results	yes
Areas	Areas Summary	Building Element Areas, Thermal Bridges, Treated Floor Area. Use exterior dimension references!	yes
U-List	U-Value Summary	List of calculation results from the U-Values worksheet, Building Element Database	yes
U-Values	Calculation of Standard Building Element U-Values	Heat transmission coefficient calculations in accordance with DIN EN ISO 6946.	yes
Ground	Calculation of Reduction Factors Against Ground	More precise calculation of heat losses through the ground	if applicable
Windows	U_W-Value Determination	Input of geometry, orientation, frame lengths, frame widths, U_g and U-values of the frame, and the thermal bridge heat loss coefficients of the connections; from these inputs, determine U_W and total radiation.	yes
WinType	Characteristic Values of Glazings and Frames	Lists of glazings and window frames with all necessary characteristics	yes
Shading	Determination of Shading Factors and Influence of Window Orientation	Input of shading parameters, e.g. balcony, neighbouring building, window reveal and calculating the shading factors	yes
Ventilation	Air Flow Rates, Exhaust/Supply Air Balancing, Pressurization Test Results	Sizing the ventilation system from extract and supply air requirements, infiltration air change rate and actual efficiency of heat recovery, input of pressurization test results	yes
Annual Heat Demand	Annual Heat Demand / Annual Method	Calculation of the annual space heat demand according to the energy balance method following EN 13790: Transmission + Ventilation - η (Solar Gains + Internal Gains)	yes
Monthly Method	Monthly Method Following EN 13790	Calculation procedure for the monthly method following EN 13790. Make appropriate selection in the Verification worksheet, if calculations should be performed following this procedure	if selected
Heating Load	Building Heat Load Calculation	Calculation of the nominal heat load using a balance procedure for the design day: max transmission + max ventilation - h (minimum solar gains + internal heat gains)	yes
Summer	Assessment of Summer Climate	Calculation of the frequency of overheating as a measure of summer comfort	yes
Shading-S	Determination of Shading Factors for the Summer	Shading factors for the summer period	yes
SummVent	Determination of Summer Ventilation	Estimation of air flow rates for natural ventilation during the summer period	if used
Cooling	Monthly Method for Cooling Demand	Calculation of the annual useful cooling demand, analogous to Monthly Method worksheet	if present
Cooling Units	Latent Cooling Energy	Calculation of the energy demand for dehumidification and choice of cooling method	if present
Cooling Load	Building Cooling Load Calculation	Calculation of the daily average cooling load of the building	no
DHW+Distribution	Distribution losses; DHW Requirement and Losses	Heat loss calculation of the distribution systems (heating; DHW); calculation of the useful heat requirement of DHW and storage losses	yes
SolarDHW	Solar DHW Heating	Calculation of the solar fraction of DHW	if a solar system is present
Electricity	Electricity Demand for Dwellings	Calculation of the electricity demand of Passive Houses with residential use	yes
Electricity Non-Dom	Electricity Demand for Non-Domestic Use	Calculation of the electricity demand for lighting, electric devices and kitchens for non-domestic buildings	no
Aux Electricity	Auxiliary Electricity Demand	Calculation of auxiliary electricity and corresponding primary energy demand	yes
PE Value	Specific Primary Energy and CO_2 Demands	Selection of heat generators, calculation of the specific primary energy and CO2 demands from the present results	yes
Compact	Efficiency of Heat Generator Compact Heat Pump Unit	Calculation of the efficiency of a combined heat generation for heating and DHW exclusively by means of an electric compact heat pump unit under the boundary conditions of the project	if present
Boiler	Efficiency of Heat Generator Boiler	For the calculation of the efficiency of heat generation with standard boilers (NT and calorific boilers) for the project given boundary conditions.	if present
District Heat	District Heat Transfer Station	Calculation of the final and primary energy demands (heat)	if present
Climate Data	Climate Region Selection or Definition of User Data	Climate data for the worksheets Annual Heat Demand, Windows, Heating Load, Monthly Method, Summer, Cooling, Cooling Units, Cooling Load	if not standard
IHG	Internal Heat Gains in Dwellings	Calculation of the internal heat gains based on the Electricity and Aux Electricity sheets.	no
IHG Non-Dom	Internal Heat Gains for Non-Domestic Use	Calculation of the internal heat gains for non-domestic buildings based on the Electricity Non-Dom worksheet and the occupancy	no
Use Non-Dom	Patterns of Non-Domestic Utilisation	Input or selection of utilisation patterns for planning of electricity demand and internal heat gains	no
Data	Database	Table of primary energy factors following Gemis and database	no

Passive House Verification

this a non-licensed workshop version

Building:
Location and Climate: Calgary AB_Calgary
Street:
Postcode/City:
Country: Canada
Building Type: Single Family With Basement Suite

Home Owner(s) / Client(s): Frank Crawford and Melissa Valgardson
Street:
Postcode/City:

Architect:
Street:
Postcode/City:

Mechanical System:
Street:
Postcode/City:

Year of Construction: 2015
Number of Dwelling Units: 2
Enclosed Volume V_e: 864.6 m^3
Number of Occupants: 7.3

Interior Temperature: 20.0 °C
Internal Heat Gains: 2.1 W/m^2

Specific Demands with Reference to the Treated Floor Area

Treated Floor Area: 256.4 m^2

	Applied:	Monthly Method	PH Certificate:	Fulfilled?
Specific Space Heat Demand:	11	kWh/(m^2a)	15 kWh/(m^2a)	Yes
Pressurization Test Result:	0.3	h^{-1}	0.6 h^{-1}	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	96	kWh/(m^2a)	120 kWh/(m^2a)	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	44	kWh/(m^2a)		
Specific Primary Energy Demand Energy Conservation by Solar Electricity:		kWh/(m^2a)		
Heating Load:	11	W/m^2		
Frequency of Overheating:	7	%	over 25 °C	
Specific Useful Cooling Energy Demand:		kWh/(m^2a)	15 kWh/(m^2a)	
Cooling Load:	3	W/m^2		

We confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The calculations with PHPP are attached to this application.

Issued on:

signed:

Passive House Planning

AREAS DETERMINATION

uilding:

Heat Demand: 11 kWh/(m²a)

Summary						
Group Nr.	**Area Group**	**Temp Zone**	**Area**	**Unit**	**Comments**	**Building Element Overview**
1	**Treated Floor Area**		**256.41**	m²	*Living area or useful area within the thermal envelope*	
2	**North Windows**	**A**	**11.25**	m²	Results are from the Windows worksheet.	**North Windows**
3	**East Windows**	**A**	**0.00**	m²		**East Windows**
4	**South Windows**	**A**	**26.60**	m²		**South Windows**
5	**West Windows**	**A**	**1.58**	m²		**West Windows**
6	**Horizontal Windows**	**A**	**0.00**	m²		**Horizontal Windows**
7	**Exterior Door**	**A**	**5.18**	m²	*Please subtract area of door from respective building element*	**Exterior Door**
8	**Exterior Wall - Ambient**	**A**	**232.20**	m²	*Window areas are subtracted from the individual areas specified in the "Windows" worksheet.*	**Exterior Wall - Ambient**
9	**Exterior Wall - Ground**	**B**	**49.77**	m²	*Temperature Zone "A" is ambient air.*	**Exterior Wall - Ground**
10	**Roof/Ceiling - Ambient**	**A**	**132.02**	m²	*Temperature zone "B" is the ground.*	**Roof/Ceiling - Ambient**
11	**Floor Slab**	**B**	**117.06**	m²		**Floor Slab**
12			**0.00**	m²	*Temperature zones "A", "B","P" and "X" may be used. NOT "I"*	
13			**0.00**	m²	*Temperature zones "A", "B","P" and "X" may be used. NOT "I"* Factor for X	
14		**X**	**0.00**	m²	*Temperature zone "X": Please provide user-defined reduction factor (0 < f_t < 1):* 75%	
						Thermal Bridge Overview
15	**Thermal Bridges Ambient**	**A**	**0.00**	m	*Units in m*	**Thermal Bridges Ambient**
16	**Perimeter Thermal Bridges**	**P**	**0.00**	m	*Units in m; temperature zone "P" is perimeter (see Ground worksheet).*	**Perimeter Thermal Bridges**
17	**Thermal Bridges Floor Slab**	**B**	**0.00**	m	*Units in m*	**Thermal Bridges Floor Slab**
18	**Partition Wall to Neighbour**	**I**	**0.00**	m²	*No heat losses, only considered for the heat load calculation.*	**Partition Wall to Neighbour**
Total Thermal Envelope			**575.65**	**m²**		**Average Therm. Envelope**

av ratio 0.30

Area Input																	
Area Nr.	**Building Element Description**	**Group Nr.**	**Assigned to Group**	**Quantity**	**x (**	**a [m]**	**x**	**b [m]**	**+**	**User-Determined [m²]**	**-**	**User Subtraction [m²]**	**-**	**Subtraction Window Areas [m²]**	**) =**	**Area [m²]**	**Selection of the Corresponding Building Element Assembly**
	Treated Floor Area	**1**	Treated Floor Area	2	x (	12.192	x	8.534	+	24.15	-				) =	256.4	
	North Windows	**2**	North Windows													11.3	From Windows sheet
	East Windows	**3**	East Windows													0.0	From Windows sheet
	South Windows	**4**	South Windows	**Please complete in Windows worksheet only!**												26.6	From Windows sheet
	West Windows	**5**	West Windows													1.6	From Windows sheet
	Horizontal Windows	**6**	Horizontal Windows													0.0	From Windows sheet
	Exterior Door	**7**	Exterior Door	2	x (	1.15	x	2.25	+		-		) -		=	5.2	U-Value Exterior Door
1	EXW North Basement	9	Exterior Wall - Ground	1	x (	12.80	x	1.22	+		-		) -	3.7	=	11.9	Basement Wall ▼
2	EXW North Basement Above Ground	8	Exterior Wall - Ambient	1	x (	12.80	x	1.52	+		-		) -	0.0	=	19.5	Basement Wall ▼
3	EXW North Main Level	8	Exterior Wall - Ambient	1	x (	12.80	x	4.88	+		-		) -	7.5	=	54.9	Wall 2x6 with ser ▼
4	EXW South Basement	9	Exterior Wall - Ground	1	x (	12.80	x	1.22	+		-		) -	0.0	=	15.6	Basement Wall ▼
5	EXW South Basement Above Ground	8	Exterior Wall - Ambient	1	x (	12.80	x	1.52	+		-		) -	6.3	=	13.2	Basement Wall ▼
6	EXW South Main Level	8	Exterior Wall - Ambient	1	x (	12.80	x	2.44	+		-		) -	20.3	=	10.9	Wall 2x6 with ser ▼
7	EXW East Basement	9	Exterior Wall - Ground	1	x (	9.14	x	1.22	+		-		) -	0.0	=	11.1	Basement Wall ▼
8	EXW East Basement Above Ground	8	Exterior Wall - Ambient	1	x (	9.14	x	1.52	+		-		) -	0.0	=	13.9	Basement Wall ▼
9	EXW East Main Level	8	Exterior Wall - Ambient	1	x (	9.14	x	4.64	+		-		) -	0.0	=	42.5	Wall 2x6 with ser ▼
10	EXW West Basement	9	Exterior Wall - Ground	1	x (	9.14	x	1.22	+		-		) -	0.0	=	11.1	Basement Wall ▼
11	EXW West Basement Above Ground	8	Exterior Wall - Ambient	1	x (	9.14	x	1.52	+		-		) -	0.0	=	13.9	Basement Wall ▼
12	EXW West Main Level	8	Exterior Wall - Ambient	1	x (	9.14	x	4.64	+		-		) -	1.6	=	40.9	Wall 2x6 with ser ▼
13	EXW South Clearstory	8	Exterior Wall - Ambient	1	x (	12.80	x	1.75	+		-		) -	0.0	=	22.4	Wall 2x6 with ser ▼
14					x (		x		+		-		) -	0.0	=		▼
15					x (		x		+		-		) -	0.0	=		▼
16	Roof North	10	Roof/Ceiling - Ambient	1	x (	12.80	x	7.010	+		-		) -	0.0	=	89.7	R60 Roof with ser ▼
17	Roof South	10	Roof/Ceiling - Ambient	1	x (	12.80	x	3.30	+		-		) -	0.0	=	42.3	R60 Roof with ser ▼
18	Basement Floor Slab	11	Floor Slab	1	x (	12.80	x	9.14	+		-		) -	0.0	=	117.1	basement floor ▼
19					x (		x		+		-		) -	0.0	=		▼
20	Ground Floor Living room	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼
21	Ground Floor Living room	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼
22	Ground Floor Kitchen	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼
23	Ground Floor Office / Guest room	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼
24	Ground Floor Utility room	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼
25	Ground Floor Storage	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼
26	First Floor Room 1	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼
27	First Floor Room 2	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼
28	First Floor Room 3	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼
29	First Floor Room 4	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼
30	First Floor Corridor	1	Treated Floor Area		x (		x		+		-		) -	0.0	=		▼

Passive House Planning
U-VALUES OF BUILDING ELEMENTS

Building:

Wedge Shaped Building Element Layers and
Still Air Spaces -> Secondary Calculation to the Right

1 Basement Wall
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}: 0.13
exterior R_{se}: 0.04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.	Quik therm insulation c/w battens, two 4in	0.033					203
2.	Concrete	2.100					203
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2:
Percentage of Sec. 3:
Total: 40.6 cm

RSI 6.42 R imp 37.13

U-Value: 0.156 W/(m²K)

15.99 in

4 basement floor
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}: 0.13
exterior R_{se}: 0.04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.	Plastifab 40psi type 3 EPS foam, R4.6/in	0.033					101
2.	Plastifab 40psi type 3 EPS foam, R4.6/in	0.033					101
3.	concerte	2.100					203
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2:
Percentage of Sec. 3:
Total: 40.5 cm

RSI 6.39 R imp 36.92

U-Value: 0.157 W/(m²K)

15.94 "

5 R60 Roof with service cavity using 16in deep I beams on 24in centers
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}: 0.13
exterior R_{se}: 0.04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.	Drywall	0.700					12
2.	service cavity	0.000			2x2 strapping	0.130	38
3.	I-beam 16" lower part	0.130			I-Beams 16" top	0.130	39
4.	fiberglass insulation	0.040	I-Beams 16" OSB377mm	0.130			406
5.	I-beam 16" upper part	0.130			I-Beams 16" bottom	0.130	39
6.	siga air barrier and air gap	0.000	1in plywood and 2x4 cross strappig				63
7.	plywood 1/2 in	0.000					12
8.	standing seam concealed fasteners 24 guag	0.000					25

Percentage of Sec. 2: 3.0%
Percentage of Sec. 3: 18.0%
Total: 63.4 cm

RSI 10.36 R imp 59.88

U-Value: 0.097 W/(m²K)

24.96 "

9 Wall 2x6 with service cavity and exterior insulation
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}: 0.13
exterior R_{se}: 0.04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.	Gypsum Plasterboard	0.800					12
2.	Service Cavity and siga vapour barrier	0.000	4 x 2 stud cut in half at 1	0.130			38
3.	Roxul comfobatt R24/5.5in	0.034			2 x 6 stud at 16 o/c	0.130	140
4.	3/8 plywood and siga air barrier	0.150					10
5.	Roxul dual density cavityrock, two x 3in la	0.034					152
6.	air space & 2x4 strapping on side	0.000					38
7.	Hardi board cladding	0.000					19
8.							

Percentage of Sec. 2: 18.0%
Percentage of Sec. 3: 20.0%
Total: 40.9 cm

RSI 7.70 R imp 44.50

U-Value: 0.130 W/(m²K)

16.10 in

10 Total thermal resistance of material outboard of vapour barrier in wall
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}: 0.13
exterior R_{se}: 0.04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.	Roxul	0.040			2 x 6 stud at 16 o/c	0.130	140
2.	plywood	0.150					19
3.	Exterior Roxul	0.040					152
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2: 0.0%
Percentage of Sec. 3: 16.0%
Total: 31.1 cm

RSI 6.87 R imp 39.70

U-Value: 0.146 W/(m²K)

11
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}: 0.13
exterior R_{se}: 0.04

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.	Gypsum Plasterboard	0.800					12
2.	Service Cavity (Roxull)	0.040	2 x 2 stud at 16 o/c	0.130			38
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2: 16.0%
Percentage of Sec. 3:
Total: 5.0 cm

RSI 0.91 R imp 5.24

U-Value: 1.103 W/(m²K)

12 main floor
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}:
exterior R_{se}:

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.	Drywall	0.700					12
2.	Air	1.222	11" floor joists	0.130			279
3.	plywood	0.150					19
4.	concrete	2.100					51
5.							
6.							
7.							
8.							

Percentage of Sec. 2: 3.1%
Percentage of Sec. 3:
Total: 36.1 cm

RSI 0.41 R imp 2.34

U-Value: 2.469 W/(m²K)

13
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}:
exterior R_{se}:

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2:
Percentage of Sec. 3:
Total: cm

U-Value: W/(m²K)

14
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}:
exterior R_{se}:

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2:
Percentage of Sec. 3:
Total: cm

U-Value: W/(m²K)

15
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}:
exterior R_{se}:

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2:
Percentage of Sec. 3:
Total: cm

U-Value: W/(m²K)

16
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}:
exterior R_{se}:

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2:
Percentage of Sec. 3:
Total: cm

U-Value: W/(m²K)

17
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}:
exterior R_{se}:

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2:
Percentage of Sec. 3:
Total: cm

U-Value: W/(m²K)

18
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}:
exterior R_{se}:

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2:
Percentage of Sec. 3:
Total: cm

U-Value: W/(m²K)

19
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}:
exterior R_{se}:

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2:
Percentage of Sec. 3:
Total: cm

U-Value: W/(m²K)

20
Assembly No. Building Assembly Description

Heat Transfer Resistance [m²K/W] interior R_{si}:
exterior R_{se}:

	Area Section 1	λ [W/(mK)]	Area Section 2 (optional)	λ [W/(mK)]	Area Section 3 (optional)	λ [W/(mK)]	Total Width Thickness [mm]
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							

Percentage of Sec. 2:
Percentage of Sec. 3:
Total: cm

Passive House Planning

HEAT LOSSES VIA THE GROUND

Ground Characteristics				Climate Data			
Thermal Conductivity	λ	2.0	W/(mK)	Av. Indoor Temp. Winter	T_i	20.0	°C
Heat Capacity	ρc	2.0	MJ/(m³K)	Av. Indoor Temp. Summer	T_i	25.0	°C
Periodic Penetration Depth	δ	3.17	m	Average Ground Surface Temperature	$T_{g,ave}$	5.4	°C
				Amplitude of $T_{g,ave}$	$T_{g,\wedge}$	13.0	°C
				Length of the Heating Period	n	6.7	months
				Heating Degree Hours - Exterior	G_t	110.7	kKh/a

Building Data				Floor Slab U-Value	U_f	0.157	W/(m²K)
Floor Slab Area	A	117.1	m²	Thermal Bridges at Floor Slab	Ψ_B*l	0.00	W/K
Floor Slab Perimeter	P	44.0	m	Floor Slab U-Value incl. TB	U_f'	0.157	W/(m²K)
Charact. Dimension of Floor Slab	B'	5.32	m	Eq. Thickness Floor	d_t	12.8	m

Floor Slab Type (select only one) Please choose one option only.

	Heated Basement or Underground Floor Slab		Unheated basement
x	Slab on Grade		Suspended Floor

For Basement or Underground Floor Slab							
Basement Depth	z	3.00	m	U-Value Belowground Wall	U_{wB}	0.156	W/(m²K)
Additionally for Unheated Basements				Height Aboveground Wall	h		m
Air Change Unheated Basement	n	0.20	h^{-1}	U-Value Aboveground Wall	U_W	0.156	W/(m²K)
Basement Volume	V	234	m³	U-Value Basement Floor Slab	U_{fB}	0.157	W/(m²K)

For Perimeter Insulation for Slab on Grade				**For Suspended Floor**			
Perimeter Insulation Width/Depth	D		m	U-Value Crawl Space	U_{Crawl}		W/(m²K)
Perimeter Insulation Thickness	d_n		m	Height of Crawl Space Wall	h		m
Conductivity Perimeter Insulation	λ_n		W/(mK)	U-Value Crawl Space Wall	U_W		W/(m²K)
				Area of Ventilation Openings	εP		m²
Location of the Perimeter Insulation	horizontal			Wind Velocity at 10 m Height	v	4.0	m/s
(check only one field)	vertical			Wind Shield factor	f_W	0.05	-

Additional Thermal Bridge Heat Losses at Perimeter				Steady-State Fraction	$\Psi_{P,stat}$*l	0.000	W/K
Phase Shift	β		months	Harmonic Fraction	$\Psi_{P,harm}$*l	0.000	W/K

Groundwater Correction							
Depth of the Groundwater Table	z_W	3.0	m	Transm. Belowground El. (w/o Ground)	L_{reg}	18.32	W/K
Groundwater Flow Rate	q_W	0.05	m/d	Relative Insulation Standard	d_t/B'	2.40	-
				Relative Groundwater Depth	z_W/B'	0.56	-
Groundwater Correction Factor	G_W	1.0044532	-	Relative Groundwater Velocity	l/B'	0.16	-

Basement or Underground Floor Slab							
Eq. Thickness Floor Slab	d_t	12.8	m	Phase Shift	β		months
U-Value Floor Slab	U_{bf}	0.12	W/(m²K)	Exterior Periodic Transmittance	L_{pe}	11.58	W/K
Eq. Thickness Basement Wall	d_w	12.85	m				
U-Value Wall	U_{bw}	0.13	W/(m²K)				
Steady-State Transmittance	L_S	30.67	W/K				

Unheated Basement							
Steady-State Transmittance	L_S	13.11	W/K	Phase Shift	β	1.41	months
				Exterior Periodic Transmittance	L_{pe}	2.59	W/K

Slab on Grade							
Heat Transfer Coefficient	U_0	0.13	W/(m²K)	Phase Shift	β	1.41	months
Eq. Ins. Thickness Perimeter Ins.	d'	0.00	m	Exterior Periodic Transmittance	L_{pe}	7.21	W/K
Perimeter Insulation Correction	$\Delta\Psi$		W/(mK)				
Steady-State Transmittance	L_S	15.46	W/K				

Suspended Floor Above a Ventilated Crawl Space (at max. 0.5 m Below Ground)							
Eq. Ins. Thickness Crawl Space	d_g		m	Phase Shift	β		months
U-Value Crawl Space Floor Slab	U_g		W/(m²K)	Exterior Periodic Transmittance	L_{pe}		W/K
U-Value Crawl Space Wall & Vent.	U_X		W/(m²K)				
Steady-State Transmittance	L_S		W/K				

Interim Results							
Phase Shift	β	1.41	months	Steady-State Heat Flow	Φ_{stat}	226.5	W
Steady-State Transmittance	L_S	15.46	W/K	Periodic Heat Flow	Φ_{harm}	38.8	W
Exterior Periodic Transmittance	L_{pe}	7.21	W/K	Heat Losses During Heating Period	Q_{tot}	1302	kWh

Ground Reduction Factor for "Annual Heat Demand" Sheet 0.642

Monthly Average Ground Temperatures for Monthly Method

Month	1	2	3	4	5	6	7	8	9	10	11	12	Average Valu
Winter	3.9	2.6	2.8	4.2	6.6	9.2	11.4	12.6	12.5	11.1	8.7	6.1	7.6
Summer	4.6	3.4	3.5	5.0	7.3	10.0	12.2	13.4	13.3	11.9	9.5	6.9	8.4

Design Ground Temperature for Heat Load Sheet 2.6 **for Cooling Load Sheet** 13.4

Passive House Planning

REDUCTION FACTOR SOLAR RADIATION, WINDOW U-VALUE

Building:

Annual Heat Demand: 10.82462 kWh/(m²a)

Heating Degree Hours: 110.7

Climate:

Window Area Orientation	Dirt	Non-Perpendicular Incident Radiation	Glazing Fraction	g-Value	Reduction Factor for Solar Radiation	Window Area	Window U-Value	Glazing Area	Average Global Radiation	Transmission Losses	Heat Gains Solar Radiation
maximum:	0.95	0.85				m²	W/(m²K)	m²	kWh/(m²a)	kWh/a	kWh/a
North	0.95	0.85	0.706	0.49	0.46	11.25	0.74	7.9	99	921	249
East	0.95	0.85	0.000	0.00	0.00	0.00	0.00	0.0	329	0	0
South	0.95	0.85	0.718	0.61	0.49	26.60	0.77	19.1	770	2271	6126
West	0.95	0.85	0.773	0.61	0.16	1.58	0.81	1.2	433	142	67
Horizontal	0.95	0.85	0.000	0.00	0.00	0.00	0.00	0.0	477	0	0
				0.58	0.47	39.43	0.76	28.3		3335	6442

6128.6939

			Window Rough Openings		Installed		Glazing		Frame		g-Value	U-Value		Window Frame Dimensions				Ψ-Value		Results			
Quantity	Description	Orientation	Width	Height	in Area in the Areas worksheet	Nr.	Select glazing from the WinType worksheet	Nr.	Select window from the WinType worksheet	Nr.	Perpendicular Radiation	Glazing	Frames	Width - Left	Width - Right	Width - Below	Width - Above	Ψ_{Spacer}	$\Psi_{Installation}$	Window Area	Glazing Area	U-Value Window	Glazed Fraction per Window
			m	m	Select:		Select:		Select:		-	W/(m²K)	W/(m²K)	m	m	m	m	W/(mK)	W/(mK)	m²	m²	W/(m²K)	%
1	Basement South Living	South	1.346	1.397	EXW South Base	5	klear wall triple high SHG	9	Klear wall future proof fixed	10	0.61	0.60	0.66	0.08	0.08	0.08	0.08	0.025	0.040	1.9	1.49	0.76	0.79
1	Basement South Living operable	South	1.346	1.397	EXW South Base	5	klear wall triple high SHG	9	Klear wall future proof operable	9	0.61	0.60	0.66	0.13	0.13	0.13	0.13	0.025	0.040	1.9	1.26	0.77	0.67
1	Basement South Master Bedroom op	South	1.219	1.397	EXW South Base	5	klear wall triple high SHG	9	Klear wall future proof operable	9	0.61	0.60	0.66	0.13	0.13	0.13	0.13	0.025	0.040	1.7	1.11	0.77	0.65
1	Basement South Master Bedroom	South	0.610	1.397	EXW South Base	5	klear wall triple high SHG	9	Klear wall future proof fixed	10	0.61	0.60	0.66	0.08	0.08	0.08	0.08	0.025	0.040	0.9	0.57	0.84	0.67
1	main Kitchen South operable	South	0.775	1.092	EXW South Mai	6	klear wall triple high SHG	9	Klear wall future proof operable	9	0.61	0.60	0.66	0.13	0.13	0.13	0.13	0.025	0.040	0.8	0.44	0.83	0.52
1	main Kitchen South	South	2.134	1.092	EXW South Mai	6	klear wall triple high SHG	9	Klear wall future proof fixed	10	0.61	0.60	0.66	0.08	0.08	0.08	0.08	0.025	0.040	2.3	1.87	0.77	0.80
2	Dining	South	1.524	1.562	EXW South Main	6	klear wall triple high SHG	9	Klear wall future proof fixed	10	0.61	0.60	0.66	0.08	0.08	0.08	0.08	0.025	0.040	4.8	3.88	0.75	0.82
1	dining door	South	0.914	2.134	EXW South Mai	6	klear wall triple high SHG	9	Klear wall future proof operable	9	0.61	0.60	0.66	0.13	0.13	0.13	0.13	0.025	0.040	2.0	1.25	0.81	0.64
1	Back Entry Window	South	1.219	1.219	EXW South Mai	6	klear wall triple high SHG	9	Klear wall future proof operable	9	0.61	0.60	0.66	0.13	0.13	0.13	0.13	0.025	0.040	1.5	0.94	0.82	0.63
2	loft south large middle	South	1.600	0.940	EXW South Mai	6	klear wall triple high SHG	9	Klear wall future proof fixed	10	0.61	0.60	0.66	0.08	0.08	0.08	0.08	0.025	0.040	3.0	2.29	0.80	0.76
2	loft south small middle	South	1.181	0.940	EXW South Mai	6	klear wall triple high SHG	9	Klear wall future proof fixed	10	0.61	0.60	0.66	0.08	0.08	0.08	0.08	0.025	0.040	2.2	1.63	0.62	0.73
2	loft south operable outside	South	1.956	0.940	EXW South Mai	6	klear wall triple high SHG	9	Klear wall future proof operable	9	0.61	0.60	0.66	0.13	0.13	0.13	0.13	0.025	0.040	3.7	2.35	0.81	0.64
2	main bedrooms north	North	1.219	1.219	EXW North Mai	3	klear wall triple low SHG	10	Klear wall future proof operable	9	0.49	0.50	0.66	0.13	0.13	0.13	0.13	0.025	0.040	3.0	1.88	0.76	0.63
1	loft north bath	North	1.219	1.067	EXW North Mai	3	klear wall triple low SHG	10	Klear wall future proof fixed	10	0.49	0.50	0.66	0.08	0.08	0.08	0.08	0.025	0.040	1.3	0.98	0.76	0.75
1	loft north bedroom operable	North	1.219	1.067	EXW North Mai	3	klear wall triple low SHG	10	Klear wall future proof operable	9	0.49	0.50	0.66	0.13	0.13	0.13	0.13	0.025	0.040	1.3	0.79	0.77	0.61
1	loft north large	North	1.219	1.588	EXW North Mai	3	klear wall triple low SHG	10	Klear wall future proof fixed	10	0.49	0.50	0.66	0.08	0.08	0.08	0.08	0.025	0.040	1.9	1.54	0.71	0.79
1	basement kitchen north	North	1.930	1.168	EXW North Base	1	klear wall triple low SHG	10	Klear wall future proof fixed	10	0.49	0.50	0.66	0.08	0.08	0.08	0.08	0.025	0.040	2.3	1.81	0.70	0.80
1	basement bedroom north op	North	1.219	1.219	EXW North Base	1	klear wall triple low SHG	10	Klear wall future proof operable	9	0.49	0.50	0.66	0.13	0.13	0.13	0.13	0.025	0.040	1.5	0.94	0.76	0.63
1	main kitchen west	West	1.448	1.092	EXW West Main	12	klear wall triple high SHG	9	Klear wall future proof fixed	10	0.61	0.60	0.66	0.08	0.08	0.08	0.08	0.025	0.040	1.6	1.22	0.81	0.77

Passive House Planning

CALCULATING SHADING FACTORS

Climate: AB_Calgary

Building:

Latitude: 51.046 °

Orien-tation	Glazing Area m²	Reduction Factor r_S
North	7.94	80%
East	0.00	100%
South	19.09	85%
West	1.22	26%
Horizontal	0.00	100%

10.825 kWh/(m2a)

6.597% Frequency of Overheating:

Quantity	Description	Deviation from North	Angle of Inclination from the Horizontal	Orientation	Glazing Width	Glazing Height	Glazing Area	Height of the Shading Object	Horizontal Distance	Window Reveal Depth	Distance from Glazing Edge to Reveal	Overhang Depth	Distance from Upper Glazing Edge to Overhang	Additional Shading Reduction Factor	Horizontal Shading Reduction Factor	Reveal Shading Reduction Factor	Overhang Shading Reduction Factor	Total Shading Reduction Factor
		Degrees	Degrees		m	m		m	m	m	m	m	m	%	%	%	%	%
					w_G	h_G	A_G	h_{Hori}	d_{Hori}	o_{Reveal}	d_{Reveal}	o_{over}	d_{over}	r_{other}	r_H	r_R	r_O	r_S
1	Basement South Living	164	90	South	1.20	1.25	1.5			0.15	0.05	0.30	0.10	100%	100%	95%	94%	89%
1	Basement South Living operable	164	90	South	1.10	1.15	1.3			0.15	0.05	0.30	0.10	100%	100%	94%	94%	89%
1	Basement South Master Bedroom o	164	90	South	0.97	1.15	1.1			0.15	0.05	0.30	0.10	100%	100%	94%	94%	88%
1	Basement South Master Bedroom	164	90	South	0.46	1.25	0.6			0.15	0.05	0.30	0.10	100%	100%	88%	94%	83%
1	main Kitchen South operable	164	90	South	0.52	0.84	0.4			0.15	0.05	0.74	0.28	100%	100%	89%	87%	78%
1	main Kitchen South	164	90	South	1.98	0.94	1.9			0.15	0.05	0.74	0.28	100%	100%	97%	88%	85%
2	Dining	164	90	South	1.37	1.41	3.9			0.15	0.05	0.74	0.28	100%	100%	95%	90%	86%
1	dining door	164	90	South	0.66	1.88	1.3			0.15	0.05	0.74	0.28	100%	100%	91%	92%	84%
1	Back Entry Window	164	90	South	0.97	0.97	0.9			0.15	0.05	0.74	0.28	100%	100%	94%	88%	82%
2	loft south large middle	164	90	South	1.45	0.79	2.3			0.23	0.05	0.90	0.58	100%	100%	93%	88%	83%
2	loft south small middle	164	90	South	1.03	0.79	1.6			0.23	0.05	0.90	0.58	100%	100%	91%	88%	80%
2	loft south operable outside	164	90	South	1.71	0.69	2.4			0.23	0.05	0.90	0.58	100%	100%	94%	88%	83%
2	main bedrooms north	344	90	North	0.97	0.97	1.9			0.15	0.05			100%	100%	92%	100%	92%
1	loft north bath	344	90	North	1.07	0.92	1.0			0.15	0.05			100%	100%	92%	100%	92%
1	loft north bedroom operable	344	90	North	0.97	0.82	0.8			0.15	0.05			100%	100%	92%	100%	92%
1	loft north large	344	90	North	1.07	1.44	1.5			0.15	0.05			100%	100%	92%	100%	92%
1	basement kitchen north	344	90	North	1.78	1.02	1.8			0.15	0.05	1.52	0.30	100%	100%	95%	61%	58%
1	basement bedroom north op	344	90	North	0.97	0.97	0.9			0.15	0.05	1.52	0.30	100%	100%	92%	60%	55%
1	main kitchen west	254	90	West	1.30	0.94	1.2	6.10	3.66	0.15	0.05			100%	28%	91%	100%	26%

Passive House Planning

VENTILATION DATA

Building:			10.8	kWh/(m2a)

Treated Floor Area A_{TFA}	m²	256	*(Areas worksheet)*
Room Height h	m	2.5	*(Annual Heat Demand worksheet)*
Room Ventilation Volume (A_{TFA}*h) = V_V	m³	641	*(Annual Heat Demand worksheet)*

Ventilation System Design - Standard Operation

Occupancy	m²/P	35				
Number of Occupants	P	7.3				
Supply Air per Person	m³/(P*h)	30	17.7			
Supply Air Requirement	m³/h	**220**	129.7			
Extract Air Rooms		Kitchen	Bathroom	Shower	WC	other
Quantity		2	4	0	1	0
Extract Air Requirement per Room	m³/h	60	40	20	20	10
Total Extract Air Requirement	m³/h	**300**				

Design Air Flow Rate (Maximum)	m³/h	300	177	5.057142857

Average Air Change Rate Calculation

Type of Operation	Daily Operation Duration h/d	Factors Referenced to Maximum	Air Flow Rate m³/h	Air Change Rate 1/h
Maximum		1.00	300	0.47
Standard	16.0	0.64	192	0.30
Basic		0.54	162	0.25
Minimum	8.0	0.40	120	0.19
			Average Air Flow Rate (m³/h)	Average Air Change Rate (1/h)
☒ Residential Building	**Average value**	**0.56**	**168**	**0.26**

Minimum air change rate 0.3 1/h.

Infiltration Air Change Rate according to EN 13790

Wind Protection Coefficients According to EN 13790		
Coefficient e for Screening Class	Several Sides Exposed	One Side Exposed
No Screening	0.10	0.03
Moderate Screening	0.07	0.02
High Screening	0.04	0.01
Coefficient f	15	20

			for Annual Demand:	for Heat Load:				
Wind Protection Coefficient, e			0.07	**0.18**				
Wind Protection Coefficient, f			15	**15**	Net Air Volume for Press. Test	V_{n50}	Air Permeability	q_{50}
Air Change Rate at Press. Test	n_{50}	1/h	0.28	0.28	531	m³	0.26	m³/(hm²)

Type of Ventilation System

			for Annual Demand:	for Heat Load:
☒ Balanced PH Ventilation	*Please Check*			
☐ Pure Extract Air				
Excess Extract Air		1/h	0.00	0.00
Infiltration Air Change Rate	$n_{V,Res}$	1/h	**0.016**	**0.041**

Effective Heat Recovery Efficiency of the Ventilation System with Heat Recovery

☒ Central unit within the thermal envelope.

☐ Central unit outside of the thermal envelope.

Efficiency of Heat Recovery	η_{HR}		0.92	Zehnder ComfoAir 200	
Transmittance Ambient Air Duct	Ψ	W/(mK)	0.471	Calculation see Secondary Calculation	
Length Ambient Air Duct		m	2		
Transmittance Exhaust Air Duct	Ψ	W/(mK)	0.471	Calculation see Secondary Calculation	
Length Exhaust Air Duct		m	2	Room Temperature (°C)	20
Temperature of Mechanical Services Room		°C		Av. Ambient Temp. Heating P. (°C)	-2.5
(Enter only if the central unit is outside of the thermal envelope.)				Av. Ground Temp (°C)	5.4

Effective Heat Recovery Efficiency	$\eta_{HR,eff}$	**89.4%**

Effective Heat Recovery Efficiency Subsoil Heat Exchanger

SHX Efficiency	η^*_{SHX}	33%
Heat Recovery Efficiency SHX	η_{SHX}	12%

Passive House Planning

SPECIFIC ANNUAL HEAT DEMAND

Climate: AB_Calgary
Building:
Location: Calgary

Interior Temperature: 20.0 °C
Building Type/Use: Single Family With Basement
Treated Floor Area A_{TFA}: 256.4 m²

	Building Element	Temperature Zone	Area m²		U-Value W/(m²K)		Temp. Factor f_t		G_t kKh/a		kWh/a	per m² Treated Floor Area
1.	Exterior Wall - Ambient	A	232.2	*	0.137	*	1.00	*	110.7	=	3511	
2.	Exterior Wall - Ground	B	49.8	*	0.156	*	0.64	*	110.7	=	550	
3.	Roof/Ceiling - Ambient	A	132.0	*	0.097	*	1.00	*	110.7	=	1410	
4.	Floor Slab	B	117.1	*	0.157	*	0.64	*	110.7	=	1302	
5.		A		*		*	1.00	*		=		
6.		A		*		*	1.00	*		=		
7.		X		*		*	0.75	*		=		
8.	Windows	A	39.4	*	0.764	*	1.00	*	110.7	=	3335	
9.	Exterior Door	A	5.2	*	0.800	*	1.00	*	110.7	=	458	
10.	Exterior TB (length/m)	A		*		*	1.00	*		=		
11.	Perimeter TB (length/m)	P		*		*	0.64	*		=		
12.	Ground TB (length/m)	B		*		*	0.64	*		=		
		Total of All Building Envelope Areas	575.6									kWh/(m²a)
	Transmission Heat Losses Q_T									Total	10566	41.2

Ventilation System:

Effective Air Volume, V_V: A_{TFA} (m²) 256.4 * Clear Room Height (m) 2.50 = 641.0 m³

Effective Heat Recovery Efficiency of Heat Recovery η_{eff} 89%

Efficiency of Subsoil Heat Exchanger η_{SHX} 12%

Energetically Effective Air Exchange n_V: $n_{V,system}$ (1/h) 0.262 (1 - Φ_{HR} 0.91) + $n_{V,Res}$ (1/h) 0.016 = 0.041 1/h

	V_V m³		n_V 1/h		c_{Air} Wh/(m³K)		G_t kKh/a		kWh/a	kWh/(m²a)
Ventilation Heat Losses Q_V	641	*	0.041	*	0.33	*	110.7	=	956	3.7

		Q_T kWh/a		Q_V kWh/a		Reduction Factor Night/Weekend Saving		kWh/a	kWh/(m²a)
Total Heat Losses Q_L	(	10566	+	956	)	1.0	=	11522	44.9

	Orientation of the Area	Reduction Factor See Windows Sheet		g-Value (perp. radiation)		Area m²		Radiation HP kWh/(m²a)		kWh/a	kWh/(m²a)
1.	North	0.46	*	0.49	*	11.25	*	99	=	249	
2.	East	0.40	*	0.00	*	0.00	*	329	=	0	
3.	South	0.49	*	0.61	*	26.60	*	770	=	6126	
4.	West	0.16	*	0.61	*	1.58	*	433	=	67	
5.	Horizontal	0.40	*	0.00	*	0.00	*	477	=	0	
	Available Solar Heat Gains Q_S								Total	6442	25.1

	kh/d		Length Heat. Period d/a		Spec. Power q_i W/m²		A_{TFA} m²		kWh/a	kWh/(m²a)
Internal Heat Gains Q_I	0.024	*	205	*	2.10	*	256.4	=	2643	10.3

Free Heat Q_F: $Q_S + Q_I$ = 9085 kWh/a; 35.4 kWh/(m²a)

Ratio of Free Heat to Losses: Q_F / Q_L = 0.79

Utilisation Factor Heat Gains η_G: $(1 - (Q_F / Q_L)^5) / (1 - (Q_F / Q_L)^6)$ = 92%

Heat Gains Q_G: $\eta_G * Q_F$ = 8314 kWh/a; 32.4 kWh/(m²a)

Annual Heat Demand Q_H: $Q_L - Q_G$ = 3208 kWh/a; 13 kWh/(m²a)

Limiting Value: 15 kWh/(m²a)

Requirement met? (Yes/No): Yes

For buildings with a gain-loss-ratio above 0,7 you should use the Monthly Method (cf. manual).

Passive House Planning

SPECIFIC SPACE HEATING LOAD

Building:

Location: Calgary

Building Type/Use: Single Family With Basement Suite

Treated Floor Area A_{TFA}: 256.4 m² Interior Temperature: 20 °C

Climate (HL): AB_Calgary

	Design Temperature		Radiation: North	East	South	West	Horizontal	
Weather Condition 1:	-24.4	°C	11	46	155	36	55	W/m²
Weather Condition 2:	-17.2	°C	10	34	116	30	42	W/m²
Ground Design Temp.	2.6	°C						

	Building Element	Temperature Zone	Area m²		U-Value W/(m²K)		Factor Always 1 (except "X")		TempDiff 1 K		TempDiff 2 K		P_T 1 W		P_T 2 W
1.	Exterior Wall - Ambient	A	232.2	*	0.137	*	1.00	*	44.4	or	37.2	=	1408	or	1180
2.	Exterior Wall - Ground	B	49.8	*	0.156	*	1.00	*	17.4	or	17.4	=	134	or	134
3.	Roof/Ceiling - Ambient	A	132.0	*	0.097	*	1.00	*	44.4	or	37.2	=	566	or	474
4.	Floor Slab	B	117.1	*	0.157	*	1.00	*	17.4	or	17.4	=	318	or	318
5.		A		*		*	1.00	*	44.4	or	37.2	=		or	
6.		A		*		*	1.00	*	44.4	or	37.2	=		or	
7.		X		*		*	0.75	*	44.4	or	37.2	=		or	
8.	Windows	A	39.4	*	0.764	*	1.00	*	44.4	or	37.2	=	1338	or	1121
9.	Exterior Door	A	5.2	*	0.800	*	1.00	*	44.4	or	37.2	=	184	or	154
10.	Exterior TB (length/m)	A		*		*	1.00	*	44.4	or	37.2	=		or	
11.	Perimeter TB (length/m)	P		*		*	1.00	*	17.4	or	17.4	=		or	
12.	Ground TB (length/m)	B		*		*	1.00	*	17.4	or	17.4	=		or	
13.	House/DU Partition Wall	I		*		*	1.00	*	3.0	or	3.0	=		or	

Transmission Heat Losses P_T

Total = 3949 or 3382

Ventilation System:

	A_{TFA} m²		Clear Room Height m		m³
Effective Air Volume, V_V	256.4	*	2.50	=	641

Efficiency of Heat Recovery of the Heat Exchanger η_{HR} 89%

Heat Recovery Efficiency SHX 33%

Efficiency SHX η_{SHX} 1: 22% or η_{SHX} 2: 20%

	n_V,Res (Heating Load) 1/h		$n_{V,system}$ 1/h		Φ_{HR}		Φ_{HR}		1/h		1/h
Energetically Effective Air Exchange n_v	0.041	+	0.262	*(1-	0.92	or	0.92	) =	0.062	or	0.063

Ventilation Heating Load P_V

V_L m³		n_L 1/h		n_L 1/h		c_{Air} Wh/(m³K)		TempDiff 1 K		TempDiff 2 K		P_V 1 W		P_V 2 W
641.0	*	0.062	or	0.063	*	0.33	*	44.4	or	37.2	=	**585**	or	**495**

Total Heating Load P_L

		P_L 1 W		P_L 2 W
$P_T + P_V$	=	**4533**	or	**3876**

	Orientation the Area	Area m²		g-Value (perp. radiation)		Reduction Factor (see Windows worksheet)		Radiation 1 W/m²		Radiation 2 W/m²		P_S 1 W		P_S 2 W
1.	North	11.3	*	0.5	*	0.5	*	9	or	9	=	23	or	23
2.	East	0.0	*	0.0	*	0.4	*	46	or	34	=	0	or	0
3.	South	26.6	*	0.6	*	0.5	*	150	or	112	=	1196	or	892
4.	West	1.6	*	0.6	*	0.2	*	59	or	47	=	9	or	7
5.	Horizontal	0.0	*	0.0	*	0.4	*	55	or	42	=	0	or	0

Solar Heat Gain, P_S

Total = **1229** or **922**

Internal Heat Gains P_I

Spec. Power W/m²		A_{TFA} m²		P_I 1 W		P_I 2 W
1.6	*	256	=	**410**	or	**410**

Heat Gains P_G

		P_G 1 W		P_G 2 W
$P_S + P_I$	=	**1639**	or	**1333**
$P_L - P_G$	=	**2894**	or	**2544**

Heating Load P_H

= **2894** **W**

Specific Heating Load P_H / A_{TFA}

= **11.3** **W/m²**

Input Max. Supply Air Temperature 52 °C

Max. Supply Air Temperature $\vartheta_{Supply,Max}$ 52 °C

Supply Air Temperature Without Heating $\vartheta_{Supply,Min}$ 16.3 °C 16.8 °C

For Comparison: Heating Load Transportable by Supply Air. $P_{Supply\ Air,Max}$

= **1980** W specific 7.7 W/m²

Supply Air Heating Sufficient? (Yes/No) **No**

Passive House Planning

SUMMER

Climate: AB_Calgary

Building:

Location: Calgary

Spec. Capacity: 84 Wh/K pro m² TFA

Overheating Limit: 25 °C

Interior Temperature: 20 °C

Building Type/Use: Single Family With

Treated Floor Area A_{TFA}: 256.4 m²

	Building Element	Temperature Zone	Area m²		U-Value W/(m²K)		Red. Factor $f_{T,Summer}$		H_{Summer} Heat Conductance
1.	Exterior Wall - Ambien	A	232.2	*	0.137	*	1.00	=	31.7
2.	Exterior Wall - Ground	B	49.8	*	0.156	*	1.00	=	7.7
3.	Roof/Ceiling - Ambient	A	132.0	*	0.097	*	1.00	=	12.7
4.	Floor Slab	B	117.1	*	0.157	*	1.00	=	18.3
5.		A		*		*	1.00	=	
6.		A		*		*	1.00	=	
7.		X		*		*	0.75	=	
8.	Windows	A	39.4	*	0.764	*	1.00	=	30.1
9.	Exterior Door	A	5.2	*	0.800	*	1.00	=	4.1
10.	Exterior TB (length/m)	A		*		*	1.00	=	
11.	Perimeter TB (length/m	P		*		*	1.00	=	
12.	Ground TB (length/m)	B		*		*	1.00	=	

Exterior Thermal Transmittance, $H_{T,e}$ 78.7 W/K

Ground Thermal Transmittance, $H_{T,g}$ 26.1 W/K

Heat Recovery Efficiency η_{HR} 89%

Effective Air Volume V_V: A_{TFA} 256.4 m² * Clear Room Height 2.50 m = 641 m³

SHX Efficiency η^*_{SHX} 33%

Summer Ventilation

continuous ventilation to provide sufficient indoor air quality

Air Change Rate by Natural (Windows & Leakages) or Exhaust-Only Mechanical Ventilation, Summer: 0.03 1/h

Mechanical Ventilation Summer: 0.30 1/h ☐ with HR (check if applicable)

	$n_{L,nat}$ 1/h		$n_{V,system}$ 1/h		Φ_{HR}		$n_{V,Rest}$ 1/h		1/h
Energetically Effective Airchange Rate n_V	0.030	+	0.300	* (1 -	0.000	) +	0.000	=	0.330

	V_V m³		$n_{V,equi,fraction}$ 1/h		c_{Air} Wh/(m³K)			
Ventilation Transm. Ambient $H_{V,e}$	641	*	0.231	*	0.33	=	48.8	W/K
Ventilation Transm. Ground $H_{V,g}$	641	*	0.099	*	0.33	=	20.9	W/K

Additional Summer Ventilation for Cooling

Temperature Amplitude Summer 13.2 K

Select: ☒ Window Night Ventilation, Manual

☐ Mechanical, Automatically Controlled Ventilation

Corresponding Air Change Rate 0.02 1/h

(for window ventilation: at 1 K temperature difference indoor - outdoor)

Minimum Acceptable Indoor Temperature 22.0 °C

	Orientation of the Area	Angle Factor Summer		Shading Factor Summer		Dirt		g-Value (perp. radiation)		Area m²		Portion of Glazing		**Aperture** m²
1.	North	0.9	*	0.81	*	0.95	*	0.49	*	11.3	*	71%	=	2.7
2.	East	0.9	*	1.00	*	0.95	*	0.00	*	0.0	*	0%	=	0.0
3.	South	0.9	*	0.63	*	0.95	*	0.61	*	26.6	*	72%	=	6.3
4.	West	0.9	*	0.38	*	0.95	*	0.61	*	1.6	*	77%	=	0.2
5.	Horizontal	0.9	*	1.00	*	0.95	*	0.00	*	0.0	*	0%	=	0.0
6	Sum Opaque Areas													0.8

Solar Aperture Total 10.0 m²/m² ##

	Specif. Power q_I W/m²		A_{TFA} m²		W	W/m²
Internal Heat Gains Q_I	2.10	*	256	=	538	2.1

Frequency of Overheating $h_{\vartheta \geq \vartheta_{max}}$ **6.6%** **at the overheating limit ϑ_{max} = 25 °C**

If the "frequency over 25°C" exceeds 10%, additional measures to protect against summer heat waves are necessary.

	Solar Load kWh/d		1/k		Spec. Capacity Wh/(m²K)		A_{TFA} m²			
Daily Temperature Swing due to Solar Load	30.8	*	1000	/ (	84	*	256	) =	**1.4**	**K**

Passive House Planning

CALCULATING SUMMER SHADING FACTORS

Climate: AB_Calgary

Building:

Latitude: 51.046

Summer!

Orien-tation	Glazing Area	Summer Shading Factor
	m²	r_S
North	7.94	81%
East	0.00	100%
South	19.09	63%
West	1.22	38%
Horizontal	0.00	100%

Results from the Summer worksheet:

Frequency of Overheating $h_{\vartheta \geq \vartheta max}$ **6.6%**

														Input Field Summer	Summer			
Quantity	Description:	Deviation from North	Angle of Inclination from the Horizontal	Orientation	Glazing Width	Glazing Height	Glazing Area	Height of the Shading Object	Horizontal Distance	Reveal Depth	Distance from Glazing Edge to Reveal	Overhang Depth	Distance from Upper Glazing Edge to Overhang	Additional Shading Reduction Factor (Summer)	Temporary Shading Reduction Factor, z	Horizontal Shading Reduction Factor	Reveal Shading Reduction Factor	Overhang Shading Reduction Factor	Total Summer Shading Reduction Factor
		Degrees	Degrees			m		m	m	m	m	m	m	%	%	%	%	%	%
					w_G	h_G	A_G	h_{Hori}	d_{Hori}	o_{Reveal}	d_{Reveal}	o_{over}	d_{over}	r_{other}		r_H	r_R	r_O	r_S
1	Basement South Liv	164	90	South	1.20	1.25	1.5			0.15	0.05	0.30	0.10			100%	94%	87%	81%
1	Basement South Liv	164	90	South	1.10	1.15	1.3			0.15	0.05	0.30	0.10			100%	93%	85%	79%
1	Basement South Mas	164	90	South	0.97	1.15	1.1			0.15	0.05	0.30	0.10			100%	92%	85%	79%
1	Basement South Mas	164	90	South	0.46	1.25	0.6			0.15	0.05	0.30	0.10			100%	86%	87%	75%
1	main Kitchen South	164	90	South	0.52	0.84	0.4			0.15	0.05	0.74	0.28			100%	88%	54%	47%
1	main Kitchen South	164	90	South	1.98	0.94	1.9			0.15	0.05	0.74	0.28			100%	96%	57%	55%
2	Dining	164	90	South	1.37	1.41	3.9			0.15	0.05	0.74	0.28			100%	94%	69%	65%
1	dining door	164	90	South	0.66	1.88	1.3			0.15	0.05	0.74	0.28			100%	90%	77%	69%
1	Back Entry Window	164	90	South	0.97	0.97	0.9			0.15	0.05	0.74	0.28			100%	92%	58%	54%
2	loft south large r	164	90	South	1.45	0.79	2.3			0.23	0.05	0.90	0.58			100%	92%	60%	55%
2	loft south small r	164	90	South	1.03	0.79	1.6			0.23	0.05	0.90	0.58			100%	90%	60%	54%
2	loft south operabl	164	90	South	1.71	0.69	2.4			0.23	0.05	0.90	0.58			100%	93%	58%	54%
2	main bedrooms nort	344	90	North	0.97	0.97	1.9			0.15	0.05					100%	93%	100%	93%
1	loft north bath	344	90	North	1.07	0.92	1.0			0.15	0.05					100%	93%	100%	93%
1	loft north bedroom	344	90	North	0.97	0.82	0.8			0.15	0.05					100%	93%	100%	93%
1	loft north large	344	90	North	1.07	1.44	1.5			0.15	0.05					100%	93%	100%	93%
1	basement kitchen r	344	90	North	1.78	1.02	1.8			0.15	0.05	1.52	0.30			100%	96%	63%	60%
1	basement bedroom r	344	90	North	0.97	0.97	0.9			0.15	0.05	1.52	0.30			100%	93%	62%	58%
1	main kitchen west	254	90	West	1.30	0.94	1.2	6.10	3.66	0.15	0.05					39%	96%	100%	38%

Passive House Planning

SUMMER VENTILATION

Building:

Location: Calgary

Building Type/Use: Single Family With Basement Suite

Building Volume 641 m³

Description	Day GRF			Night			
Fraction of Opening Duration	10%			50%			
Climate Boundary Conditions							
Temperature Diff Interior - Exterior	4			1			K
Wind Velocity	1			0			m/s
Window Group 1							
Quantity	4			1			
Clear Width	0.78			0.99			m
Clear Height	2.12			2.12			m
Tilting Windows?	x			x			
Opening Width (for tilting windows)	0.060			0.060			m
Window Group 2 (Cross Ventilation)							
Quantity							
Clear Width							m
Clear Height							m
Tilting Windows?							
Opening Width (for Tilting Windows)							m
Difference in Height to Window 1							m
Single-Sided Ventilation 1 - Airflow Volume	**191**	**0**	**0**	**25**	**0**	**0**	**m³/h**
Single-Sided Ventilation 2 - Airflow Volume	**0**	**0**	**0**	**0**	**0**	**0**	**m³/h**
Cross Ventilation Airflow Volume	**191**	**0**	**0**	**25**	**0**	**0**	**m³/h**
Contribution to Air Change Rate	**0.03**	**0.00**	**0.00**	**0.02**	**0.00**	**0.00**	**1/h**

Summary of Summer Ventilation Distribution

Description Ventilation Type		Daily Average Air Change Rate	
Day GRF		0.03	1/h
		0.00	1/h
Night		0.02	1/h

Passive House Planning

COOLING LOAD

Building:
Location: Calgary
Spec. Capacity: 84 Wh/(m²K) (Enter in "Summer" worksheet.)
Building Type/Use: Single Family With B
Interior Temperature: 25 °C
Treated Floor Area A_{TFA}: 256.4 m²
Climate (Cooling Load): AB_Calgary

	Ambient Air		Sky		Ground	
Design Temperature:	20.5	°C	0.0	°C	13.4	°C

Radiation:	North	East	South	West	Horizontal	
	75	170	140	140	250	W/m²

	Building Elements	Temperature Zone	Area m²		U-Value W/(m²K)		Factor Always 1 (except "X")		TempDiff K		W
1.	Exterior Wall - Ambient	A	232.2	*	0.137	*	1.00	*	-4.5	=	-143
2.	Exterior Wall - Ground	B	49.8	*	0.156	*	1.00	*	-11.6	=	-90
3.	Roof/Ceiling - Ambient	A	132.0	*	0.097	*	1.00	*	-4.5	=	-57
4.	Floor Slab	B	117.1	*	0.157	*	1.00	*	-11.6	=	-212
5.		A		*		*	1.00	*	-4.5	=	
6.		A		*		*	1.00	*	-4.5	=	
7.		X		*		*	0.75	*	-4.5	=	
8.	Windows	A	39.4	*	0.764	*	1.00	*	-4.5	=	-136
9.	Exterior Door	A	5.2	*	0.800	*	1.00	*	-4.5	=	-19
10.	Exterior TB (length/m)	A		*		*	1.00	*	-4.5	=	
11.	Perimeter TB (length/m)	P		*		*	1.00	*	-11.6	=	
12.	Ground TB (length/m)	B		*		*	1.00	*	-11.6	=	
13.	House/DU Partition Wall	I		*		*	1.00	*	3.0	=	
			$L_{ambient}$ W/K		TempDiff K		L_{Sky} W/K		TempDiff K		
14.	Radiation Correction		-4.6	*	-4.5	+	4.5	*	-25.0	=	-93

Transmission Heat Losses P_T Total = **-749**

Ventilation System:

	A_{TFA} m²		Clear Room Height m		m³
Effective Air Volume, V_V	256.4	*	2.50	=	641

	Vent. Transm. W/K		TempDiff kKh/a		W
Exterior	48.8	*	-4.5	=	-220
Ground	20.9	*	-11.6	=	-242

Additional Summer Ventilation:

☒ Window Night Ventilation, Manual — Corresponding Air Change Rate 0.02 1/h
☐ Mechanical, Automatically Controlled Ventilation — Minimum Indoor Temperature 22.0 °C

		kWh/d		kh/d		W
Heat Removal Cooling Design Day	Window Ventilation	-2.1	/	0.024	=	-89
(from Cooling worksheet)	Automatic Night Ventilation	0.0	/	0.024	=	0

Ventilation Heat Load P_v Total = W **-551**

	Orientation of the Area	Area m²		g-Value (perp. radiation)		Reduction Factor		Radiation W/m²		P_S W
1.	North	11.3	*	0.5	*	0.49	*	76	=	205
2.	East	0.0	*	0.0	*	0.40	*	170	=	0
3.	South	26.6	*	0.6	*	0.39	*	146	=	919
4.	West	1.6	*	0.6	*	0.25	*	146	=	35
5.	Horizontal	0.0	*	0.0	*	0.40	*	250	=	0
6.	Sum Opaque Areas									123

Heat Gain - Solar Heat Load, P_S Total = **1282**

	Spec. Power W/m²		A_{TFA} m²		P_I W
Internal Heat Load P_I	3.1	*	256	=	**795**

Cooling Load P_C $P_T + P_V + P_S + P_I$ = **777** **W**

Specific Maximum Cooling Load P_C / A_{EB} = **3.0** **W/m²**

	Solar Load W		Time h/d		Spec. Capacity Wh/(m²K)		A_{TFA} m²			
Daily Temperature Swing due to Solar Load	1281.6	*	24	/ (	84	*	256	) =	**1.4**	**K**

Passive House Planning

HEAT DISTRIBUTION AND DHW SYSTEM

Building:		
Location:	Calgary	
Interior Temperature:	20	°C
Building Type/Use:	Single Family With Basement Suite	
Treated Floor Area A_{TFA}:	256	m²
Occupancy:	7.3	Pers
Number of Residences:	2	
Annual Heat Demand $q_{Heating}$:	2776	kWh/a
Length of Heating Period:	205	d
Average Heat Load P_{ave}:	0.6	kW
Marginal Utilisability of Additional Heat Gains:	65%	

Parts

				Warm Region	Cold Region		Total		
Space Heat Distribution				1	2	3			
Length of Distribution Pipes	L_H	*(Project)*		39.62				m	
Heat Loss Coefficient per m Pipe	Ψ	*(Project)*		0.151				W/(mK)	
Temperature of the Room Through Which the Pipes Pass	ϑ_X	*Mechanical Room*		20				°C	
Design Flow Temperature	ϑ_{dist}	*Flow, Design Value*		55.0				°C	
Design System Heat Load	$P_{heating}$	*(exist./calc.)*		2.9				kW	
Flow Temperature Control (check)									
Design Return Temperature	ϑ_R		$=0.714*(\vartheta_{dist}-20)+20$	45.0				°C	
Annual Heat Emission per m of Plumbing	q^*_{HL}		$= \Psi\ (\vartheta_m - \vartheta_X)\ t_{Heating}*0.024$	22			Total 1,2,3	kWh/(m·a)	
Possible Utilization Factor of Released Heat	η_G			65%				-	
Annual Losses	Q_{HL}		$= L_H \cdot q^*_{HL} \cdot (1-\eta_G)$	**312**	**0**	**0**	**312**	kWh/a	
Specif. Losses	q_{HL}		$= \Sigma Q_{HL} / A_{TFA}$					kWh/(m²a)	**1.2**
Utilisation Factor of Space Heat Distribution	$h_{a,HL}$		$= q_H / (q_H + q_{HL})$				**90%**	-	

DHW: Standard Useful Heat						
5.5.45.	V_{DHW}	*(Project or Average Value 25 Litres/P/d)*		25.0	Litre/Person/d	
Average Cold Water Temperature of the Supply	ϑ_{DW}	*Temperature of Drinking Water (10°)*		5.4	°C	
DHW Non-Electric Wash and Dish		*(Electricity worksheet)*		588	kWh/a	
Useful Heat - DHW	Q_{DHW}			**4826**	kWh/a	
Specif. Useful Heat - DHW	q_{DHW}		$= Q_{DHW} / A_{TFA}$		kWh/(m²a)	**18.8**

				Warm Region	Cold Region		Total		
DHW Distribution and Storage									
Length of Circulation Pipes (Flow + Return)	L_{HS}	*(Project)*		99.1				m	
Heat Loss Coefficient per m Pipe	Ψ	*(Project)*		0.151				W/m/K	
Temperature of the Room Through Which the Pipes Pass	ϑ_X	*Mechanical Room*		20				°C	
Design Flow Temperature	ϑ_{dist}	*Flow, Design Value*		60.0				°C	
Daily circulation period of operation.	td_{Circ}	*(Project)*		18.0				h/d	
Design Return Temperature	ϑ_R		$=0.875*(\vartheta_{dist}-20)+20$	55				°C	
Circulation period of operation per year	t_{Circ}		$= 365\ td_{Circ}$	6570				h/a	
Annual Heat Released per m of Pipe	q^*_Z		$= \Psi\ (\vartheta_m - \vartheta_X)\ t_{Circ}$	37.3				kWh/m/a	
Possible Utilization Factor of Released Heat	η_{GDHW}		$=t_{heating}/365d * \eta_G$	36.2%				-	
Annual Heat Loss from Circulation Lines	Q_Z		$= L_{HS} \cdot q^*_Z \cdot (1-\eta_{GDHW})$	**2355**			**2355**	kWh/a	
Total Length of Individual Pipes	L_U	*(Project)*		49.5				m	
Exterior Pipe Diameter	d_{U_Pipe}	*(Project)*		0.014				m	
Heat Loss Per Tap Opening	$q_{Individual}$		$=(c_{pH2O}V_{H2O}+c_{pMat}V_{Mat})(\vartheta_{dist}-\vartheta_X)$	0.2542				kWh/tap opening	
Occupancy Coefficient	n_{Tap}		$= n_{Pers}\ .\ 3\ .\ 365\ /\ n_{LU}$	4011				Tap openings per year	
Annual Heat Loss	q_U		$= n_{Tap}\ \dot{}\ q_{Individual}$	1019.7				kWh/a	
Possible Utilization Factor of Released Heat	η_{G_U}		$=t_{heating}/8760*\eta_G$	36.2%				-	
Annual Heat Loss of Individual Pipes	Q_U		$= q_U \cdot (1-\eta_{G\_U})$	650.5			**651**	kWh/a	
							Total 1,2,3		
Average Heat Released From Storage	P_S							W	
Possible Utilization Factor of Released Heat	η_{G_S}		$=t_{heating}/8760*\eta_G$						
Annual Heat Losses from Storage	Q_S		$= P_S \cdot 8.760\ kh \cdot (1-\eta_{G\_S})$				**0**	kWh/a	
							Total 1,2,3		
Total Heat Losses of the DHW System	Q_{WL}		$= Q_Z+Q_U+Q_S$				**3005**	kWh/a	
Specif. Losses of the DHW System	q_{WL}		$= Q_{WL} / A_{TFA}$					kWh/(m²a)	**11.7**
Utilisation Factor DHW Distrib and Storage	$\eta_{a,WL}$		$= q_{DHW} / (q_{DHW} + q_{WV})$				**61.6%**	-	
Total Heat Demand of DHW system	Q_{gDHW}		$= Q_{DHW}+Q_{WL}$				**7831**	kWh/a	
Total Spec. Heat Demand of DHW System	q_{gDHW}		$= Q_{gDHW} / A_{TFA}$					kWh/(m²a)	**30.5**

Passive House Planning

HOT WATER PROVIDED BY SOLAR

Building:		Building Type/Use:	Single Family With Basement Suite
Location:	Calgary	Treated Floor Area A_{TFA}:	256.4 m²

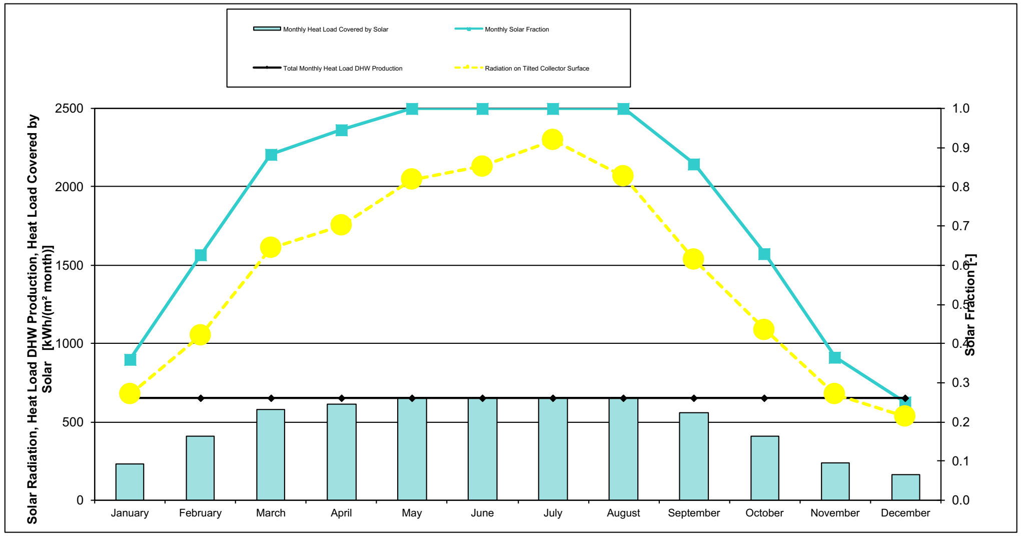
Solar Fraction with DHW Demand including Washing and Dish-Washing

Heat Demand DHW	q_{gDHW}	7831	kWh/a	from DHW+Distribution worksheet
Latitude:		51.0	°	from Climate Data worksheet
Selection of collector from list (see below):		7	Selection:	7 Improved Flat Plate Collector
Solar Collector Area		11.00	m²	
Deviation from North		157	°	
Angle of Inclination from the Horizontal		18	°	
Height of the Collector Field			m	
Height of Horizon	h_{Hori}		m	
Horizontal Distance	a_{Hori}		m	
Additional Reduction Factor Shading	r_{other}		%	
Occupancy		7.3	Persons	
Specific Collector Area		1.5	m²/Pers	

Estimated Solar Fraction of DHW Production	**74%**			
Solar Contribution to Useful Heat	**5815**	kWh/a	**23**	kWh/(m²a)

Secondary Calculation of Storage Losses

Selection of DHW storage from list (see below):	17	Selection:	17 Stratified Solar Storage with DH er
Total Storage Volume	1000	litre	
Volume Standby Part (above)	300	litre	
Volume Solar Part (below)	700	litre	
Specific Heat Losses Storage (total)	3.1	W/K	
Typical Temperature DHW	60	°C	
Room Temperature	10	°C	
Storage Heat Losses (Standby Part Only)	**110**	W	
Total Storage Heat Losses	**155**	W	



Passive House Planning

ELECTRICITY DEMAND

Building:

# Households	2	HH
Persons	7.3	P
Living Area	256	m²
Annual Heat Demand	11	kWh/(m²a)

Solar Fraction of DHW Wash&Dish	50%
Marginal Performance Ratio DHW	100%
Marginal Performance Ratio Heating	107%

Prim. Energy Factors:	Electricity	2.7	kWh/kWh
	Natural Gas	1.1	kWh/kWh
Energy Carrier for Space Heating/DHW:			

Column Nr.	1	2	3			4	5		6		7	8	8a	9	10	11	12	13	14
Application	Used ? (1/0)	Within the Thermal Envelope? (1/0)	Norm Demand			Utilization Factor	Frequency		Reference Quantity		Useful Energy (kWh/a)	Electric Fraction	Non-Electric Fraction	Electricity Demand (kWh/a)	Additional Demand	Marginal Performance Ratio	Solar Fraction	Non-Electric Demand (kWh/a)	Primary Energy-Demand (kWh/a)
Dishwashing	1	1	1.20	kWh/Use		* 1.00	* 65	/(P*a)	* 7.3	P	= 571	* 50%		= 286					771
DHW Connection													* 50%		* (1+ 0.30) *	1.00	*(1- 0.50) =	184	497
Clothes Washing	1	1	1.10	kWh/Use		* 1.00	* 57	/(P*a)	* 7.3	P	= 459	* 55%		= 253					682
DHW Connection													* 45%		* (1+ 0.05) *	1.00	*(1- 0.50) =	108	290
Clothes Drying with:	0.5	1	3.50	kWh/Use	Residual dampness 0.60	0.88	* 57	/(P*a)	* 7.3	P	= 639	100%		= 639					1726
Condensation Dryer											= 0		0%			1.00 *		0	0
Energy Consumed by Evaporation	0	1	3.13	kWh/Use		* 0.60	* 57	/(P*a)	* 7.3	P	= 0	*	100%		* (1+ 0.00) *	1.07	*(1- 0.73) =	0	0
Refrigerating	0	1	0.78	kWh/d		* 1.00	* 365	d/a	* 2	HH	= 0	* 100%		= 0					0
Freezing	0	1	0.88	kWh/d		* 1.00	* 365	d/a	* 2	HH	= 0	* 100%		= 0					0
or Combined Unit	1	1	1.00	kWh/d		* 1.00	* 365	d/a	* 2	HH	= 730	* 100%		= 730					1971
Cooking with:	1	1	0.22	kWh/Use		* 1.00	* 500	/(P*a)	* 7.3	P	= 806	* 100%		= 806					2176
Electricity					Percentage CFLs							*	0%					0	0
Lighting	1	1	60	W	0%	* 1.00	* 2.90	kh/(P*a)	* 7.3	P	= 1275	* 100%		= 1275					3442
Consumer Electronics	1	1	80	W		* 1.00	* 0.55	kh/(P*a)	* 7.3	P	= 322	* 100%		= 322					870
Small Appliances, etc.	1	1	50	kWh		* 1.00	* 1.00	/(P*a)	* 7.3	P	= 366	* 100%		= 366					989
Total Aux. Electricity											1139			1139					3076
Other:																			
											0			0					0
											0			0					0
											0			0					0
Total											6309 kWh			5816 kWh		DHW Non-Electric - Wash&Dish 588	kWh	291	16491
Specific Demand														22.7 kWh/(m²a)		Non-Renewable Non-Electric DHW Wash&Dish 1.1	kWh/(m²a)	1.1	64.3
Recommended Maximum Value														18					50

Passive House Planning

AUXILIARY ELECTRICITY

Building:

1	Living Area	256	m^2
2	Heating Period	205	d
3	Air Volume	641	m^3
4	Dwelling Units	2	HH
5	Enclosed Volume	865	m^3

Operation Vent. System Winter	4.91	kh/a
Operation Vent. System Summer	3.85	kh/a
Air Change Rate	0.26	h^{-1}
Defrosting HX from		°C

Primary Energy Factor - Electricity	2.7	kWh/kWh
Annual Space Heat Demand	11	$kWh/(m^2a)$
Boiler Rated Power	10	kW
DHW System Heat Demand	7831	kWh/a
Design Flow Temperature	55	°C

Column Nr.	1	2	3			4			5			6			7		8		9		10	11
Application	Used ? (1/0)	Within the Thermal Envelope? (1/0)	Norm Demand			Utilization Factor			Period of Operation			Reference Size			**Electricity Demand (kWh/a)**		**Available as Interior Heat**		Used During Time Period (kh/a)		**Internal Heat Source (W)**	**Primary Energy Demand (kWh/a)**
Ventilation System																						
Winter Ventilation	1	0	0.42	Wh/m^3	*	0.26	h^{-1}	*	4.9	kh/a	*	641.031	m^3	=	**347**		considered in heat recovery efficiency					**936**
Summer Ventilation	1	0	0.42	Wh/m^3	*	0.26	h^{-1}	*	3.9	kh/a	*	641.031	m^3	=	**272**		no summer contribution to IHG					**735**
Defroster HX	0	0	0	W	*	1.00		*	0.2	kh/a	*	1		=	**0**	*	1.0	/	4.91	=	**0**	**0**
Heating System						Controlled/Uncontrolled (1/0)																
Enter the Rated Power of the Pump			40	W		1																
Circulation Pump	1	0	40	W	*	0.8		*	4.9	kh/a	*	1		=	**148**	*	1.0	/	4.91	=	**0**	**399**
Boiler Electricity Consumption at 30% Load				W																		
Aux. Energy - Heat. Boiler	1	0	45	W	*	1.00		*	1.03	kh/a	*	1		=	**47**	*	1.0	/	4.91	=	**0**	**126**
DHW system																						
Enter Average Power Consumption of Pump				W																		
Circulation Pump	1	0	29	W	*	1.00		*	5.1	kh/a	*	1		=	**149**	*	0.6	/	8.76	=	**0**	**403**
Enter the Rated Power of the Pump				W																		
Storage Load Pump DHW	1	0	60	W	*	1.00		*	0.0	kh/a	*	1		=	**0**	*	1.0	/	4.91	=	**0**	**0**
Boiler Electricity Consumption at 100% Load				W																		
DHW Boiler Aux. Energy	0	0	136	W	*	1.00		*	0.0	kh/a	*	1		=	**0**	*	1.0	/	4.91	=	**0**	**0**
Enter the Rated Power of the Solar DHW Pump				W																		
Solar Aux Electricity	1	1	44	W	*	1.00		*	1.8	kh/a	*	1		=	**77**	*	0.6	/	8.76	=	**5**	**207**
Misc. Aux. Electricity																						
Misc. Aux. Electricity	1	0	50	kWh/a	*	1.00		*	1.0		*	2	HH	=	**100**	*	1.0	/	8.76	=	**0**	**270**
Total															**1139**						**5**	**3076**
Specific Demand	$kWh/(m^2a)$				Divide by Living Area:										**4.4**							**12.0**

Passive House Planning

EFFICIENCY OF DISTRICT HEATING STATIONS

Building:		Building Type/Use:	Single Family With Basement Suite	
Location:	Calgary	Treated Floor Area A_{TFA}:	256	m²

Covered Fraction of Space Heat Demand		*(PE Value worksheet)*	0%	
Annual Heat Demand kWh/a	Q_H	*(DHW+Distribution)*	3088	kWh
Solar Fraction for Space Heat	$\eta_{Solar, H}$	*(Separate Calculation)*		
Effective Annual Heat Demand	$Q_{H,Wi}=Q_H*(1-\eta_{Solar, H})$		0	kWh
Covered Fraction of DHW Demand		*(PE Value worksheet)*	0%	
DHW Demand	Q_{DHW}	*(DHW+Distribution)*	7831	kWh
Solar Fraction for DHW	$\eta_{Solar, DHW}$	*(SolarDHW worksheet)*	74%	
Effective DHW Demand	$Q_{DHW,Wi}=Q_{DHW}*(1-\eta_{Solar, DHW})$		0	kWh
Heat Source			Gas CGS 35% PHC ▼	
Primary Energy Factor		*(Data worksheet)*	1.1	kWh/kWh
CO_2-Emissions factor (CO_2-Equivalent)		*(Data worksheet)*	130	g/kWh
Utilisation Factor Heat Transfer Station	$\eta_{a,HX}$		107%	

		kWh/a	kWh/(m²a)
Final Energy Demand Heat Generation	$Q_{final} = Q_{Use} * e_{a,DH}$	0	0.0
Annual Primary Energy Demand		0	0.0
		kg/a	kg/(m²a)
Annual CO_2-Equivalent Emissions		0	0.0

Passive House Planning

INTERNAL HEAT GAINS

Building:

Utilisation Pattern: Dwelling ▼ 2.10 W/m²

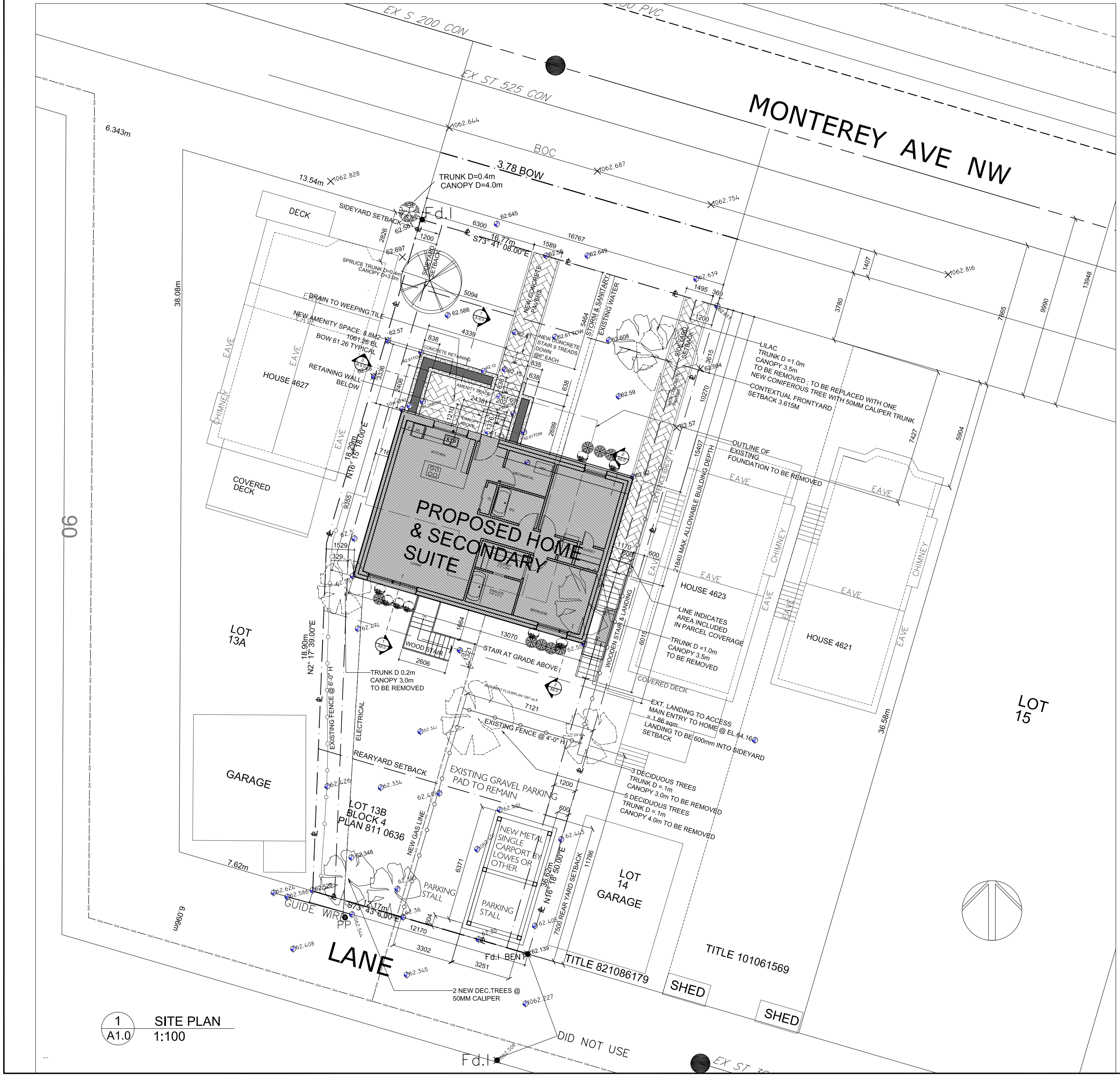
Type of Values Used: Standard ▼

No Input Required W/m²

Calculation Internal Heat Household	Persons Living Area	7.3 256	P m²
	Annual Heat Deman Heating Period	11 205	kWh/(m²a) d/a

Column Nr.	1	2	3		4	5		6		7		8		9		10
Application	Existing (1/0), or number of people	In the Thermal Envelope (1/0)	Norm Consumption		Utilization Factor	Frequency		Useful Energy (kWh/a)		Included in Electricity Balance?		Availability		Used During Time Period (kh/a)		Internal Heat Source (W)
Dishwashing	1	1	1.2	kWh/Use	1.00	65	/(P*a)	571	*			0.30	/	8.76	=	20
Clothes Washing	1	1	1.1	kWh/Use	1.00	57	/(P*a)	459	*			0.30	/	8.76	=	16
Clothes Drying with:	1	1	3.5	kWh/Use	0.88	57	/(P*a)	639	*			0.70	/	8.76	=	51
Condensation Dryer		1	0.0					0				0.80				
Energy Consumed by Evaporation	0	1	-3.1	kWh/Use	0.60	57	/(P*a)	0	* (1-	0	) *	0.00	/	8.76	=	0
Refrigerating	0	1	0.8	kWh/d	1.00	365	d/a	0	*			1.00	/	8.76	=	0
Freezing	0	1	0.9	kWh/d	1.00	365	d/a	0	*			1.00	/	8.76	=	0
or Combination	1	1	1.0	kWh/d	1.00	365	d/a	730	*			1.00	/	8.76	=	83
Cooking	1	1	0.2	kWh/Use	1.00	500	/(P*a)	806	*			0.50	/	8.76	=	46
Lighting	1	1	60.0	W	1.00	2.9	kh/(P*a)	1275	*			1.00	/	8.76	=	146
Consumer Electronics	1	1	80.0	W	1.00	0.55	kh/(P*a)	322	*			1.00	/	8.76	=	37
Household Appliances/Other	1	1	50.0	kWh	1.00	1.0	/(P*a)	366	*			1.00	/	8.76	=	42
Auxiliary Appliances (cf. Aux Electricity Sheet)															=	5
Other Applications (cf. Electricity Sheet)	0	0.0						0	*				/	8.76	=	0
Persons	7	1	80.0	W/P	1.00	8.76	kh/a	5134	*			0.55	/	8.76	=	322
Cold Water	7	1	-5.0	W/P	1.00	8.76	kh/a								=	-37
Evaporation	7	1	-25.0	W/P	1.00	8.76	kh/a	-1604	*			1.00	/	8.76	=	-183
Total														W		**548**
Specific Demand														W/m²		**2.14**
Heat Available From Internal Sources										204.5	d/a			**kWh/(m²a)**		**10.5**

Appendix II: Reference House Drawings



1
A1.0

SITE PLAN
1:100

90

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MAY 12 2015

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APPLICATION APRIL 17 2015

SUBMITTED FOR
APPLICATION REV.#2 NOVEMBER 10

SUBMITTED FOR DEVELOPMENT
APPLICATION

PROPOSED
NEW RESIDENCE

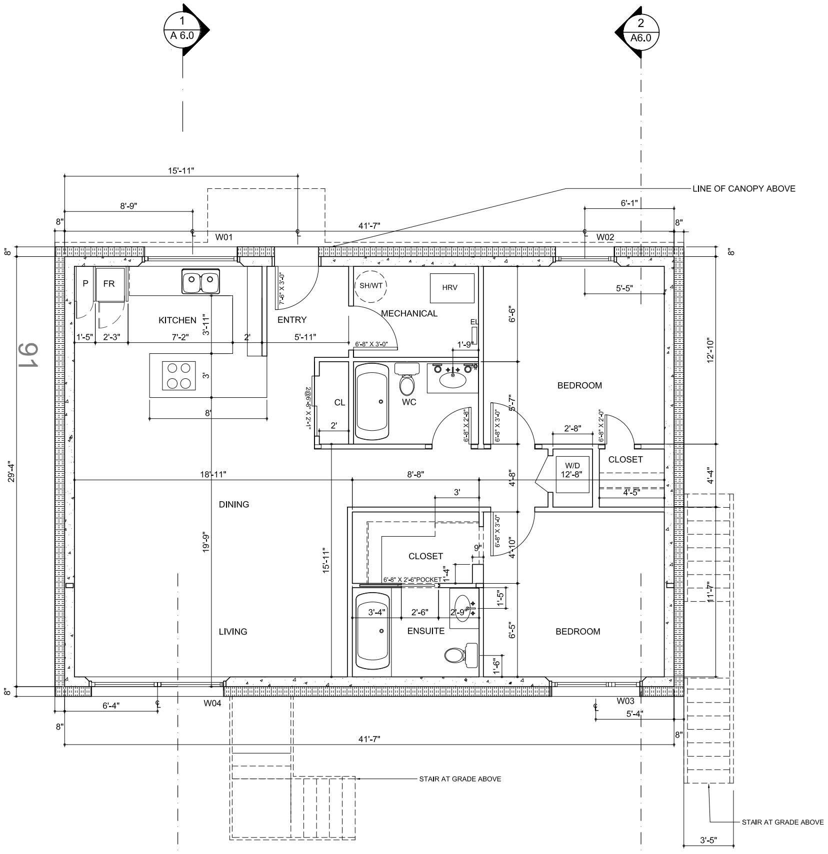
4625 MONTEREY AVE NW
MONTGOMERY
CALGARY AB

SITE PLAN

▫ DATE:	JULY 29 2014
▫ SCALE:	AS NOTED
▫ DRAWN BY:	LV
▫ CHECKED:	L.F.V.
▫ JOB NO:	2014.02.03

A1.0

91



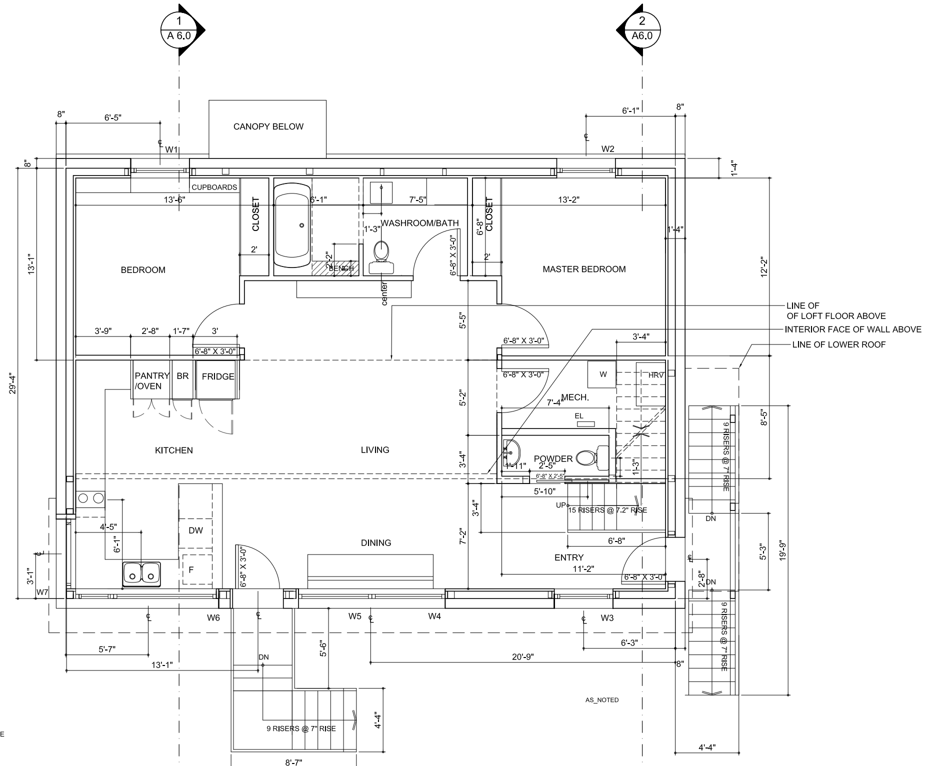
BASEMENT FLOORPLAN 1315.3 sq ft

GENERAL NOTE:

ALL BASEMENT WALL BOTTOM PLATE 2X4'S

ARE TO BE PRESSURE TREATED TO PREVENT MOLD FROM CONCRETE MOISTURE

1
A2.0
BASEMENT FLOOR PLAN: SECONDARY SUITE
1/4"= 1'-0"



MAIN FLOOR1315.3sq ft

GENERAL NOTE:

ALL INTERIOR WALLS TO BE

2 x 4 STUDS @ 16" OC WITH 1/2" DRYWALL BOTH SIDES

2
A2.0
MAIN FLOOR PLAN
1/4"= 1'-0"

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APPLICATION JULY 29 2014

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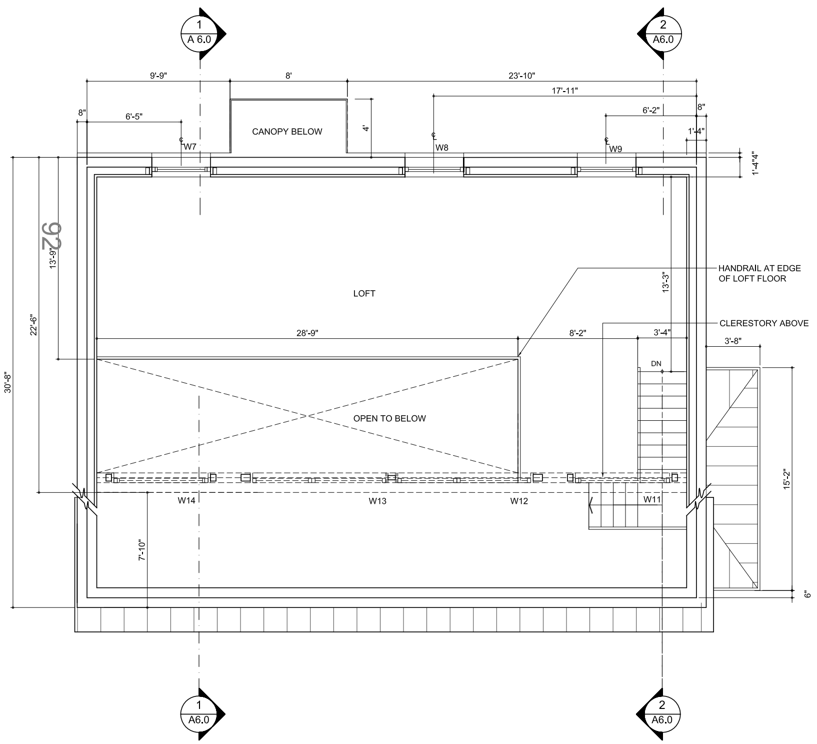
BASEMENT FLOOR PLAN:
SECONDARY SUITE

MAIN FLOOR PLAN

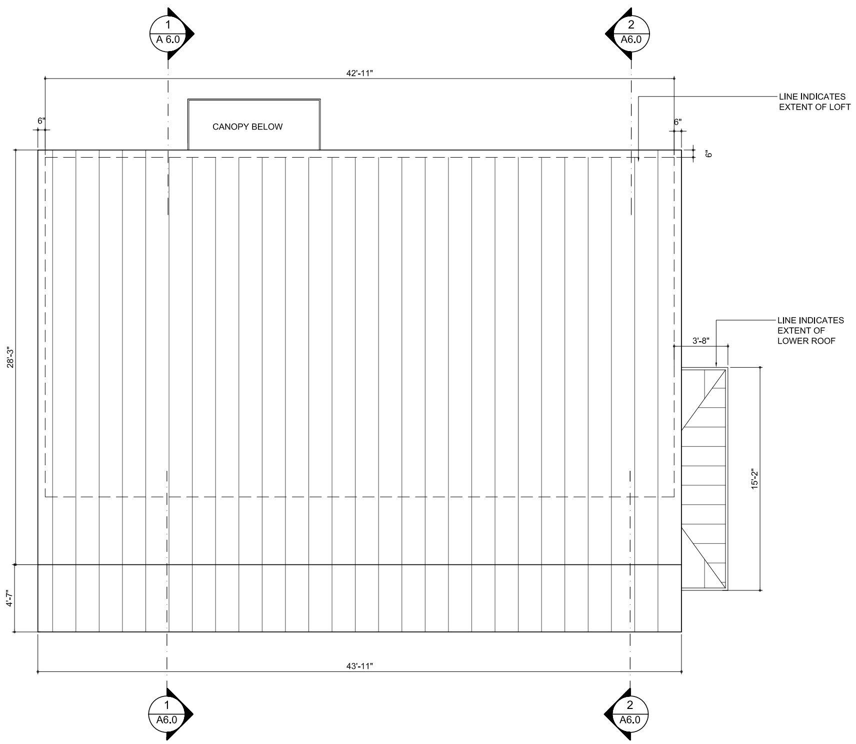
▫ DATE:	JULY 29 2014
▫ SCALE:	AS NOTED
▫ DRAWN BY:	LV
▫ CHECKED:	L.F.V.
▫ JOB NO:	2014,03,02

A2.0



1 A3.0 LOFT FLOOR PLAN
1/4"= 1'-0"

LOFT FLOOR 574 sq ft



2 A3.0 ROOF PLAN
1/4"= 1'-0"

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LOFT & ROOF PLAN

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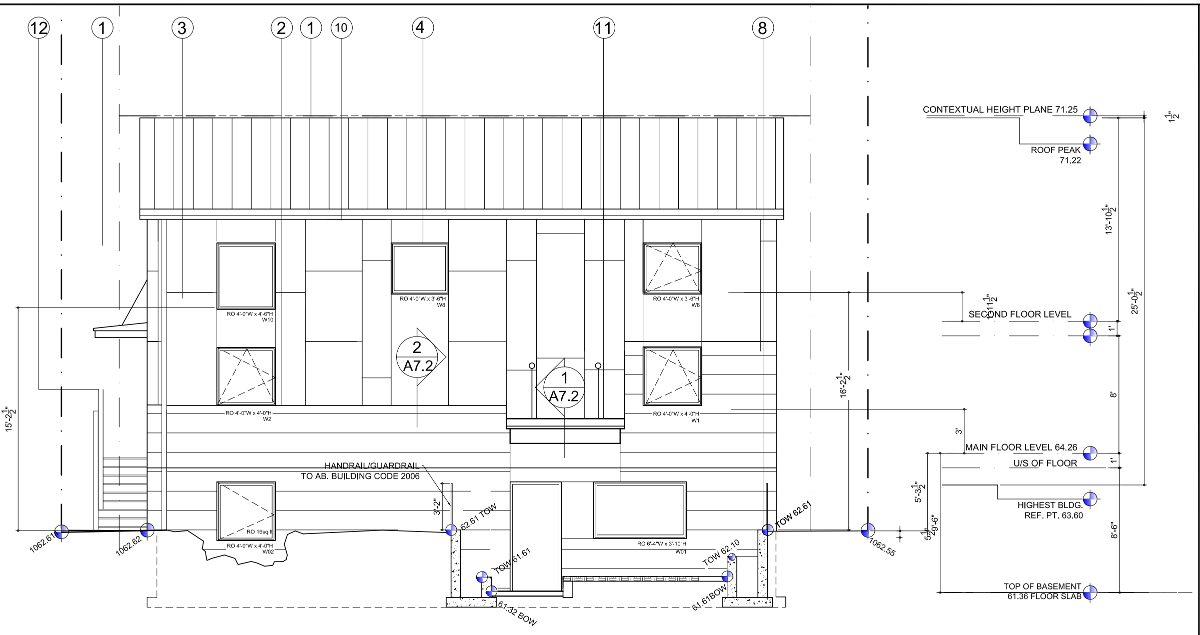
▫ SCALE:	AS NOTED
▫ DRAWN BY:	LV
▫ CHECKED:	L.F.V.
▫ JOB NO:	2014,03,02

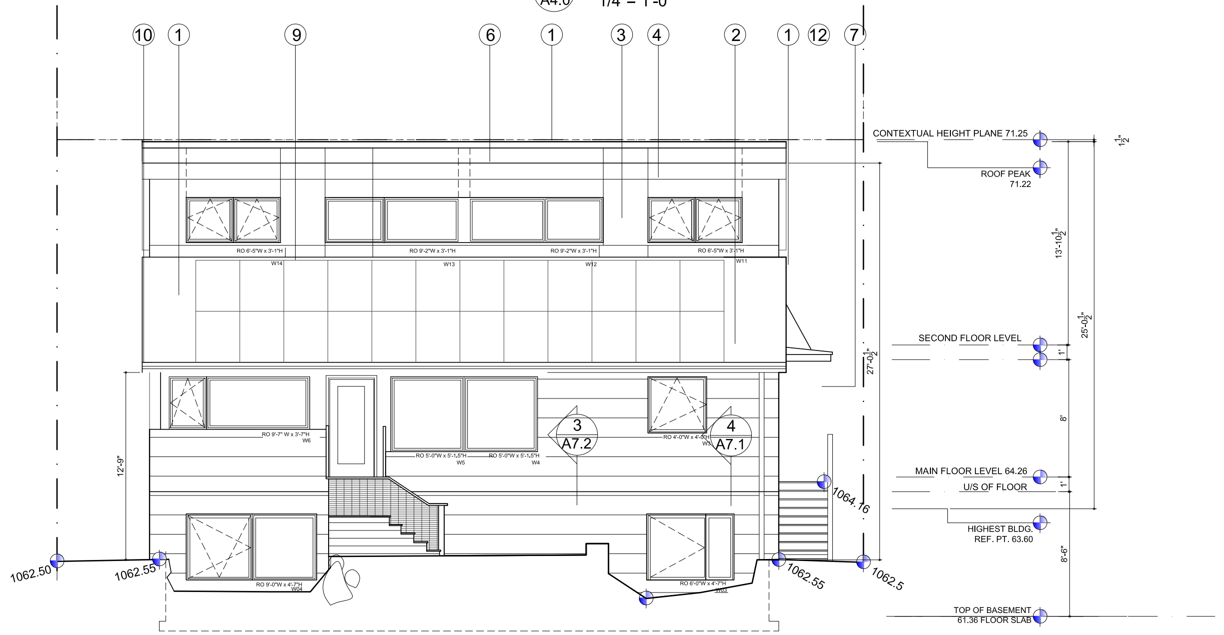
A3.0

MATERIALS LEGEND
① STANDING SEAM METAL ROOF
② HARDI BOARD SIDING
③ 4' x 8' HARDI BOARD PANEL SIDING
④ METAL CLAD WINDOWS & DOORS
⑤ CIP CONCRETE STAIRS
⑥ HARDI BOARD SOFFIT & EAVE
⑦ NEW TIMBER FRAMING AT PORCH
⑧ CONCRETE RETAINING

⑨ PVC PANELS
⑩ METAL EAVES TROUGH
⑪ STEEL CANOPY WITH SUPPORTING CABLES
⑫ WOOD STAIRS
TIMBER EAVE, SOFFIT & FRAMING
⑬ METAL HANDRAIL



1 A4.0 NORTH ELEVATION (FRONT)
1/4"= 1'-0"



2 A4.0 SOUTH ELEVATION (BACK)
1/4"= 1'-0"

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APPLICATION JULY 29 2014

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ELEVATIONS

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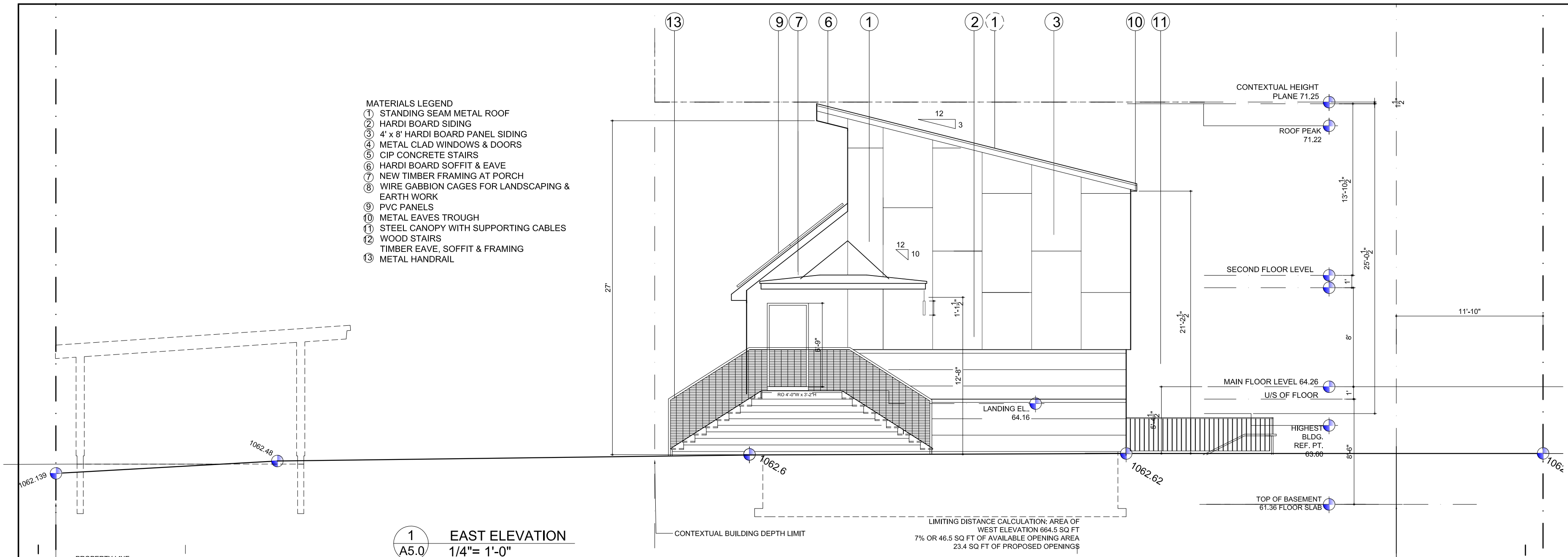
☐ CHECKED:	L.F.V.
☐ JOB NO:	2014.02.03

A4.0

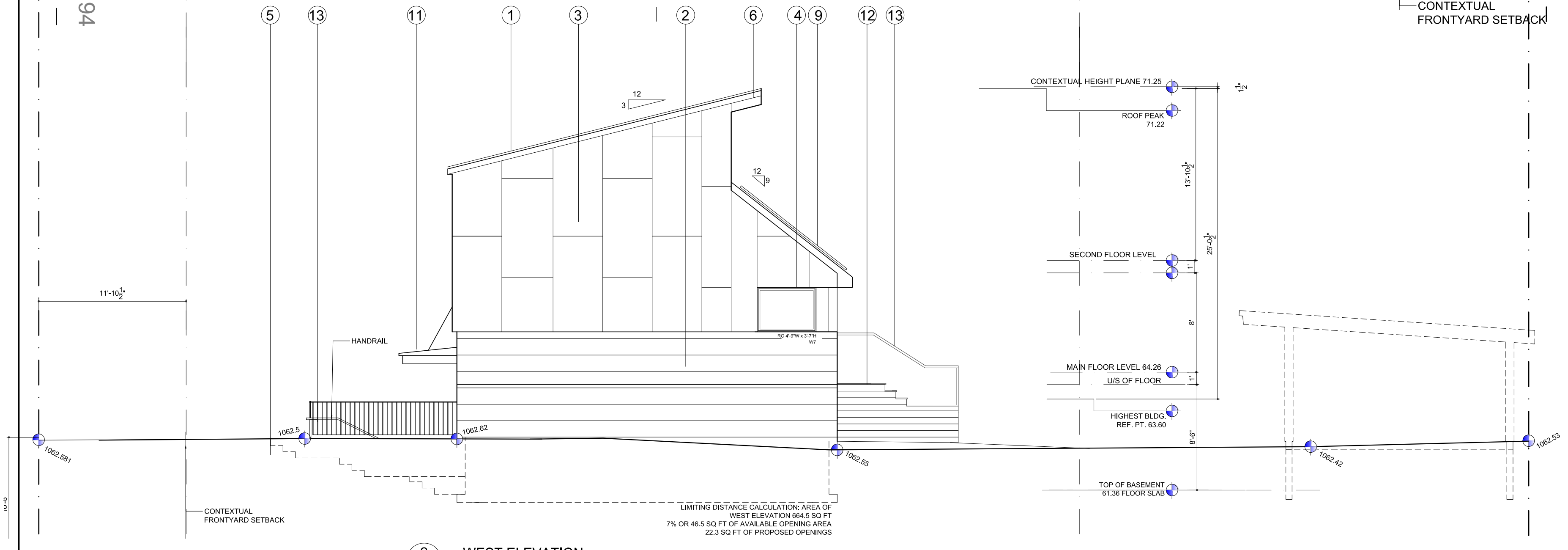
MATERIALS LEGEND
1. STANDING SEAM METAL ROOF
2. HARDI BOARD SIDING
3. 4' x 8' HARDI BOARD PANEL SIDING
4. METAL CLAD WINDOWS & DOORS
5. CIP CONCRETE STAIRS
6. HARDI BOARD SOFFIT & EAVE
7. NEW TIMBER FRAMING AT PORCH
8. WIRE GABBION CAGES FOR LANDSCAPING & EARTH WORK
9. PVC PANELS
10. METAL EAVES TROUGH
11. STEEL CANOPY WITH SUPPORTING CABLES
12. WOOD STAIRS
TIMBER EAVE, SOFFIT & FRAMING
13. METAL HANDRAIL



LIMITING DISTANCE CALCULATION: AREA OF WEST ELEVATION 664.5 SQ FT
7% OR 46.5 SQ FT OF AVAILABLE OPENING AREA
23.4 SQ FT OF PROPOSED OPENINGS

1 / A5.0 EAST ELEVATION
1/4"= 1'-0"

CONTEXTUAL FRONTYARD SETBACK



LIMITING DISTANCE CALCULATION: AREA OF WEST ELEVATION 664.5 SQ FT
7% OR 46.5 SQ FT OF AVAILABLE OPENING AREA
22.3 SQ FT OF PROPOSED OPENINGS

2 / A5.0 WEST ELEVATION
1/4"= 1'-0"

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APPLICATION JULY 29 2014

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ELEVATIONS

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☐ SCALE:	AS NOTED
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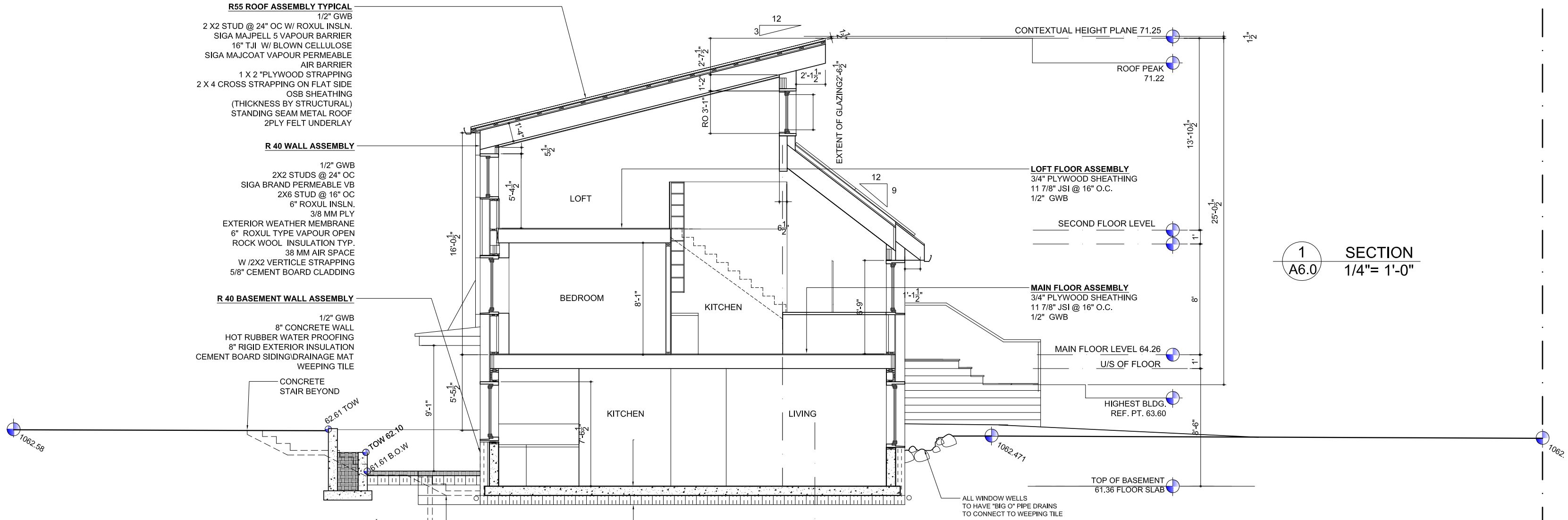
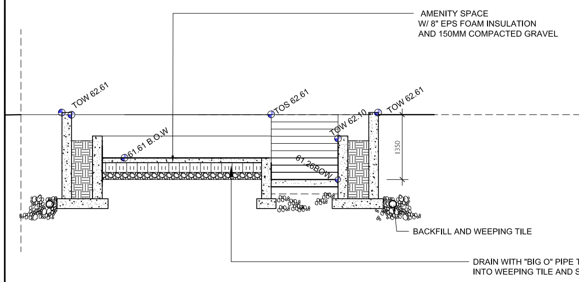
☐ JOB NO:	2014.02.03

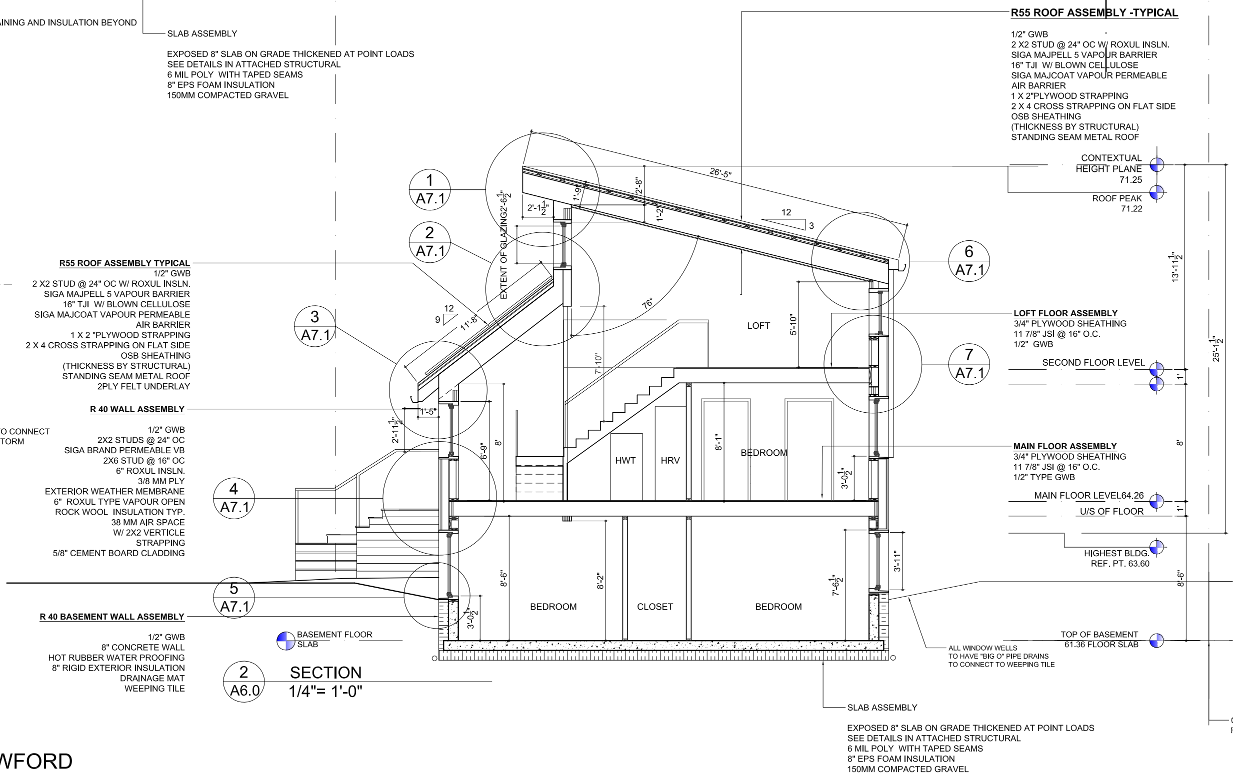
A5.0



1 A6.0 SECTION
1/4"= 1'-0"



3 A6.0 SECTION @ STAIR
1/4"= 1'-0"



2 A6.0 SECTION
1/4"= 1'-0"

DETAILS DESIGNED AND AUTHORIZED BY FRANK CRAWFORD

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SUBMITTED FOR DEVELOPMENT
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SECTIONS @ STAIR &
KITCHEN

▫ DATE:	JULY 29 2014
▫ SCALE:	AS NOTED
▫ DRAWN BY:	LV
▫ CHECKED:	L.F.V.
▫ JOB NO:	2014.02.03

A6.0

Appendix III: WUFI Passive Reports

PHIUS+ 2015 VERIFICATION

1

BUILDING INFORMATION

Category:	**Residential**
Status:	**In planning**
Building type:	**New construction**
Year of construction:	
Units:	**2**
Number of occupants:	**6 (Design)**

Boundary conditions

Climate:	**Saskatoon, SK**
Internal heat gains:	**3.2** W/m²
Interior temperature:	**20** °C
Overheat temperature:	**25** °C

Building geometry

Enclosed volume:	**1,043.3** m³
Net-volume:	**864.6** m³
Total area envelope:	**631.6** m²
AV ratio:	**0.6** 1/m
Floor area:	**245.7** m²

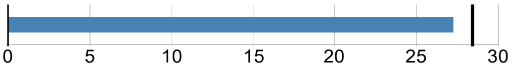
PASSIVEHOUSE REQUIREMENTS

Certificate criteria:

PHIUS+ 2015 Standard

Heating demand

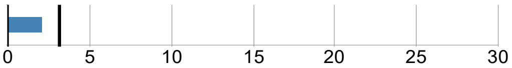
specific:	**27.3** kWh/m²a
target:	**28.39** kWh/m²a
total:	6,706.64 kWh/a



✓

Cooling demand

sensible:	**2** kWh/m²a
latent:	**0** kWh/m²a
specific:	**2** kWh/m²a
target:	**3.15** kWh/m²a
total:	490.68 kWh/a



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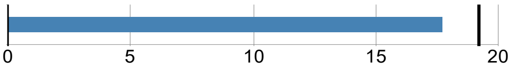
Heating load

specific:	**17.71** W/m²
target:	**19.24** W/m²
total:	4,351.66 W



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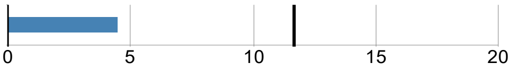
Cooling load

specific:	**4.45** W/m²
target:	**11.67** W/m²
total:	1,094.08 W



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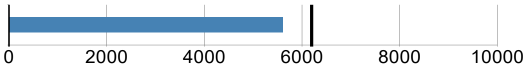
PHIUS+ 2015 VERIFICATION

2

Source energy

PHIUS+ Source Zero: NO

total:	**33,631.87**	kWh/a
specific:	**5,605**	kWh/Person a
target:	**6,200**	kWh/Person a
specific:	136.88	kWh/m²a



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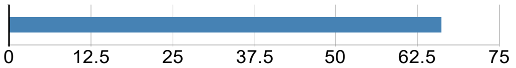
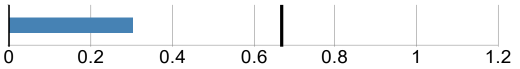
Site energy

total:	16,242.74	kWh/a
specific:	66.11	kWh/m²a



Air tightness

ACH50:	**0.3**	1/h
CFM50 per envelope area:	**0.41**	m³/m²h
target:	**0.67**	1/h
target CFM50:	**0.91**	m³/m²h



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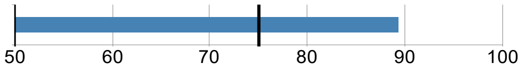
PASSIVEHOUSE RECOMMENDATIONS

HRV efficiency:	**89.4**	%
Frequency of overheating: Cooling system is not required	**2.9**	%



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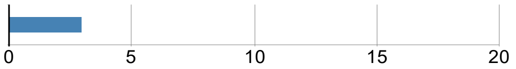

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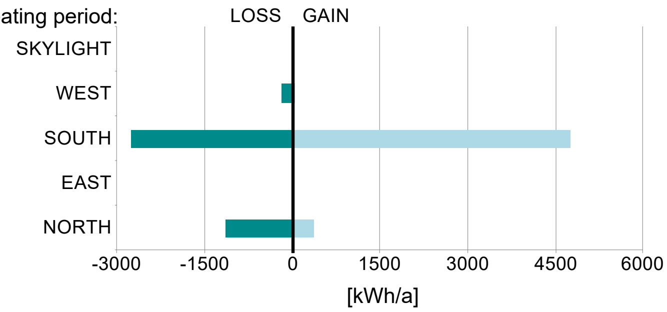
Frequency of overheating only applies if there is not a [properly sized] cooling system installed.

BUILDING ELEMENTS

Windows

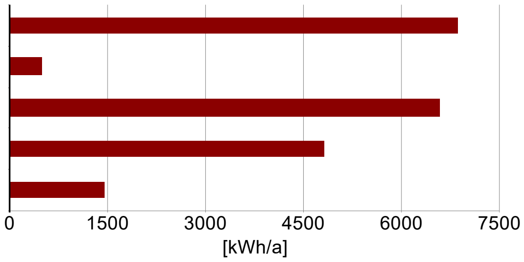
Average SHGC:	**0.5**
Average solar reduction factor heating:	**0.44**
Average solar reduction factor cooling:	**0.42**
Average U-value:	**0.742** W/m²K
Total glazing area:	**28** m²
Total window area:	**39.7** m²

Heat gain/loss heating period:



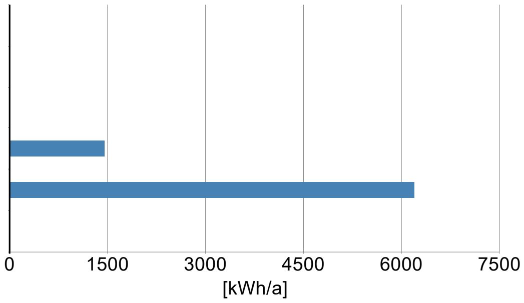
HVAC

Total heating demand:	**6,872** kWh/a
Total cooling demand:	**491** kWh/a
Total DHW energy demand:	**6,599** kWh/a
Solar DHW contribution:	**4,808** kWh/a
Auxiliary electricity:	**1,442** kWh/a



Electricity

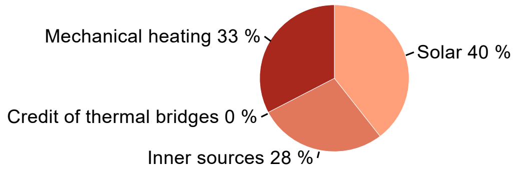
Direct heating / DHW:	**0** kWh/a
Heatpump heating:	**0** kWh/a
Cooling:	**0** kWh/a
HVAC auxiliary energy:	**1,442** kWh/a
Appliances:	**6,211** kWh/a
Renewable generation, coincident production and use:	**0** kWh/a
Total electricity demand:	**7,653** kWh/a



HEAT FLOW - HEATING PERIOD

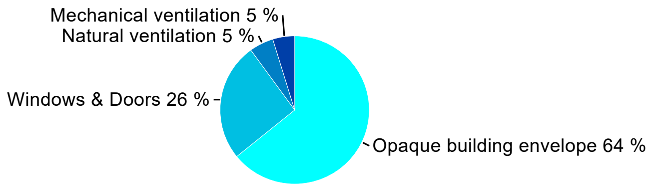
Heat gains

Solar:	**6,663** kWh/a
Inner sources:	**4,684** kWh/a
Credit of thermal bridges:	**0** kWh/a
Mechanical heating:	**6,707** kWh/a



Heat losses

Opaque building envelope:	**11,586** kWh/a
Windows & Doors:	**4,662** kWh/a
Natural ventilation:	**948** kWh/a
Mechanical ventilation:	**857** kWh/a

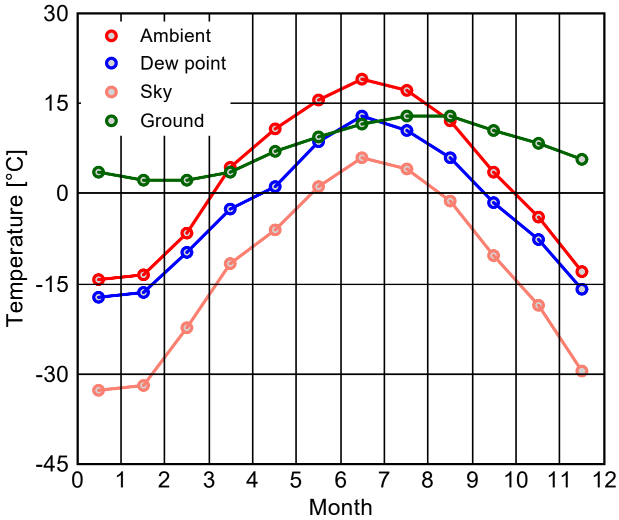


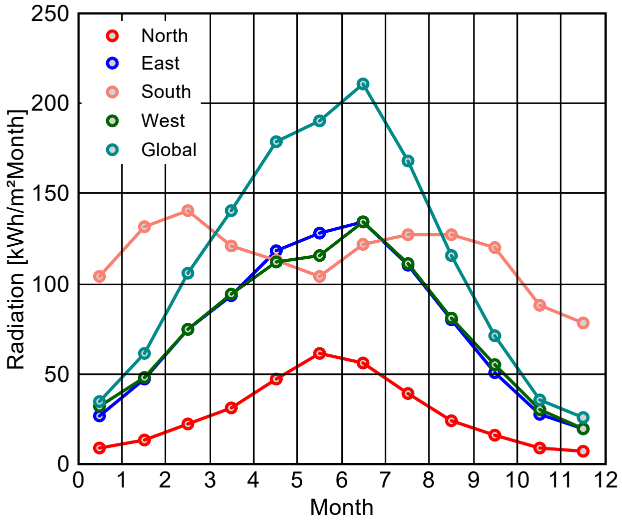
CLIMATE

Latitude:	**52.1**	°
Longitude:	**-106.6**	°
Elevation of weather station:	**515**	m
Elevation of building site:	**515**	m
Heat capacity air:	**0.33**	Wh/m³K
Daily temperature swing summer:	**12.9**	K
Average wind speed:	**4**	m/s

Ground

Average ground surface temperature:	**3.6**	°C
Amplitude ground surface temperature:	**16.7**	°C
Ground thermal conductivity:	**2**	W/mK
Ground heat capacity:	**2**	MJ/m³K
Depth below grade of groundwater:	**3**	m
Flow rate groundwater:	**0.1**	m/d





Calculation parameters

Length of heating period	**303** days/a
Heating degree hours	**138.3** kKh/a
Phase shift months	**1.4** mths
Time constant heating demand	**118.1** h

Time constant cooling demand

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
69.2	69.2	69.2	69.2	69.2	69.2	69.2	69.2	69.2	69.2	69.2	69.2

Climate for	Heating load 1	Heating load 2	Cooling
Temperature [°C]	-28.4	-21.5	23.2
Solar radiation North [W/m²]	11	9	74
Solar radiation East [W/m²]	37	24	188
Solar radiation South [W/m²]	148	85	173
Solar radiation West [W/m²]	43	24	191
Solar radiation Global [W/m²]	46	30	290

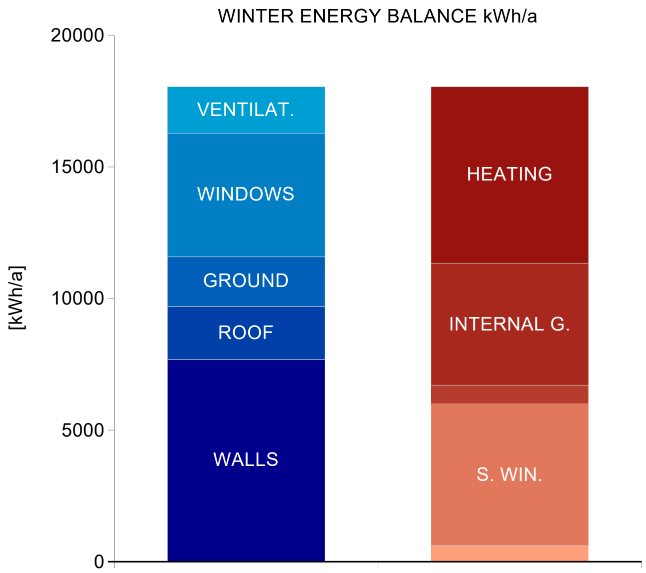
Relevant boundary conditions for heating load calculation: Heating load 1

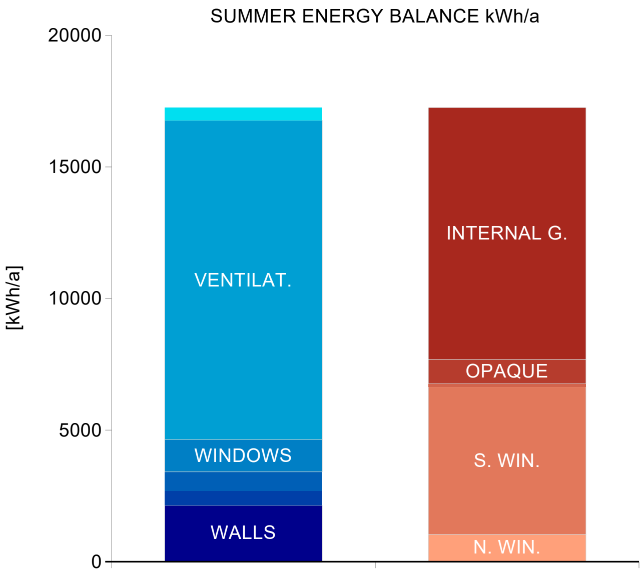
ANNUAL HEAT DEMAND

Transmission losses :	**16,248**	kWh/a
Ventilation losses:	**1,805**	kWh/a
Total heat losses:	**18,053**	kWh/a
Solar heat gains:	**8,105**	kWh/a
Internal heat gains:	**5,698**	kWh/a
Total heat gains:	**13,803**	kWh/a
Utilization factor:	**82.2**	%
Useful heat gains:	**11,346**	kWh/a
Annual heat demand:	**6,707**	kWh/a
Specific annual heat demand:	**27.3**	kWh/m²a

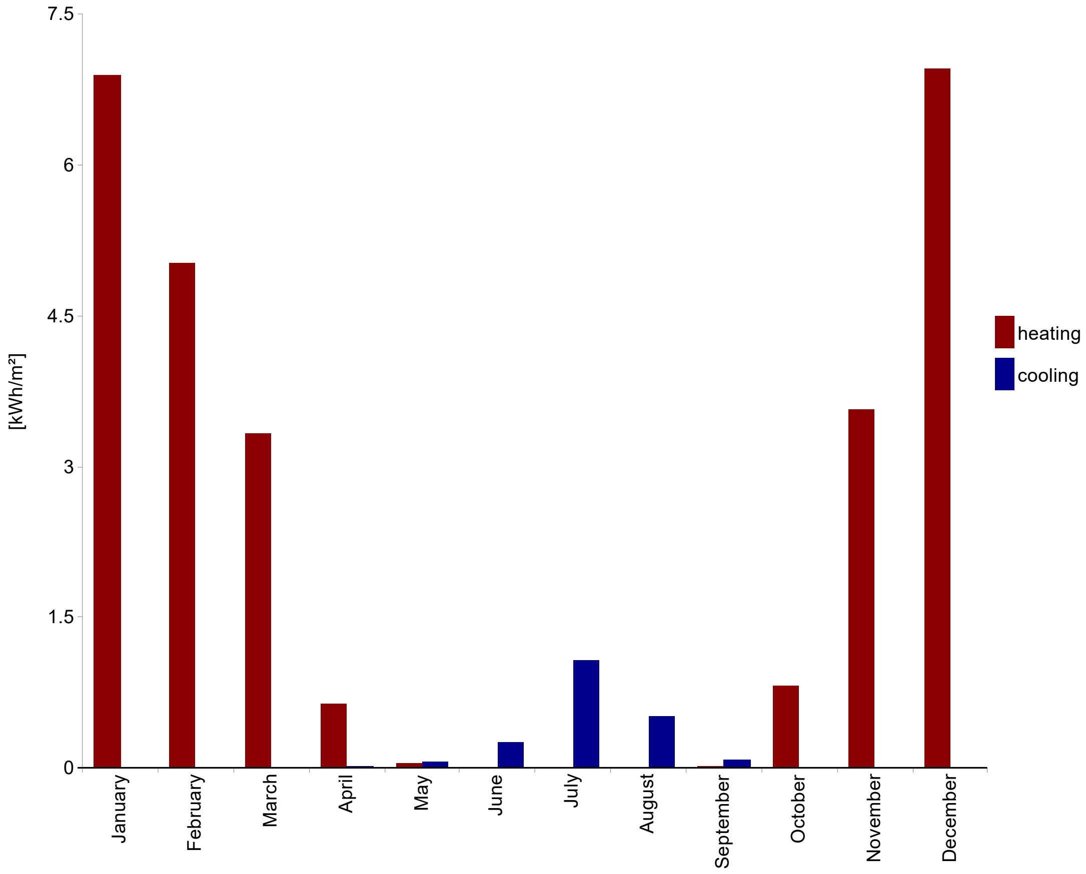
ANNUAL COOLING DEMAND

Solar heat gains:	**7,661**	kWh/a
Internal heat gains:	**9,582**	kWh/a
Total heat gains:	**17,242**	kWh/a
Transmission losses :	**13,261**	kWh/a
Ventilation losses:	**35,133**	kWh/a
Total heat losses:	**48,394**	kWh/a
Utilization factor:	**34.6**	%
Useful heat losses:	**16,752**	kWh/a
Cooling demand - sensible:	**491**	kWh/a
Cooling demand - latent:	**0**	kWh/a
Annual cooling demand:	**491**	kWh/a
Specific annual cooling demand:	**2**	kWh/m²a





SPECIFIC HEAT/COOLING DEMAND MONTHLY



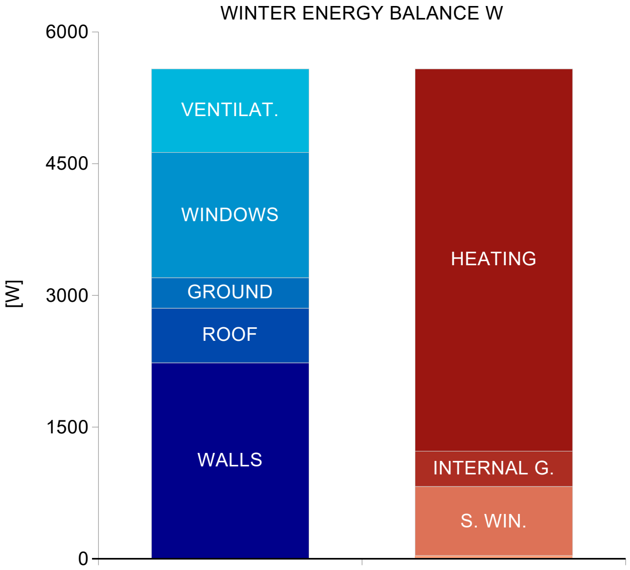
Month	Heating [kWh/m²]	Cooling [kWh/m²]
January	6.9	0
February	5	0
March	3.3	0
April	0.6	0
May	0	0.1
June	0	0.3
July	0	1.1
August	0	0.5
September	0	0.1
October	0.8	0
November	3.6	0
December	7	0

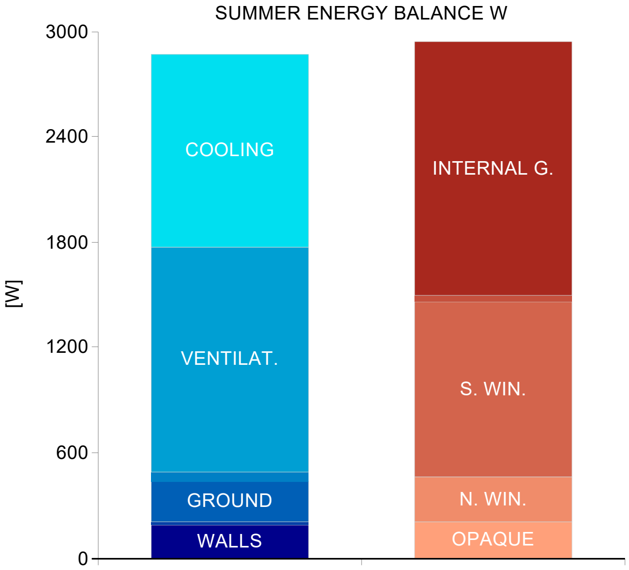
HEATING LOAD

	First climate	Second climate
Transmission heat losses:	**4,613.9** W	**4,027** W
Ventilation heat losses:	**949.2** W	**818.4** W
Total heat loss:	**5,563** W	**4,845.4** W
Solar heat gain:	**818.3** W	**472.6** W
Internal heat gain:	**393.1** W	**393.1** W
Total heat gains heating:	**1,211.4** W	**865.7** W
Heating load:	**4,351.7** W	**3,979.7** W
Relevant heating load:	**4,351.7** W	
Specific heating load:	**17.7** W/m²	

COOLING LOAD

Solar heat gain:	**1,491.9** W
Internal heat gain:	**1,451.8** W
Total heat gains cooling:	**2,943.7** W
Transmission heat losses:	**569.9** W
Ventilation heat losses:	**1,279.7** W
Total heat loss:	**1,849.6** W
Cooling load - sensible:	**1,094.1** W
Cooling load - latent:	**0** W
Relevant cooling load:	**1,094.1** W
Specific maximum cooling load:	**4.5** W/m²





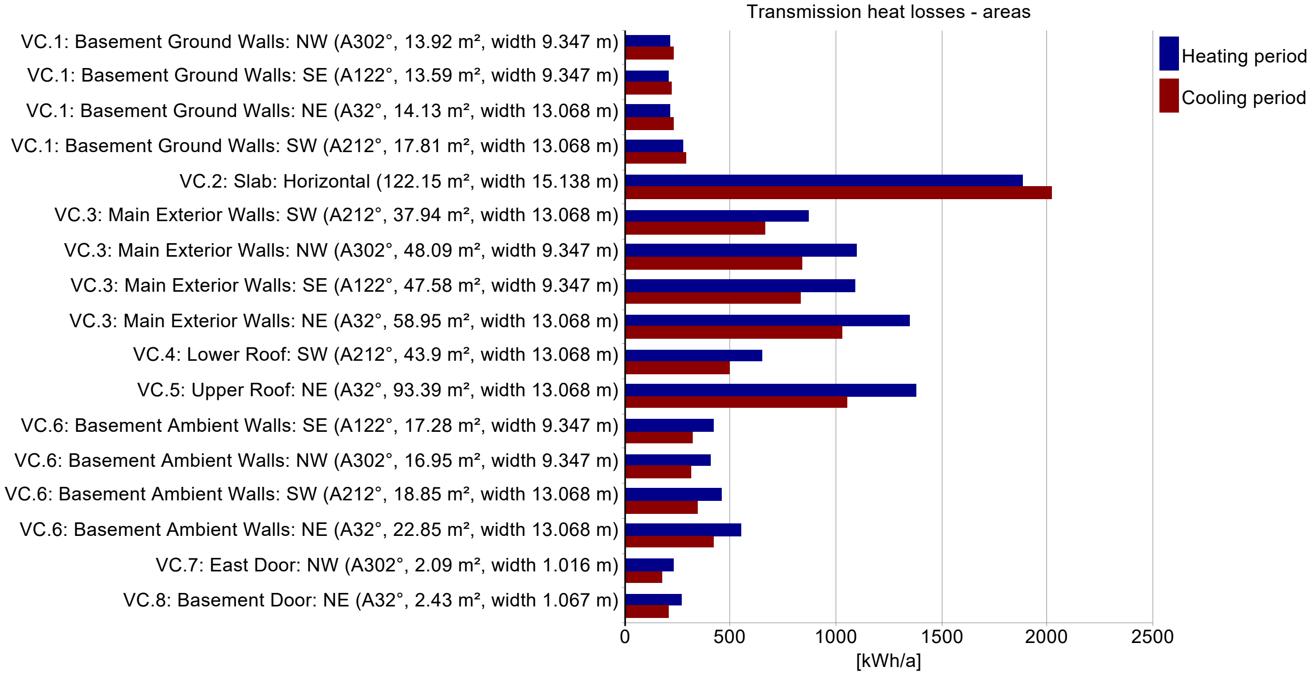
AREAS

Transmission heat losses - areas

Name	Area [m²]	Average U-value [W/m²K]	Absorption coefficient	Emission coefficient	Reduction factor shading [%]	Transmission losses heating [kWh/a]	Transmission losses cooling [kWh/a]
VC.1: Basement Ground Walls: NW (A302°, 13.92 m², width 9.347 m)	13.9	0.154	0	0	0	214.1	229.7
VC.1: Basement Ground Walls: SE (A122°, 13.59 m², width 9.347 m)	13.6	0.154	0	0	0	209.1	224.3
VC.1: Basement Ground Walls: NE (A32°, 14.13 m², width 13.068 m)	14.1	0.154	0	0	0	217.5	233.3
VC.1: Basement Ground Walls: SW (A212°, 17.81 m², width 13.068 m)	17.8	0.154	0	0	0	274	293.9
VC.2: Slab: Horizontal (122.15 m², width 15.138 m)	122.2	0.154	0	0	0	1886.7	2023.9
VC.3: Main Exterior Walls: SW (A212°, 37.94 m², width 13.068 m)	37.9	0.145	0.4	0.9	100	870.2	663.7
VC.3: Main Exterior Walls: NW (A302°, 48.09 m², width 9.347 m)	48.1	0.145	0.4	0.9	100	1103	841.3
VC.3: Main Exterior Walls: SE (A122°, 47.58 m², width 9.347 m)	47.6	0.145	0.4	0.9	100	1091.4	832.4
VC.3: Main Exterior Walls: NE (A32°, 58.95 m², width 13.068 m)	59	0.145	0.4	0.9	100	1352.2	1031.3
VC.4: Lower Roof: SW (A212°, 43.9 m², width 13.068 m)	43.9	0.094	0.4	0.9	100	649.2	495.1
VC.5: Upper Roof: NE (A32°, 93.39 m², width 13.068 m)	93.4	0.094	0.4	0.9	100	1381	1053.3
VC.6: Basement Ambient Walls: SE (A122°, 17.28 m², width 9.347 m)	17.3	0.153	0.4	0.9	100	417.6	318.5
VC.6: Basement Ambient Walls: NW (A302°, 16.95 m², width 9.347 m)	16.9	0.153	0.4	0.9	100	409.7	312.5
VC.6: Basement Ambient Walls: SW (A212°, 18.85 m², width 13.068 m)	18.9	0.153	0.4	0.9	100	455.6	347.5
VC.6: Basement Ambient Walls: NE (A32°, 22.85 m², width 13.068 m)	22.9	0.153	0.4	0.9	100	552.3	421.3
VC.7: East Door: NW (A302°, 2.09 m², width 1.016 m)	2.1	0.703	0.4	0.9	100	232.4	177.2
VC.8: Basement Door: NE (A32°, 2.43 m², width 1.067 m)	2.4	0.703	0.4	0.9	100	269.6	205.6

Degree hours [kKh/a]

	Heating	Cooling
Ambient heating	158.1	120.6
Ground heating	100	107.3



THERMAL BRIDGES

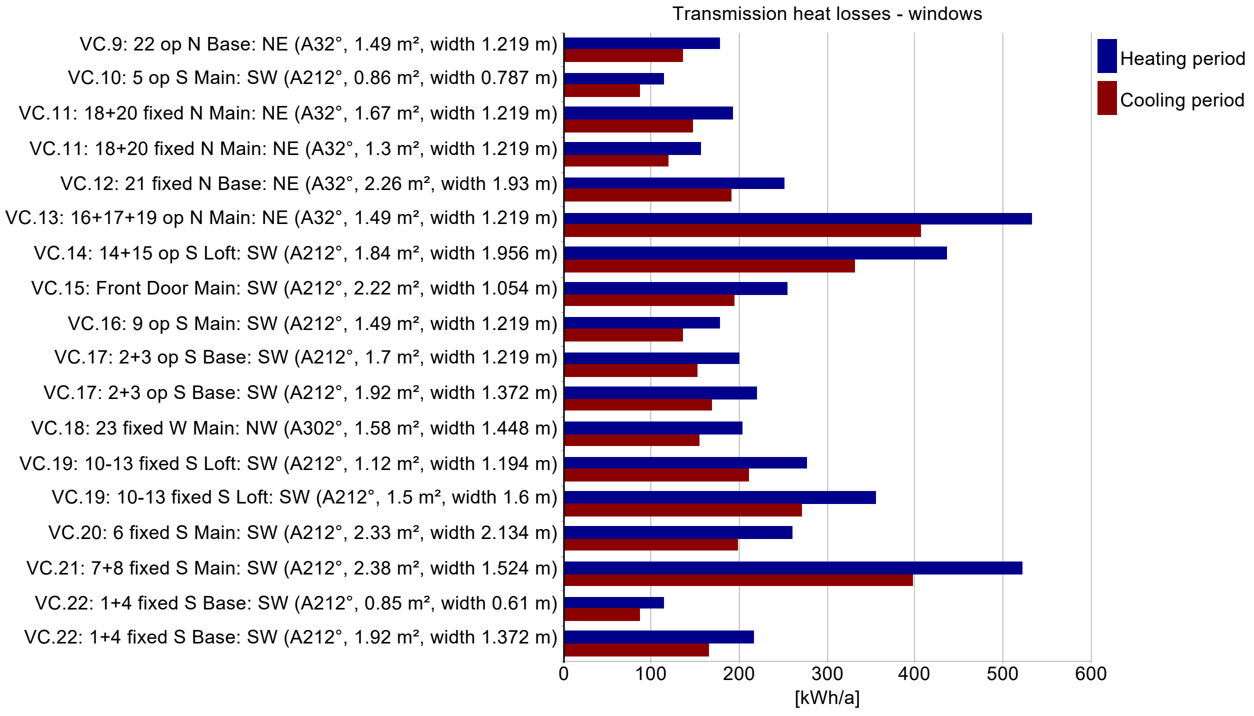
Transmission heat losses - thermal bridges

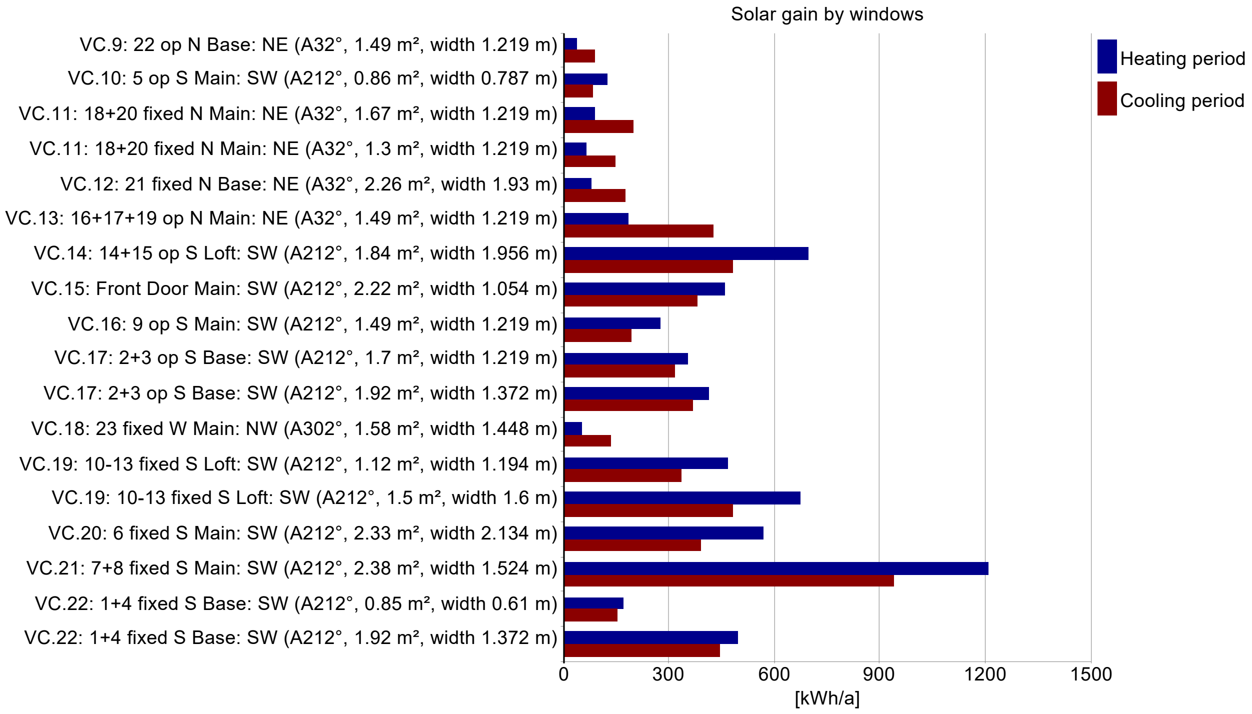
Name	Length [m]	Psi-value [W/mK]	Transmission losses [kWh/a]	Transmission losses cooling [kWh/a]

WINDOWS

Transmission heat losses - windows

Name	Quan-tity	Incli-nation [°]	U-value total [W/m²K]	SHGC (perpen-dicular)	Reduction factor shading [%]	Reduction factor shading summer [%]	Solar gain heating [kWh/a]	Solar gain cooling [kWh/a]	Transmission losses heating [kWh/a]	Transmission losses cooling [kWh/a]
VC.9: 22 op N Base: NE (A32°, 1.49 m², width 1.219 m)	1	90	0.757	0.5	54.5	56.4	39.3	87.5	177.8	135.6
VC.10: 5 op S Main: SW (A212°, 0.86 m², width 0.787 m)	1	90	0.832	0.5	74.5	53	123	82.5	113.1	86.3
VC.11: 18+20 fixed N Main: NE (A32°, 1.67 m², width 1.219 m)	1	90	0.729	0.5	86	92.4	86.5	200	192.7	147
VC.11: 18+20 fixed N Main: NE (A32°, 1.3 m², width 1.219 m)	1	90	0.758	0.5	84.5	91.5	63.6	148.2	155.9	118.9
VC.12: 21 fixed N Base: NE (A32°, 2.26 m², width 1.93 m)	1	90	0.705	0.5	57.6	58.9	80.6	177.2	251.3	191.7
VC.13: 16+17+19 op N Main: NE (A32°, 1.49 m², width 1.219 m)	3	90	0.757	0.5	84.6	91.5	183.1	426	533.5	406.9
VC.14: 14+15 op S Loft: SW (A212°, 1.84 m², width 1.956 m)	2	90	0.75	0.5	80	59	694.5	482.2	436	332.6
VC.15: Front Door Main: SW (A212°, 2.22 m², width 1.054 m)	1	90	0.728	0.5	82.8	73.3	457.6	380.9	255.6	195
VC.16: 9 op S Main: SW (A212°, 1.49 m², width 1.219 m)	1	90	0.757	0.5	79.5	58.8	275.3	191.7	177.8	135.6
VC.17: 2+3 op S Base: SW (A212°, 1.7 m², width 1.219 m)	1	90	0.742	0.5	86.2	81.7	353.8	315.6	199.8	152.4
VC.17: 2+3 op S Base: SW (A212°, 1.92 m², width 1.372 m)	1	90	0.729	0.5	87	82.4	414	368.9	220.7	168.4
VC.18: 23 fixed W Main: NW (A302°, 1.58 m², width 1.448 m)	1	90	0.813	0.6	28.1	37.5	50.3	132.1	203.3	155
VC.19: 10-13 fixed S Loft: SW (A212°, 1.12 m², width 1.194 m)	2	90	0.778	0.5	77.5	58.8	470.2	336	276	210.5
VC.19: 10-13 fixed S Loft: SW (A212°, 1.5 m², width 1.6 m)	2	90	0.749	0.5	79.7	60.4	674	480.3	356.4	271.8
VC.20: 6 fixed S Main: SW (A212°, 2.33 m², width 2.134 m)	1	90	0.707	0.5	82.3	60.1	570	392	260.4	198.6
VC.21: 7+8 fixed S Main: SW (A212°, 2.38 m², width 1.524 m)	2	90	0.693	0.5	84	69.2	1,208.8	937.2	521.8	398
VC.22: 1+4 fixed S Base: SW (A212°, 0.85 m², width 0.61 m)	1	90	0.843	0.5	80.8	78	169.1	153.6	113.5	86.6
VC.22: 1+4 fixed S Base: SW (A212°, 1.92 m², width 1.372 m)	1	90	0.714	0.5	87.9	84.1	495.9	446.7	216.4	165





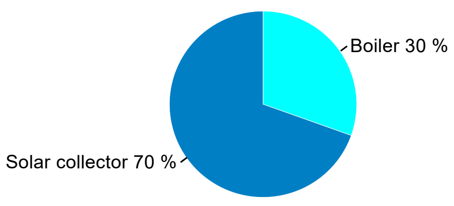
Summary building envelope

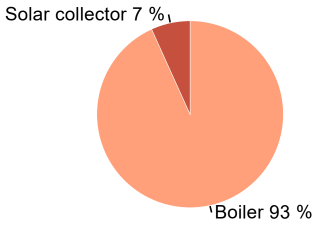
	Total area / length	Average U-value / Psi value	Transmission losses
Exterior wall ambient:	**273** m²	**0.156** W/m²K	**6,754** kWh/a
Exterior wall ground:	**59.4** m²	**0.154** W/m²K	**914.6** kWh/a
Basement:	**122.2** m²	**0.154** W/m²K	**1,886.7** kWh/a
Roof:	**137.3** m²	**0.094** W/m²K	**2,030.2** kWh/a
Windows:	**39.7** m²	**0.742** W/m²K	**4,662.1** kWh/a
Doors:	**0** m²	**0** W/m²K	**0** kWh/a
Thermal bridge ambient:	**0** m	**0** W/mK	**0** kWh/a
Thermal bridge perimeter:	**0** m	**0** W/mK	**0** kWh/a
Thermal bridge floor slab:	**0** m	**0** W/mK	**0** kWh/a

Shading

	Heating	Cooling
Reduction factor North:	**75** %	**79.9** %
Reduction factor East:	**100** %	**100** %
Reduction factor South:	**82.3** %	**67.6** %
Reduction factor West:	**28.1** %	**37.5** %
Reduction factor Horizontal:	**100** %	**100** %

System	DHW			Heating			Total		
	Covered DHW demand [%]	Estimated solar fraction [%]	Final energy demand [kWh/a]	Covered heating demand [%]	Estimated solar fraction [%]	Final energy demand [kWh/a]	Performance ratio	CO2 equivalent emissions [kg/a]	Source energy demand [kWh/a]
Boiler, Example Boiler	100	72.9	2,104.9	100	6.8	6,485	1	2,147.5	9,448.9
Solar collector, Example Solar Collector	0	0	4,807.9	0	0	470.7	0	0	0
Σ	100	72.9	6,912.8	100	6.8	6,955.7		2,147.5	9,448.9


DHW - final energy


Heating - final energy

Boiler

Boiler type:	**Gas**
Condensing:	**yes**
In thermal envelope:	**yes**
Boiler output:	**10** kW
Efficiency at 30% load:	**99** %
Efficiency at normal output:	**93** %
Heatloss at 70°C standby:	**1.7** %

VENTILATION

Infiltration pressure test ACH50:	**0.3** 1/h
Total extract air demand:	**300** m³/h
Supply air per person:	**30** m³/h
Occupancy:	**6**

Average air flow rate:	**168** m³/h
Average air change rate:	**0.19** 1/h
Effective ACH ambient:	**0.03** 1/h
Effective ACH ground:	**0.01** 1/h
Energetically effective air exchange:	**0.04** 1/h
Infiltration air change rate:	**0.02** 1/h
Infiltration air change rate (heating load):	**0.05** 1/h

Type of ventilation system:	**Balanced PH ventilation**
Wind screening coefficient (e):	**0.07**
Wind exposure factor:	**15**
Wind shield factor:	**0.05**

Ventilation heat losses:	**1,555.74** kWh/a

Devices

Name	HRV / ERV efficiency [-]	Electric efficiency [Wh/m³]	Heat recovery efficiency SHX [-]	Effective recovery efficiency [-]
Main Floor HRV	0.9	0.42	0.3	0.9
Basement Suite HRV	0.9	0.42	0.3	0.9
Altogether	0.9	0.42	0.1	0.9

Ducts

Name	Length (total) [m]	Clear cross-section [m²]	U-value [W/m²K]	Assigned ventilation units
Supply / outdoor air duct	2	0.0324	9.26	Main Floor HRV, Basement Suite HRV
Extract / Exhaust air duct	2	0.0324	9.26	Main Floor HRV, Basement Suite HRV
Σ	4			

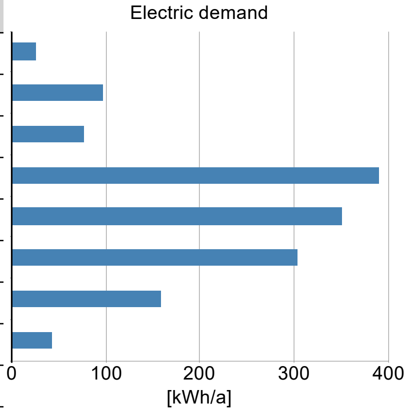
*length * quantity ** thermal conductivity / thickness

SUMMER VENTILATION

ACH night ventilation:	**0.3** 1/h
ACH natural summer:	**0.03** 1/h
Mechanical ventilation summer:	**0.3** 1/h
Mechanical ventilation summer with HR:	**no**
Preferred minimum indoor temperature for night ventilation:	**20** °C
Overheating temperature:	**25** °C

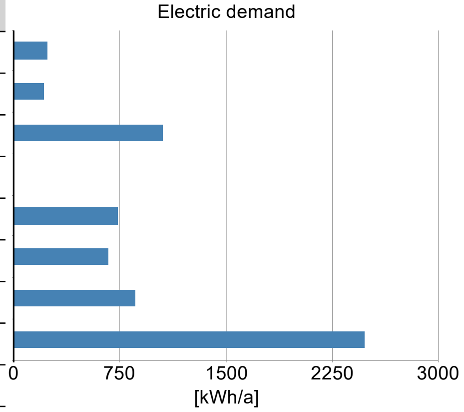
ELECTRICITY DEMAND - AUXILIARY ELECTRICITY

Type	Quantity	Indoor	Norm demand	Electric demand [kWh/a]	Source energy [kWh/a]
Boiler DHW system auxiliary energy	1	yes	136 W	24.4	77
Boiler heating auxiliary energy	1	yes	45 W	96	303.4
Solarcollector auxiliary energy	1	no	44 W	77	243.3
Ventilation winter	1	yes	0.4 Wh/m^3	390.9	1235.3
Ventilation summer	1	yes	0.4 Wh/m^3	350.8	1108.5
Heating system circulation pump	1	yes	73.4 W	303.4	958.6
DHW circulating pump	1	yes	29.7 W	157.6	497.9
DHW storage load pump	1	yes	63.7 W	42	132.8
Σ				1442	4556.8



ELECTRICITY DEMAND RESIDENTIAL BUILDING

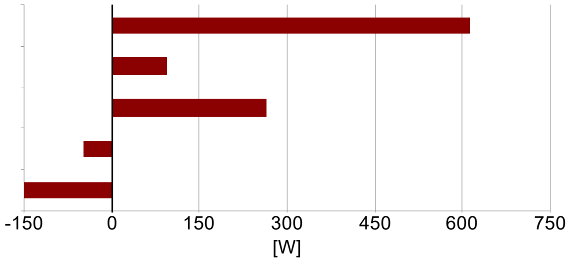
Type	Quantity	Indoor	Norm demand	Electric demand [kWh/a]	Non-electric demand [kWh/a]	Source energy [kWh/a]
Kitchen dishwasher	1	yes	1.2	234	134.7	887.6
Laundry - washer	1	yes	1.1	206.9	78.7	740.4
Laundry - dryer	1	yes	3.5	1047.4	0	3309.7
Energy consumed by evaporation	0	yes	3.1	0	273.9	301.3
Kitchen fridge/freeze combo	2	yes	1	730	0	2306.8
Kitchen cooktop	1	yes	0.2	660	0	2085.6
PHIUS+ 2015 Interior lighting	1	yes	856	856	0	2704.9
PHIUS+ 2015 Misc electric loads	1	yes	2,476.5	2476.5	0	7825.9
Σ	8			6210.8	487.2	20162.1



INTERNAL HEAT GAINS

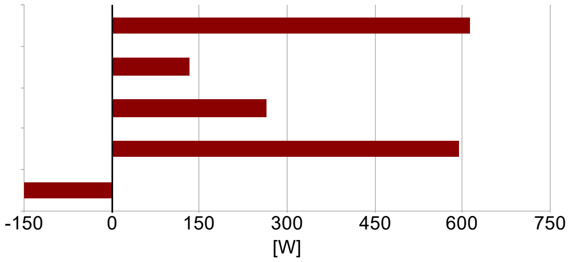
Heating season

Electricity total:	**614**	W
Auxiliary electricity:	**95.4**	W
People:	**264**	W
Cold water:	**-47.6**	W
Evaporation:	**-150**	W
Σ:	**783.6**	W
Specific internal heat gains:	**3.2**	W/m²



Cooling season

Electricity total:	**614**	W
Auxiliary electricity:	**132.3**	W
People:	**264**	W
Cold and hot water:	**592.6**	W
Evaporation:	**-150**	W
Σ:	**783.6**	W
Specific internal heat gains:	**3.2**	W/m²



DHW AND DISTRIBUTION

DHW consumption per person per day:	**25** Ltr/Person/day
Average cold water temperature supply:	**5.4** °C
Useful heat DHW:	**3,949.6** kWh/a
Specific useful heat DHW:	**16.1** kWh/m²a
Total heat losses of the DHW system:	**2,649.8** kWh/a
Specific losses of the DHW system:	**10.8** kWh/m²a
Performance ratio DHW distribution system and storage:	**1.7**
Utilization ratio DHW distribution system and storage:	**0.6**
Total heat demand of DHW system:	**6,599.4** kWh/a
Total specific heat demand of DHW system:	**26.9** kWh/m²a
Total heat losses of the hydronic heating distribution:	**165** kWh/a
Specific losses of the hydronic heating distribution:	**0.7** kWh/m²a
Performance ratio of heat distribution:	**102.5** %

Region	Length [m]	Annual heat loss [kWh/a]
Hydronic heating distribution pipes		
In conditioned space	39.6	165
Σ	39.6	165
DHW circulation pipes		
In conditioned space	99.1	1742.1
Σ	99.1	1742.1
Individual pipes		
In conditioned space	49.5	394.4
Σ	49.5	394.4
Water storage		
Device 5 (Water storage: DHW)		513.3
Σ		513.3

SOLAR DHW

Name	Area of solar thermal array [m²]	Solar thermal yield [kWh/m²a]	Useful storage capacity [Liter]	Optimal storage capacity [Liter]	Reduction factor shading [-]	Estimated solar fraction of DHW [-]	Contribution to useful heat [kWh/m²a]
Device 4 (Solar collector: Heating, DHW): Example Solar Collector	11	546	700	825	1	0.729	4,807.934
Σ	11	546	700	825		0.7	4807.9

PHIUS+ 2015 VERIFICATION

1

BUILDING INFORMATION

Category:	**Residential**
Status:	**In planning**
Building type:	**New construction**
Year of construction:	
Units:	**2**
Number of occupants:	**6 (Design)**

Boundary conditions

Climate:	**Calgary Int. Airp. AB**
Internal heat gains:	**3.8** W/m²
Interior temperature:	**20** °C
Overheat temperature:	**25** °C

Building geometry

Enclosed volume:	**1,043.3** m³
Net-volume:	**864.6** m³
Total area envelope:	**631.6** m²
AV ratio:	**0.6** 1/m
Floor area:	**245.7** m²

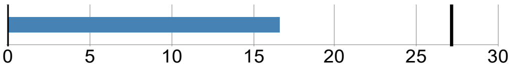
PASSIVEHOUSE REQUIREMENTS

Certificate criteria:

PHIUS+ 2015 Standard

Heating demand

specific:	**16.63** kWh/m²a
target:	**27.13** kWh/m²a
total:	4,085.4 kWh/a



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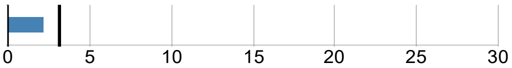
Cooling demand

sensible:	**2.16** kWh/m²a
latent:	**0** kWh/m²a
specific:	**2.16** kWh/m²a
target:	**3.15** kWh/m²a
total:	531.53 kWh/a



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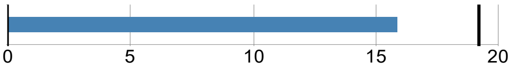
Heating load

specific:	**15.86** W/m²
target:	**19.24** W/m²
total:	3,896 W



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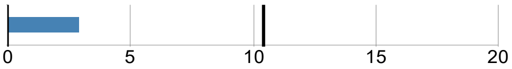
Cooling load

specific:	**2.86** W/m²
target:	**10.41** W/m²
total:	702 W



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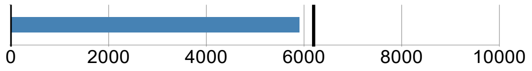
PHIUS+ 2015 VERIFICATION

2

Source energy

PHIUS+ Source Zero: NO

total:	**35,354.41**	kWh/a
specific:	**5,892**	kWh/Person a
target:	**6,200**	kWh/Person a
specific:	143.89	kWh/m²a



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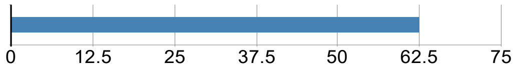
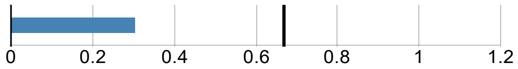
Site energy

total:	15,360.24	kWh/a
specific:	62.52	kWh/m²a



Air tightness

ACH50:	**0.3**	1/h
CFM50 per envelope area:	**0.41**	m³/m²h
target:	**0.67**	1/h
target CFM50:	**0.91**	m³/m²h



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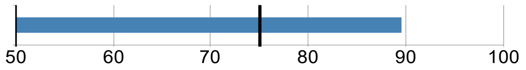
PASSIVEHOUSE RECOMMENDATIONS

HRV efficiency:	**89.4**	%
Frequency of overheating: Cooling system is not required	**2.1**	%



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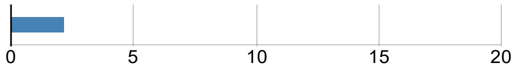

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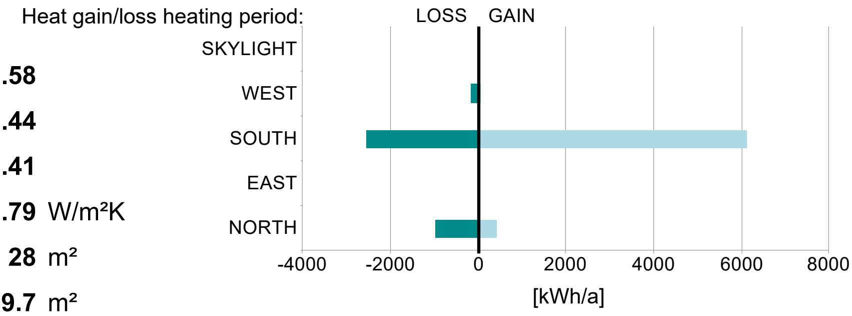
Frequency of overheating only applies if there is not a [properly sized] cooling system installed.

BUILDING ELEMENTS

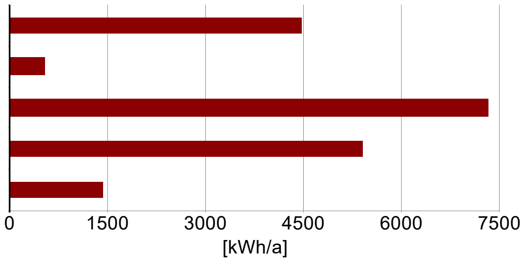
Windows

Average SHGC:	**0.58**
Average solar reduction factor heating:	**0.44**
Average solar reduction factor cooling:	**0.41**
Average U-value:	**0.79** W/m²K
Total glazing area:	**28** m²
Total window area:	**39.7** m²



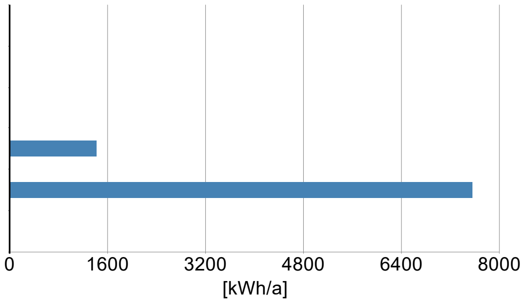
HVAC

Total heating demand:	**4,471** kWh/a
Total cooling demand:	**532** kWh/a
Total DHW energy demand:	**7,326** kWh/a
Solar DHW contribution:	**5,419** kWh/a
Auxiliary electricity:	**1,415** kWh/a



Electricity

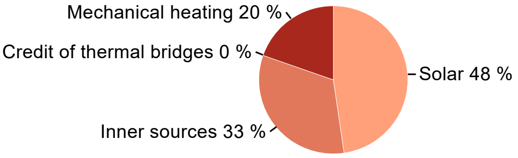
Direct heating / DHW:	**0** kWh/a
Heatpump heating:	**0** kWh/a
Cooling:	**0** kWh/a
HVAC auxiliary energy:	**1,415** kWh/a
Appliances:	**7,545** kWh/a
Renewable generation, coincident production and use:	**0** kWh/a
Total electricity demand:	**8,960** kWh/a



HEAT FLOW - HEATING PERIOD

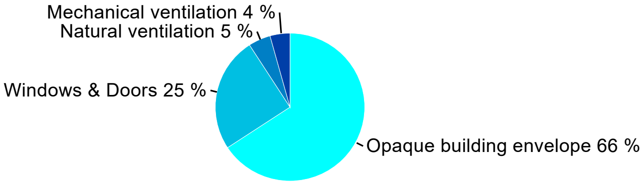
Heat gains

Solar:	**7,945** kWh/a
Inner sources:	**5,442** kWh/a
Credit of thermal bridges:	**0** kWh/a
Mechanical heating:	**4,085** kWh/a



Heat losses

Opaque building envelope:	**11,489** kWh/a
Windows & Doors:	**4,390** kWh/a
Natural ventilation:	**839** kWh/a
Mechanical ventilation:	**754** kWh/a

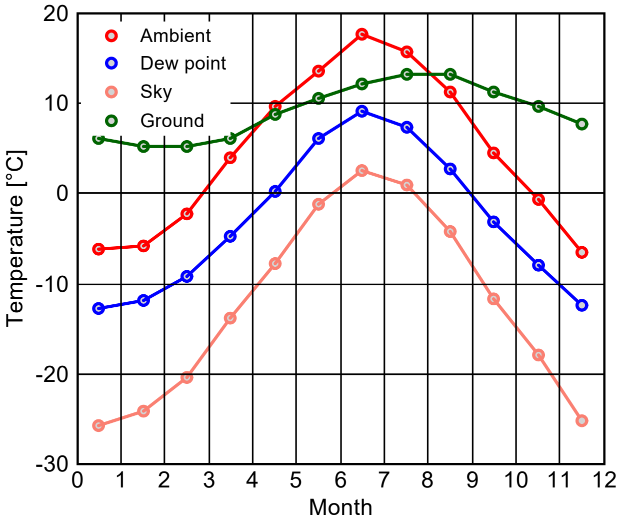


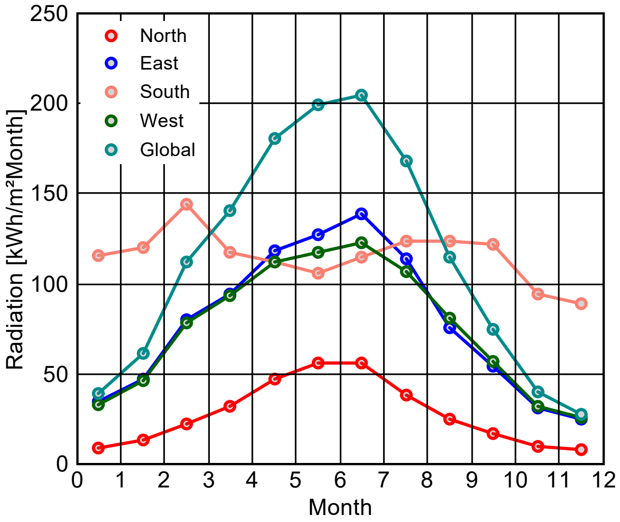
CLIMATE

Latitude:	**51.1** °
Longitude:	**-114** °
Elevation of weather station:	**1,077** m
Elevation of building site:	**1,077** m
Heat capacity air:	**0.33** Wh/m³K
Daily temperature swing summer:	**13.1** K
Average wind speed:	**4** m/s

Ground

Average ground surface temperature:	**5.6** °C
Amplitude ground surface temperature:	**12.1** °C
Ground thermal conductivity:	**2** W/mK
Ground heat capacity:	**2** MJ/m³K
Depth below grade of groundwater:	**3** m
Flow rate groundwater:	**0.1** m/d





Calculation parameters

Length of heating period	**303** days/a
Heating degree hours	**117.5** kKh/a
Phase shift months	**1.4** mths
Time constant heating demand	**108.5** h

Time constant cooling demand

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
65.8	65.8	65.8	65.8	65.8	65.8	65.8	65.8	65.8	65.8	65.8	65.8

Climate for	Heating load 1	Heating load 2	Cooling
Temperature [°C]	-23	-16.8	20.9
Solar radiation North [W/m²]	12	10	80
Solar radiation East [W/m²]	49	40	212
Solar radiation South [W/m²]	166	137	163
Solar radiation West [W/m²]	40	35	171
Solar radiation Global [W/m²]	53	42	285

Relevant boundary conditions for heating load calculation: Heating load 1

ANNUAL HEAT DEMAND

Transmission losses : **15,879** kWh/a
Ventilation losses: **1,593** kWh/a
Total heat losses: **17,472** kWh/a

Solar heat gains: **9,926** kWh/a
Internal heat gains: **6,799** kWh/a
Total heat gains: **16,724** kWh/a
Utilization factor: **80** %
Useful heat gains: **13,386** kWh/a

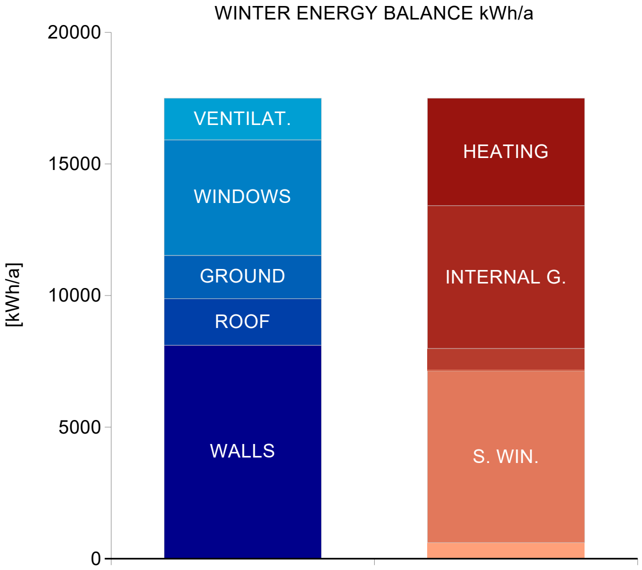
Annual heat demand: **4,085** kWh/a
Specific annual heat demand: **16.6** kWh/m²a

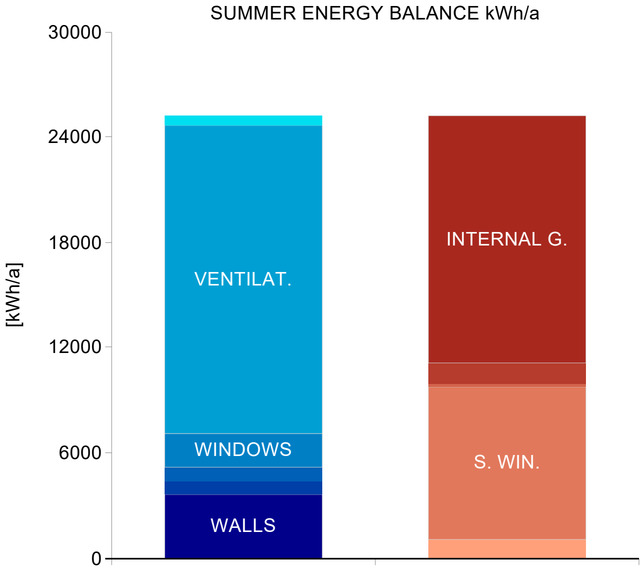
ANNUAL COOLING DEMAND

Solar heat gains: **11,131** kWh/a
Internal heat gains: **14,099** kWh/a
Total heat gains: **25,230** kWh/a

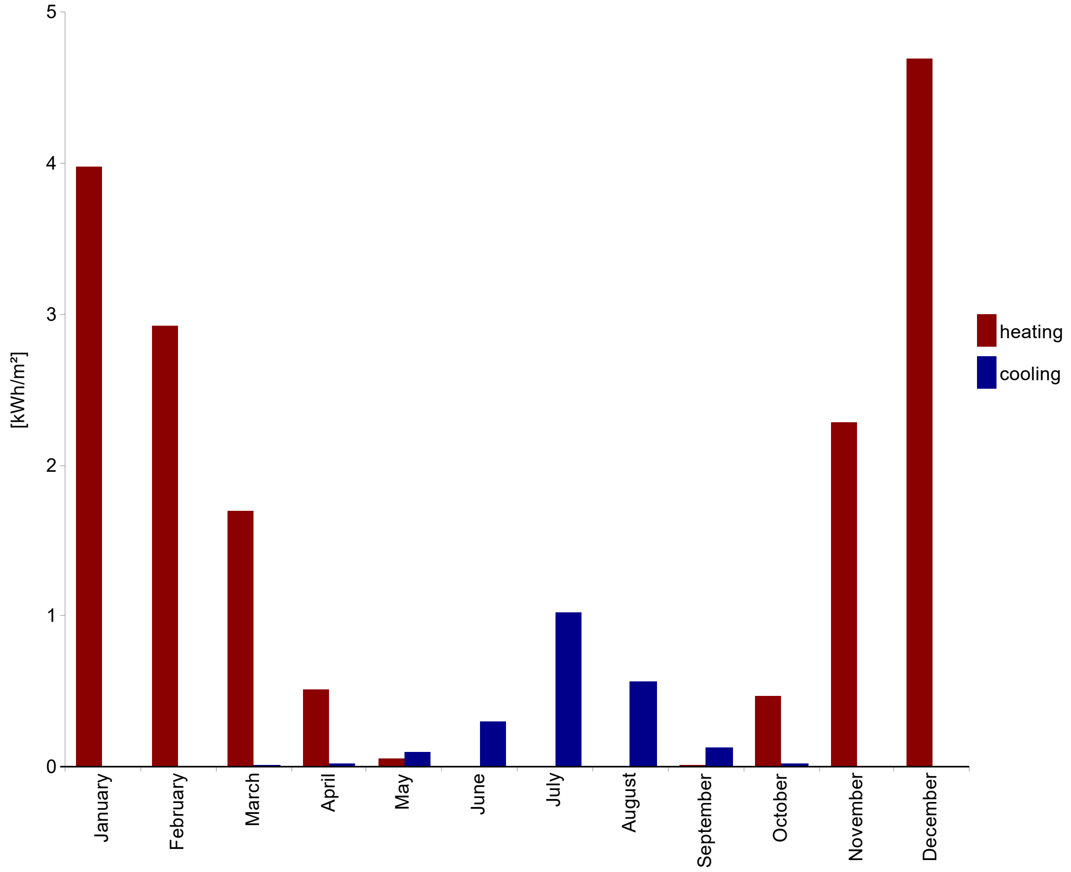
Transmission losses : **22,320** kWh/a
Ventilation losses: **55,043** kWh/a
Total heat losses: **77,363** kWh/a
Utilization factor: **31.9** %
Useful heat losses: **24,699** kWh/a

Cooling demand - sensible: **532** kWh/a
Cooling demand - latent: **0** kWh/a
Annual cooling demand: **532** kWh/a
Specific annual cooling demand: **2.2** kWh/m²a





SPECIFIC HEAT/COOLING DEMAND MONTHLY



Month	Heating [kWh/m²]	Cooling [kWh/m²]
January	4	0
February	2.9	0
March	1.7	0
April	0.5	0
May	0.1	0.1
June	0	0.3
July	0	1
August	0	0.6
September	0	0.1
October	0.5	0
November	2.3	0
December	4.7	0

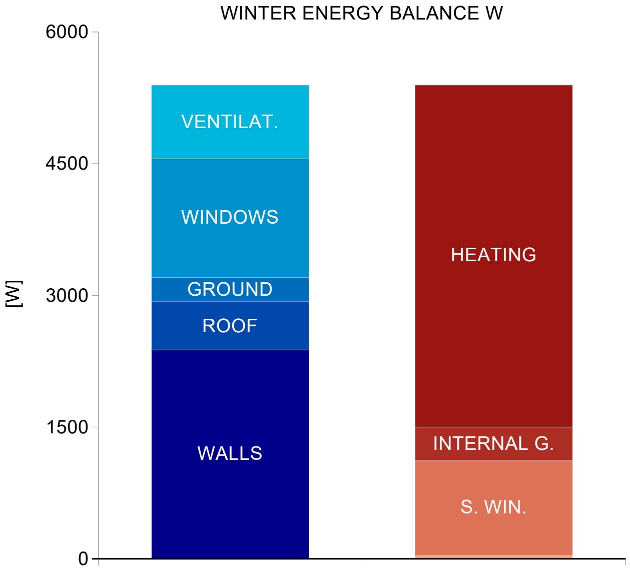
HEATING LOAD

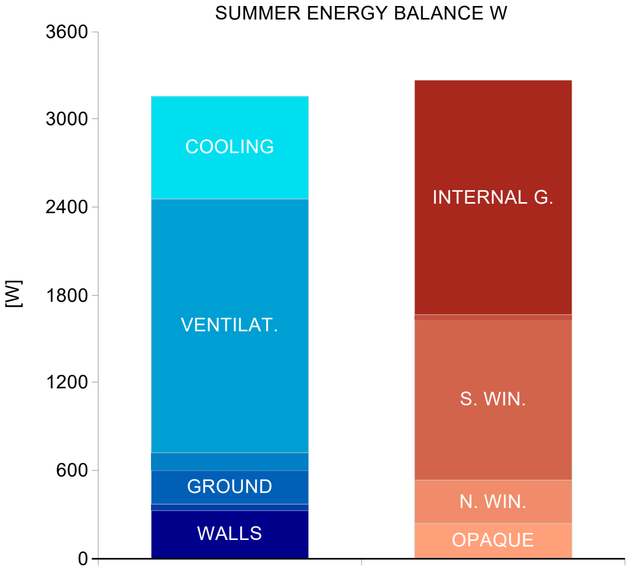
	First climate	Second climate
Transmission heat losses:	**4,551.1** W	**3,954.9** W
Ventilation heat losses:	**842.3** W	**724.9** W
Total heat loss:	**5,393.4** W	**4,679.8** W
Solar heat gain:	**1,104.3** W	**917.4** W
Internal heat gain:	**393.1** W	**393.1** W
Total heat gains heating:	**1,497.4** W	**1,310.5** W
Heating load:	**3,896** W	**3,369.2** W

Relevant heating load:	**3,896** W
Specific heating load:	**15.9** W/m²

COOLING LOAD

Solar heat gain:	**1,658.5** W
Internal heat gain:	**1,609.5** W
Total heat gains cooling:	**3,268** W
Transmission heat losses:	**836.7** W
Ventilation heat losses:	**1,729.3** W
Total heat loss:	**2,566** W
Cooling load - sensible:	**702** W
Cooling load - latent:	**0** W
Relevant cooling load:	**702** W
Specific maximum cooling load:	**2.9** W/m²





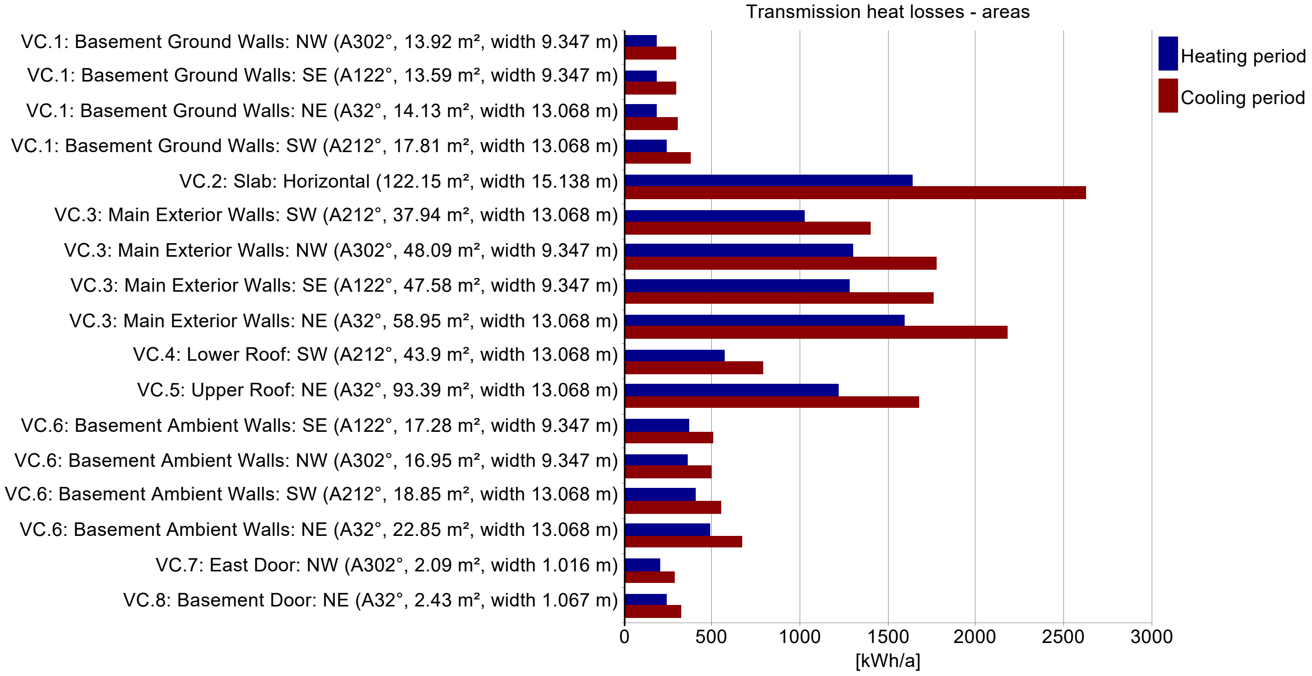
AREAS

Transmission heat losses - areas

Name	Area [m²]	Average U-value [W/m²K]	Absorption coefficient	Emission coefficient	Reduction factor shading [%]	Transmission losses heating [kWh/a]	Transmission losses cooling [kWh/a]
VC.1: Basement Ground Walls: NW (A302°, 13.92 m², width 9.347 m)	13.9	0.154	0	0	0	186	298.1
VC.1: Basement Ground Walls: SE (A122°, 13.59 m², width 9.347 m)	13.6	0.154	0	0	0	181.6	291.1
VC.1: Basement Ground Walls: NE (A32°, 14.13 m², width 13.068 m)	14.1	0.154	0	0	0	188.9	302.7
VC.1: Basement Ground Walls: SW (A212°, 17.81 m², width 13.068 m)	17.8	0.154	0	0	0	238	381.4
VC.2: Slab: Horizontal (122.15 m², width 15.138 m)	122.2	0.154	0	0	0	1638.9	2626.6
VC.3: Main Exterior Walls: SW (A212°, 37.94 m², width 13.068 m)	37.9	0.193	0.4	0.9	100	1023.2	1401.8
VC.3: Main Exterior Walls: NW (A302°, 48.09 m², width 9.347 m)	48.1	0.193	0.4	0.9	100	1296.9	1776.9
VC.3: Main Exterior Walls: SE (A122°, 47.58 m², width 9.347 m)	47.6	0.193	0.4	0.9	100	1283.2	1758.1
VC.3: Main Exterior Walls: NE (A32°, 58.95 m², width 13.068 m)	59	0.193	0.4	0.9	100	1589.9	2178.2
VC.4: Lower Roof: SW (A212°, 43.9 m², width 13.068 m)	43.9	0.094	0.4	0.9	100	574.1	786.5
VC.5: Upper Roof: NE (A32°, 93.39 m², width 13.068 m)	93.4	0.094	0.4	0.9	100	1221.3	1673.3
VC.6: Basement Ambient Walls: SE (A122°, 17.28 m², width 9.347 m)	17.3	0.153	0.4	0.9	100	369.3	505.9
VC.6: Basement Ambient Walls: NW (A302°, 16.95 m², width 9.347 m)	16.9	0.153	0.4	0.9	100	362.3	496.4
VC.6: Basement Ambient Walls: SW (A212°, 18.85 m², width 13.068 m)	18.9	0.153	0.4	0.9	100	403	552.1
VC.6: Basement Ambient Walls: NE (A32°, 22.85 m², width 13.068 m)	22.9	0.153	0.4	0.9	100	488.5	669.2
VC.7: East Door: NW (A302°, 2.09 m², width 1.016 m)	2.1	0.703	0.4	0.9	100	205.5	281.6
VC.8: Basement Door: NE (A32°, 2.43 m², width 1.067 m)	2.4	0.703	0.4	0.9	100	238.4	326.7

Degree hours [kKh/a]

	Heating	Cooling
Ambient heating	139.8	191.5
Ground heating	86.9	139.2



THERMAL BRIDGES

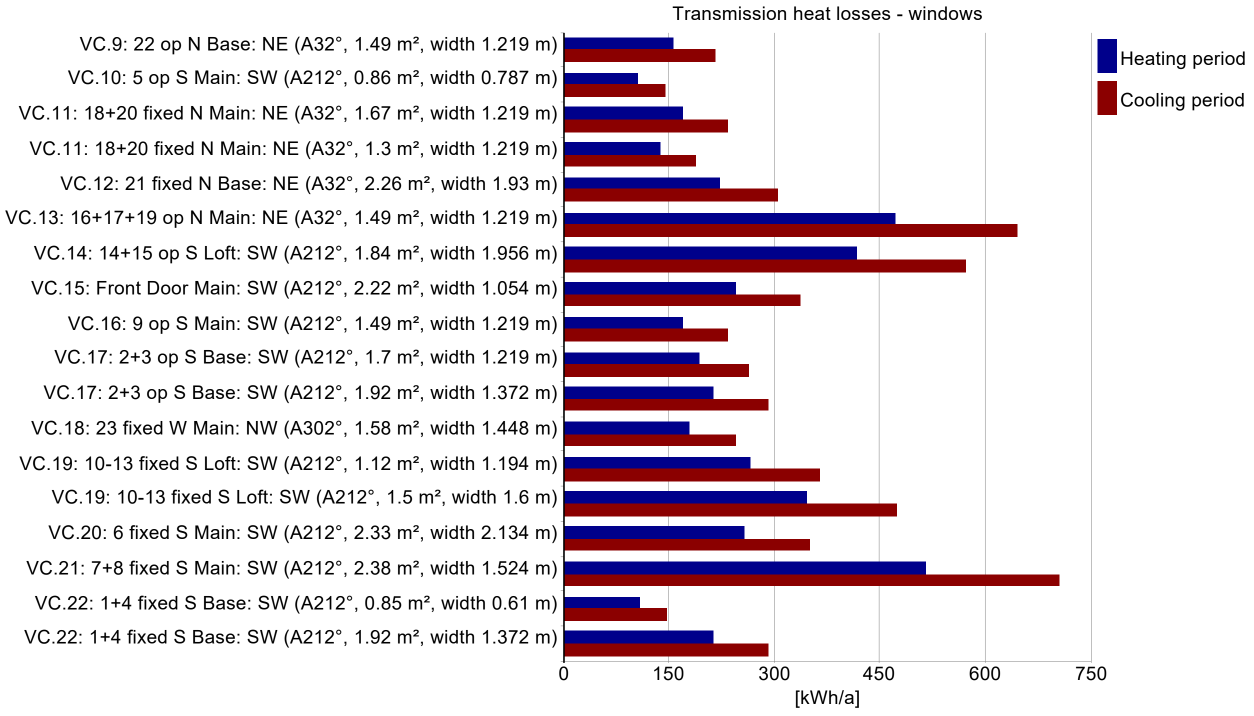
Transmission heat losses - thermal bridges

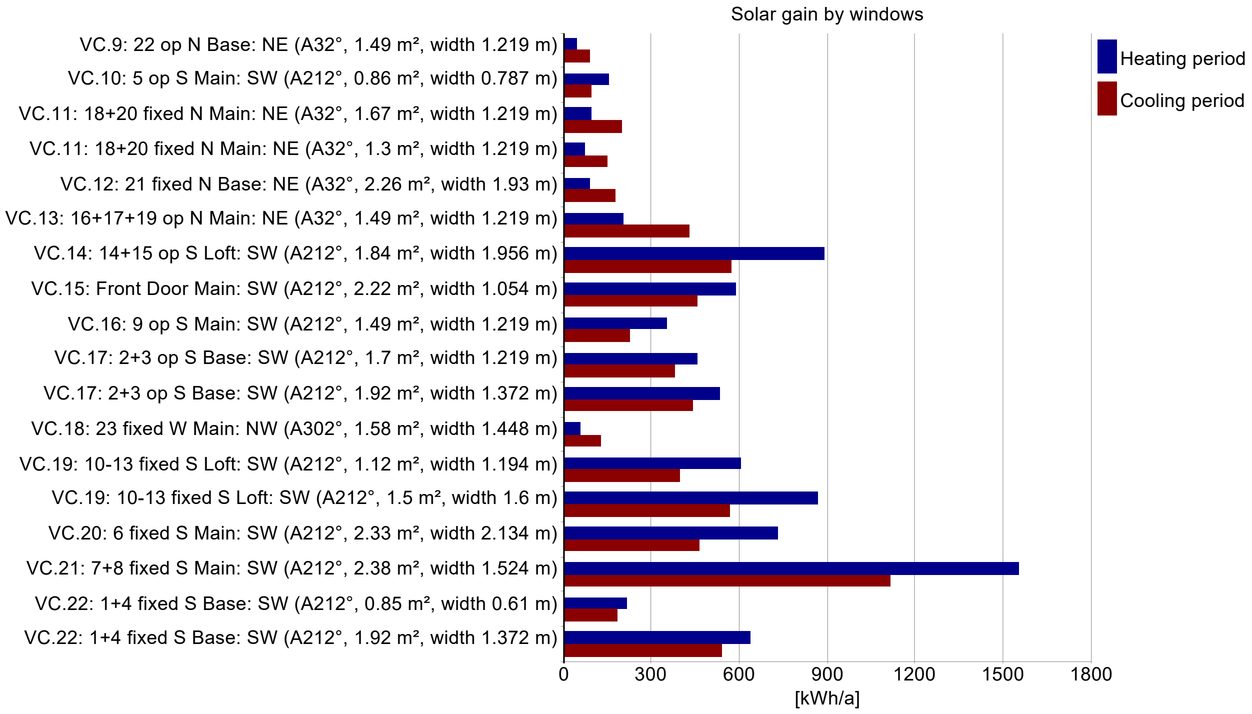
Name	Length [m]	Psi-value [W/mK]	Transmission losses [kWh/a]	Transmission losses cooling [kWh/a]

WINDOWS

Transmission heat losses - windows

Name	Quan-tity	Incli-nation [°]	U-value total [W/m²K]	SHGC (perpen-dicular)	Reduction factor shading [%]	Reduction factor shading summer [%]	Solar gain heating [kWh/a]	Solar gain cooling [kWh/a]	Transmission losses heating [kWh/a]	Transmission losses cooling [kWh/a]
VC.9: 22 op N Base: NE (A32°, 1.49 m², width 1.219 m)	1	90	0.757	0.5	54.7	56	44.3	87.3	157.3	215.5
VC.10: 5 op S Main: SW (A212°, 0.86 m², width 0.787 m)	1	90	0.883	0.6	73.8	51.7	158	97.4	106.2	145.5
VC.11: 18+20 fixed N Main: NE (A32°, 1.67 m², width 1.219 m)	1	90	0.729	0.5	86	92.4	97.3	201	170.5	233.5
VC.11: 18+20 fixed N Main: NE (A32°, 1.3 m², width 1.219 m)	1	90	0.758	0.5	84.5	91.4	71.6	148.8	137.8	188.9
VC.12: 21 fixed N Base: NE (A32°, 2.26 m², width 1.93 m)	1	90	0.705	0.5	57.7	58.5	90.8	177	222.3	304.5
VC.13: 16+17+19 op N Main: NE (A32°, 1.49 m², width 1.219 m)	3	90	0.757	0.5	84.7	91.4	206.1	427.9	471.8	646.4
VC.14: 14+15 op S Loft: SW (A212°, 1.84 m², width 1.956 m)	2	90	0.813	0.6	79.4	57.7	893	570.9	417.9	572.5
VC.15: Front Door Main: SW (A212°, 2.22 m², width 1.054 m)	1	90	0.794	0.6	82.4	72.3	589.9	455.4	246.6	337.8
VC.16: 9 op S Main: SW (A212°, 1.49 m², width 1.219 m)	1	90	0.819	0.6	78.9	57.4	354	227	170.1	233.1
VC.17: 2+3 op S Base: SW (A212°, 1.7 m², width 1.219 m)	1	90	0.806	0.6	85.9	81	456.7	379.3	191.9	263
VC.17: 2+3 op S Base: SW (A212°, 1.92 m², width 1.372 m)	1	90	0.795	0.6	86.7	81.7	534.5	443.4	212.9	291.7
VC.18: 23 fixed W Main: NW (A302°, 1.58 m², width 1.448 m)	1	90	0.813	0.6	28.3	37.8	54.6	129.7	179.8	246.3
VC.19: 10-13 fixed S Loft: SW (A212°, 1.12 m², width 1.194 m)	2	90	0.85	0.6	76.9	57.5	604.7	398.2	266.6	365.3
VC.19: 10-13 fixed S Loft: SW (A212°, 1.5 m², width 1.6 m)	2	90	0.824	0.6	79.1	59	867	569.4	346.6	474.8
VC.20: 6 fixed S Main: SW (A212°, 2.33 m², width 2.134 m)	1	90	0.786	0.6	81.7	58.7	733.1	464.1	256	350.7
VC.21: 7+8 fixed S Main: SW (A212°, 2.38 m², width 1.524 m)	2	90	0.774	0.6	83.5	68	1,557.2	1,116.4	515	705.5
VC.22: 1+4 fixed S Base: SW (A212°, 0.85 m², width 0.61 m)	1	90	0.908	0.6	80.5	77.3	218.2	184.7	108.2	148.2
VC.22: 1+4 fixed S Base: SW (A212°, 1.92 m², width 1.372 m)	1	90	0.793	0.6	87.6	83.5	640.3	537.4	212.3	290.9





Summary building envelope

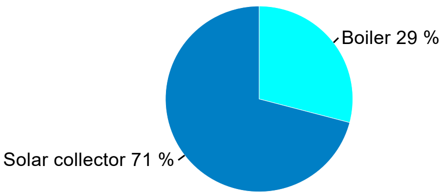
	Total area / length	Average U-value / Psi value	Transmission losses
Exterior wall ambient:	**273** m²	**0.19** W/m²K	**7,260.2** kWh/a
Exterior wall ground:	**59.4** m²	**0.154** W/m²K	**794.5** kWh/a
Basement:	**122.2** m²	**0.154** W/m²K	**1,638.9** kWh/a
Roof:	**137.3** m²	**0.094** W/m²K	**1,795.4** kWh/a
Windows:	**39.7** m²	**0.79** W/m²K	**4,389.6** kWh/a
Doors:	**0** m²	**0** W/m²K	**0** kWh/a
Thermal bridge ambient:	**0** m	**0** W/mK	**0** kWh/a
Thermal bridge perimeter:	**0** m	**0** W/mK	**0** kWh/a
Thermal bridge floor slab:	**0** m	**0** W/mK	**0** kWh/a

Shading

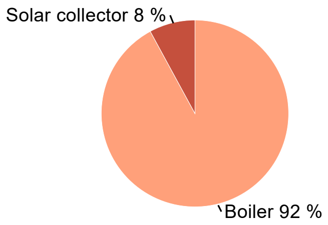
	Heating	Cooling
Reduction factor North:	**75.1** %	**79.7** %
Reduction factor East:	**100** %	**100** %
Reduction factor South:	**81.8** %	**66.5** %
Reduction factor West:	**28.3** %	**37.8** %
Reduction factor Horizontal:	**100** %	**100** %

System	DHW			Heating			Total		
	Covered DHW demand [%]	Estimated solar fraction [%]	Final energy demand [kWh/a]	Covered heating demand [%]	Estimated solar fraction [%]	Final energy demand [kWh/a]	Performance ratio	CO2 equivalent emissions [kg/a]	Source energy demand [kWh/a]
Boiler, Example Boiler	100	74	2,223.3	100	8	4,176.7	1.1	1,600	7,040
Solar collector, Example Solar Collector	0	0	5,419.2	0	0	359	0	0	0
Σ	100	74	7,642.5	100	8	4,535.7		1,600	7,040

DHW - final energy



Heating - final energy



Boiler

Boiler type:	**Gas**
Condensing:	**yes**
In thermal envelope:	**yes**
Boiler output:	**10** kW
Efficiency at 30% load:	**99** %
Efficiency at normal output:	**93** %
Heatloss at 70°C standby:	**1.7** %

VENTILATION

Infiltration pressure test ACH50:	**0.3** 1/h
Total extract air demand:	**300** m³/h
Supply air per person:	**30** m³/h
Occupancy:	**6**

Average air flow rate:	**168** m³/h
Average air change rate:	**0.19** 1/h
Effective ACH ambient:	**0.03** 1/h
Effective ACH ground:	**0.01** 1/h
Energetically effective air exchange:	**0.04** 1/h
Infiltration air change rate:	**0.02** 1/h
Infiltration air change rate (heating load):	**0.05** 1/h

Type of ventilation system:	**Balanced PH ventilation**
Wind screening coefficient (e):	**0.07**
Wind exposure factor:	**15**
Wind shield factor:	**0.05**

Ventilation heat losses:	**1,326.78** kWh/a

Devices

Name	HRV / ERV efficiency [-]	Electric efficiency [Wh/m³]	Heat recovery efficiency SHX [-]	Effective recovery efficiency [-]
Main Floor HRV	0.9	0.42	0.3	0.9
Basement Suite HRV	0.9	0.42	0.3	0.9
Altogether	0.9	0.42	0.1	0.9

Ducts

Name	Length (total) [m]	Clear cross-section [m²]	U-value [W/m²K]	Assigned ventilation units
Supply / outdoor air duct	2	0.0324	9.2	Main Floor HRV, Basement Suite HRV
Extract / Exhaust air duct	2	0.0324	9.2	Main Floor HRV, Basement Suite HRV
Σ	4			

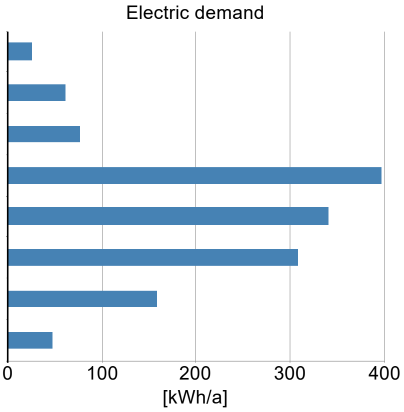
*length * quantity ** thermal conductivity / thickness

SUMMER VENTILATION

ACH night ventilation:	**0.3** 1/h
ACH natural summer:	**0.03** 1/h
Mechanical ventilation summer:	**0.3** 1/h
Mechanical ventilation summer with HR:	**no**
Preferred minimum indoor temperature for night ventilation:	**20** °C
Overheating temperature:	**25** °C

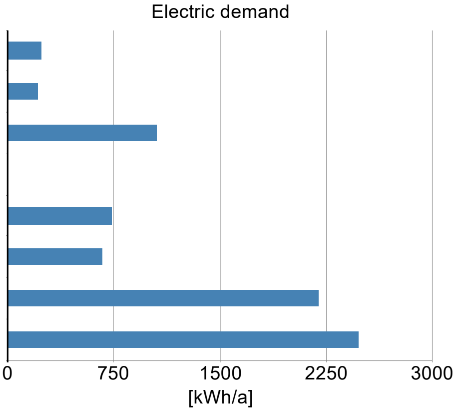
ELECTRICITY DEMAND - AUXILIARY ELECTRICITY

Type	Quantity	Indoor	Norm demand	Electric demand [kWh/a]	Source energy [kWh/a]
Boiler DHW system auxiliary energy	1	yes	136 W	25.9	81.9
Boiler heating auxiliary energy	1	yes	45 W	61.7	194.9
Solarcollector auxiliary energy	1	no	44 W	77	243.3
Ventilation winter	1	yes	0.4 Wh/m³	397.6	1256.4
Ventilation summer	1	yes	0.4 Wh/m³	340.5	1075.9
Heating system circulation pump	1	yes	73.4 W	308.5	975
DHW circulating pump	1	yes	29.7 W	157.6	497.9
DHW storage load pump	1	yes	63.7 W	46.7	147.5
Σ				1415.4	4472.8



ELECTRICITY DEMAND RESIDENTIAL BUILDING

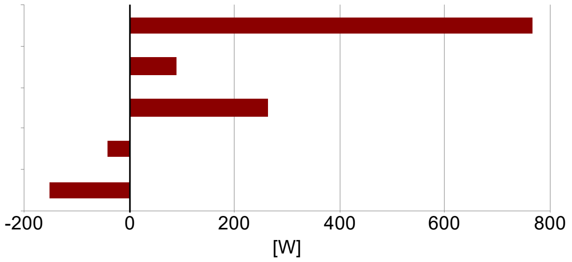
Type	Quantity	Indoor	Norm demand	Electric demand [kWh/a]	Non-electric demand [kWh/a]	Source energy [kWh/a]
Kitchen dishwasher	1	yes	1.2	234	148.5	902.8
Laundry - washer	1	yes	1.1	206.9	86.8	749.3
Laundry - dryer	1	yes	3.5	1047.4	0	3309.7
Energy consumed by evaporation	0	yes	3.1	0	199	218.9
Kitchen fridge/freeze combo	2	yes	1	730	0	2306.8
Kitchen cooktop	1	yes	0.2	660	0	2085.6
PHIUS+ 2015 Interior lighting	1	yes	2,190	2190	0	6920.4
PHIUS+ 2015 Misc electric loads	1	yes	2,476.5	2476.5	0	7825.9
Σ	8			7544.8	434.4	24319.5



INTERNAL HEAT GAINS

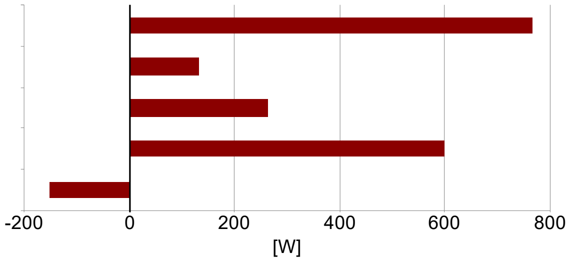
Heating season

Electricity total:	**766.3**	W
Auxiliary electricity:	**90.2**	W
People:	**264**	W
Cold water:	**-41.8**	W
Evaporation:	**-150**	W
Σ:	**934.9**	W
Specific internal heat gains:	**3.8**	W/m²



Cooling season

Electricity total:	**766.3**	W
Auxiliary electricity:	**133.4**	W
People:	**264**	W
Cold and hot water:	**598.4**	W
Evaporation:	**-150**	W
Σ:	**934.9**	W
Specific internal heat gains:	**3.8**	W/m²



DHW AND DISTRIBUTION

DHW consumption per person per day:	**25** Ltr/Person/day
Average cold water temperature supply:	**5.4** °C
Useful heat DHW:	**3,949.6** kWh/a
Specific useful heat DHW:	**16.1** kWh/m²a
Total heat losses of the DHW system:	**3,376.3** kWh/a
Specific losses of the DHW system:	**13.7** kWh/m²a
Performance ratio DHW distribution system and storage:	**1.9**
Utilization ratio DHW distribution system and storage:	**0.5**
Total heat demand of DHW system:	**7,325.9** kWh/a
Total specific heat demand of DHW system:	**29.8** kWh/m²a
Total heat losses of the hydronic heating distribution:	**385.6** kWh/a
Specific losses of the hydronic heating distribution:	**1.6** kWh/m²a
Performance ratio of heat distribution:	**109.4** %

Region	Length [m]	Annual heat loss [kWh/a]
Hydronic heating distribution pipes		
In conditioned space	39.6	385.6
Σ	39.6	385.6
DHW circulation pipes		
In conditioned space	99.1	2219.7
Σ	99.1	2219.7
Individual pipes		
In conditioned space	49.5	502.5
Σ	49.5	502.5
Water storage		
Device 5 (Water storage: DHW)		654
Σ		654

SOLAR DHW

Name	Area of solar thermal array [m²]	Solar thermal yield [kWh/m²a]	Useful storage capacity [Liter]	Optimal storage capacity [Liter]	Reduction factor shading [-]	Estimated solar fraction of DHW [-]	Contribution to useful heat [kWh/m²a]
Device 4 (Solar collector: Heating, DHW): Example Solar Collector	11	546	700	825	1	0.74	5,419.22
Σ	11	546	700	825		0.7	5419.2

PHIUS+ 2015 VERIFICATION

1

BUILDING INFORMATION

Category:	**Residential**
Status:	**In planning**
Building type:	**New construction**
Year of construction:	
Units:	**2**
Number of occupants:	**6 (Design)**

Boundary conditions

Climate:	**Kelowna AP, BC**
Internal heat gains:	**3.2** W/m²
Interior temperature:	**20** °C
Overheat temperature:	**25** °C

Building geometry

Enclosed volume:	**1,043.3** m³
Net-volume:	**864.6** m³
Total area envelope:	**631.6** m²
AV ratio:	**0.6** 1/m
Floor area:	**245.7** m²

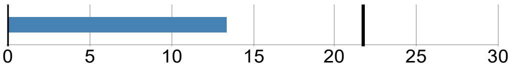
PASSIVEHOUSE REQUIREMENTS

Certificate criteria:

PHIUS+ 2015 Standard

Heating demand

specific:	**13.35** kWh/m²a
target:	**21.77** kWh/m²a
total:	3,279.45 kWh/a



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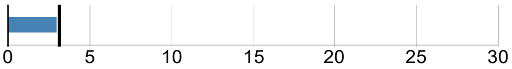
Cooling demand

sensible:	**2.91** kWh/m²a
latent:	**0** kWh/m²a
specific:	**2.91** kWh/m²a
target:	**3.15** kWh/m²a
total:	715.6 kWh/a



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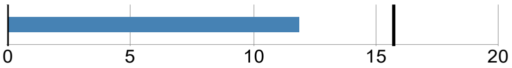
Heating load

specific:	**11.89** W/m²
target:	**15.77** W/m²
total:	2,922.48 W



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Cooling load

specific:	**5.2** W/m²
target:	**11.99** W/m²
total:	1,277.05 W

✓

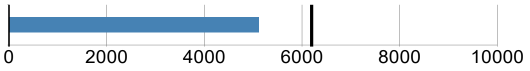
PHIUS+ 2015 VERIFICATION

2

Source energy

PHIUS+ Source Zero: NO

total:	**30,656.81**	kWh/a
specific:	**5,109**	kWh/Person a
target:	**6,200**	kWh/Person a
specific:	124.77	kWh/m²a



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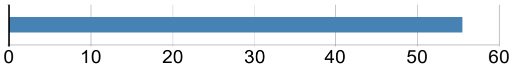
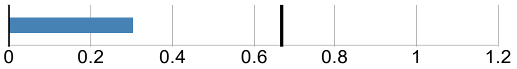
Site energy

total:	13,612.37	kWh/a
specific:	55.4	kWh/m²a



Air tightness

ACH50:	**0.3**	1/h
CFM50 per envelope area:	**0.41**	m³/m²h
target:	**0.67**	1/h
target CFM50:	**0.91**	m³/m²h



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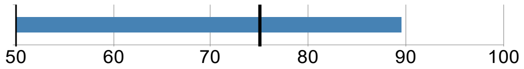
PASSIVEHOUSE RECOMMENDATIONS

HRV efficiency:	**89.4**	%



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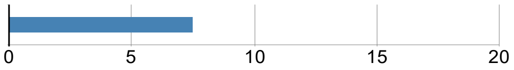
Frequency of overheating: Cooling system is not required	**7.5**	%



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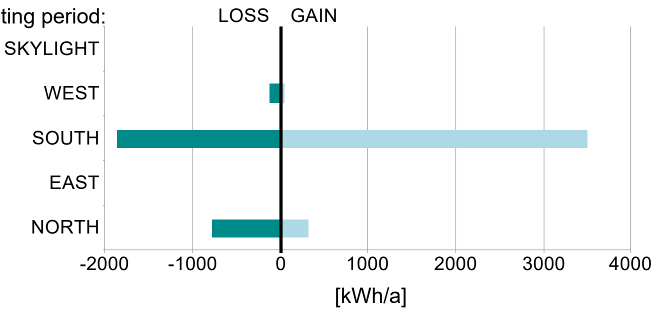
Frequency of overheating only applies if there is not a [properly sized] cooling system installed.

BUILDING ELEMENTS

Windows

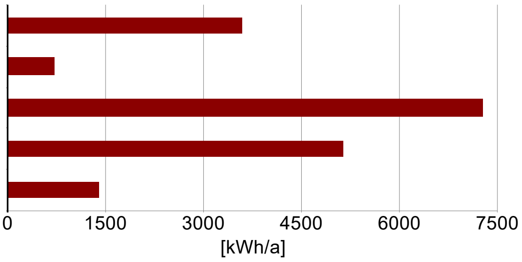
Average SHGC:	**0.5**	
Average solar reduction factor heating:	**0.44**	
Average solar reduction factor cooling:	**0.41**	
Average U-value:	**0.742**	W/m²K
Total glazing area:	**28**	m²
Total window area:	**39.7**	m²

Heat gain/loss heating period:



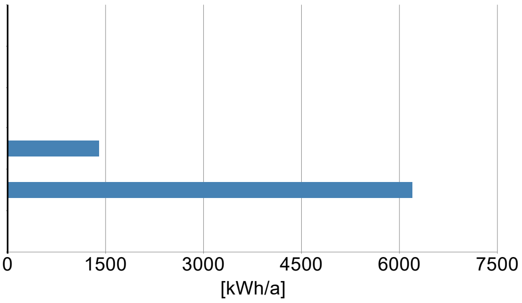
HVAC

Total heating demand:	**3,590**	kWh/a
Total cooling demand:	**716**	kWh/a
Total DHW energy demand:	**7,294**	kWh/a
Solar DHW contribution:	**5,132**	kWh/a
Auxiliary electricity:	**1,402**	kWh/a



Electricity

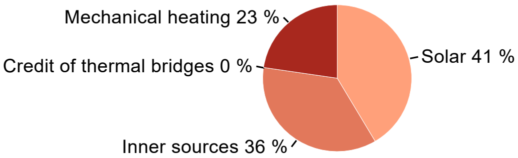
Direct heating / DHW:	**0**	kWh/a
Heatpump heating:	**0**	kWh/a
Cooling:	**0**	kWh/a
HVAC auxiliary energy:	**1,402**	kWh/a
Appliances:	**6,211**	kWh/a
Renewable generation, coincident production and use:	**0**	kWh/a
Total electricity demand:	**7,613**	kWh/a



HEAT FLOW - HEATING PERIOD

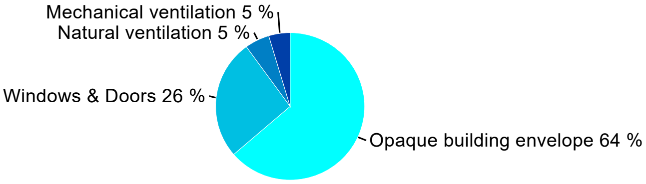
Heat gains

Solar:	**4,779**	kWh/a
Inner sources:	**4,128**	kWh/a
Credit of thermal bridges:	**0**	kWh/a
Mechanical heating:	**3,279**	kWh/a



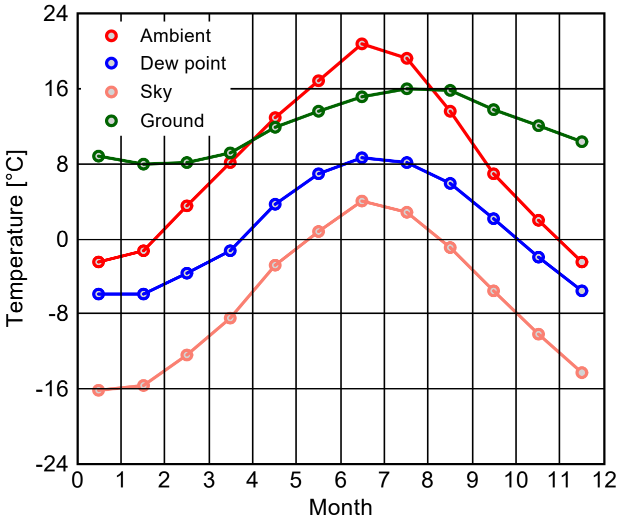
Heat losses

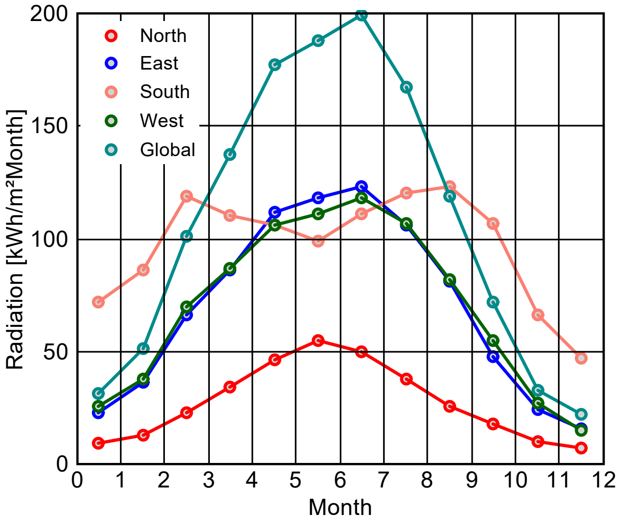
Opaque building envelope:	**7,761**	kWh/a
Windows & Doors:	**3,207**	kWh/a
Natural ventilation:	**652**	kWh/a
Mechanical ventilation:	**565**	kWh/a



CLIMATE

Latitude:	**50** °		**Ground**		
Longitude:	**-119.4** °		Average ground surface temperature:	**9.1**	°C
Elevation of weather station:	**430** m		Amplitude ground surface temperature:	**11.7**	°C
Elevation of building site:	**430** m		Ground thermal conductivity:	**2**	W/mK
Heat capacity air:	**0.33** Wh/m³K		Ground heat capacity:	**2**	MJ/m³K
Daily temperature swing summer:	**16.9** K		Depth below grade of groundwater:	**3**	m
Average wind speed:	**4** m/s		Flow rate groundwater:	**0.1**	m/d





Calculation parameters

Length of heating period	**273** days/a
Heating degree hours	**93.7** kKh/a
Phase shift months	**1.4** mths
Time constant heating demand	**118.1** h

Time constant cooling demand

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
69.2	69.2	69.2	69.2	69.2	69.2	69.2	69.2	69.2	69.2	69.2	69.2

Climate for	Heating load 1	Heating load 2	Cooling
Temperature [°C]	-12.3	-7.6	24
Solar radiation North [W/m²]	12	10	63
Solar radiation East [W/m²]	26	17	204
Solar radiation South [W/m²]	68	50	174
Solar radiation West [W/m²]	27	22	171
Solar radiation Global [W/m²]	35	27	309

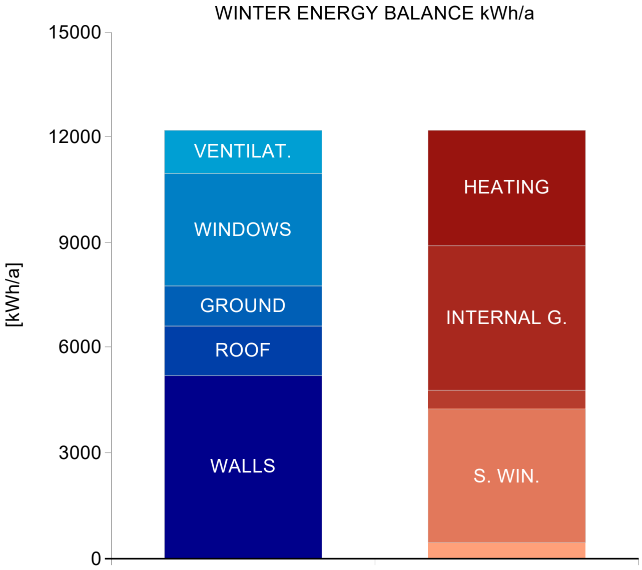
Relevant boundary conditions for heating load calculation: Heating load 1

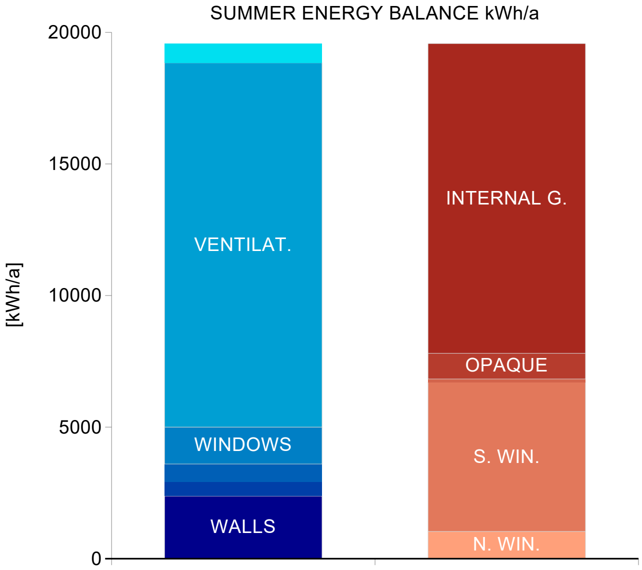
ANNUAL HEAT DEMAND

Transmission losses :	**10,968**	kWh/a
Ventilation losses:	**1,217**	kWh/a
Total heat losses:	**12,186**	kWh/a
Solar heat gains:	**6,004**	kWh/a
Internal heat gains:	**5,186**	kWh/a
Total heat gains:	**11,190**	kWh/a
Utilization factor:	**79.6**	%
Useful heat gains:	**8,906**	kWh/a
Annual heat demand:	**3,279**	kWh/a
Specific annual heat demand:	**13.3**	kWh/m²a

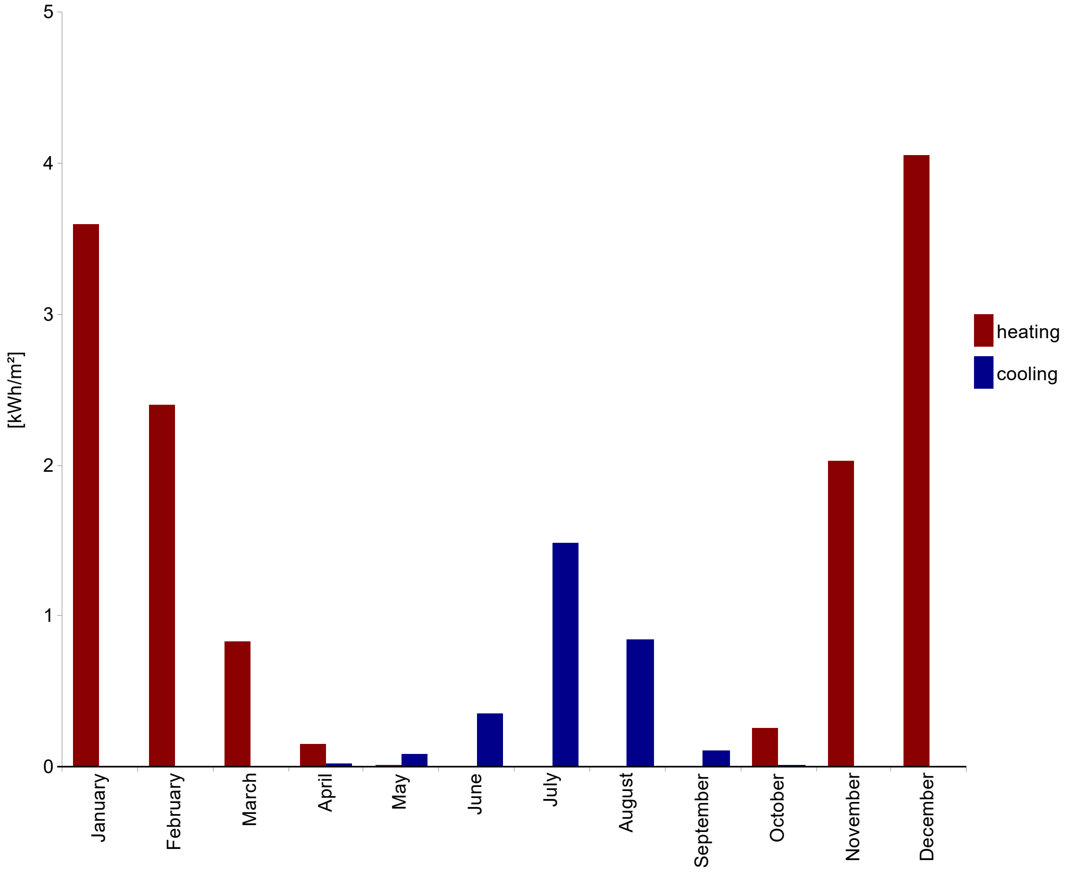
ANNUAL COOLING DEMAND

Solar heat gains:	**7,788**	kWh/a
Internal heat gains:	**11,770**	kWh/a
Total heat gains:	**19,558**	kWh/a
Transmission losses :	**14,620**	kWh/a
Ventilation losses:	**40,800**	kWh/a
Total heat losses:	**55,421**	kWh/a
Utilization factor:	**34**	%
Useful heat losses:	**18,843**	kWh/a
Cooling demand - sensible:	**716**	kWh/a
Cooling demand - latent:	**0**	kWh/a
Annual cooling demand:	**716**	kWh/a
Specific annual cooling demand:	**2.9**	kWh/m²a





SPECIFIC HEAT/COOLING DEMAND MONTHLY



Month	Heating [kWh/m²]	Cooling [kWh/m²]
January	3.6	0
February	2.4	0
March	0.8	0
April	0.1	0
May	0	0.1
June	0	0.4
July	0	1.5
August	0	0.8
September	0	0.1
October	0.3	0
November	2	0
December	4.1	0

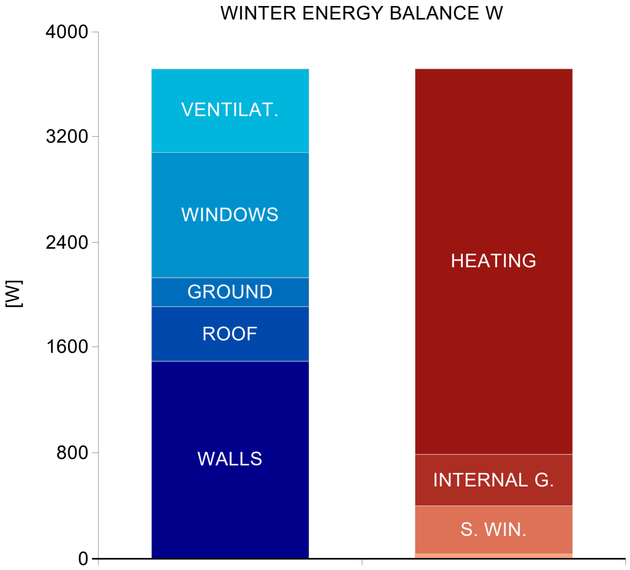
HEATING LOAD

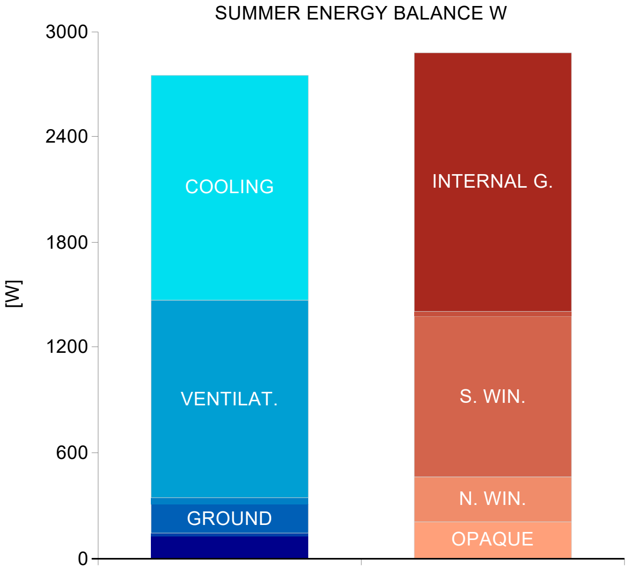
	First climate	Second climate
Transmission heat losses:	**3,083** W	**2,683.2** W
Ventilation heat losses:	**632.3** W	**543.4** W
Total heat loss:	**3,715.3** W	**3,226.6** W
Solar heat gain:	**399.7** W	**300.3** W
Internal heat gain:	**393.1** W	**393.1** W
Total heat gains heating:	**792.8** W	**693.4** W
Heating load:	**2,922.5** W	**2,533.2** W

Relevant heating load:	**2,922.5** W
Specific heating load:	**11.9** W/m²

COOLING LOAD

Solar heat gain:	**1,408.4** W
Internal heat gain:	**1,468.4** W
Total heat gains cooling:	**2,876.8** W
Transmission heat losses:	**469.1** W
Ventilation heat losses:	**1,130.6** W
Total heat loss:	**1,599.7** W
Cooling load - sensible:	**1,277** W
Cooling load - latent:	**0** W
Relevant cooling load:	**1,277** W
Specific maximum cooling load:	**5.2** W/m²





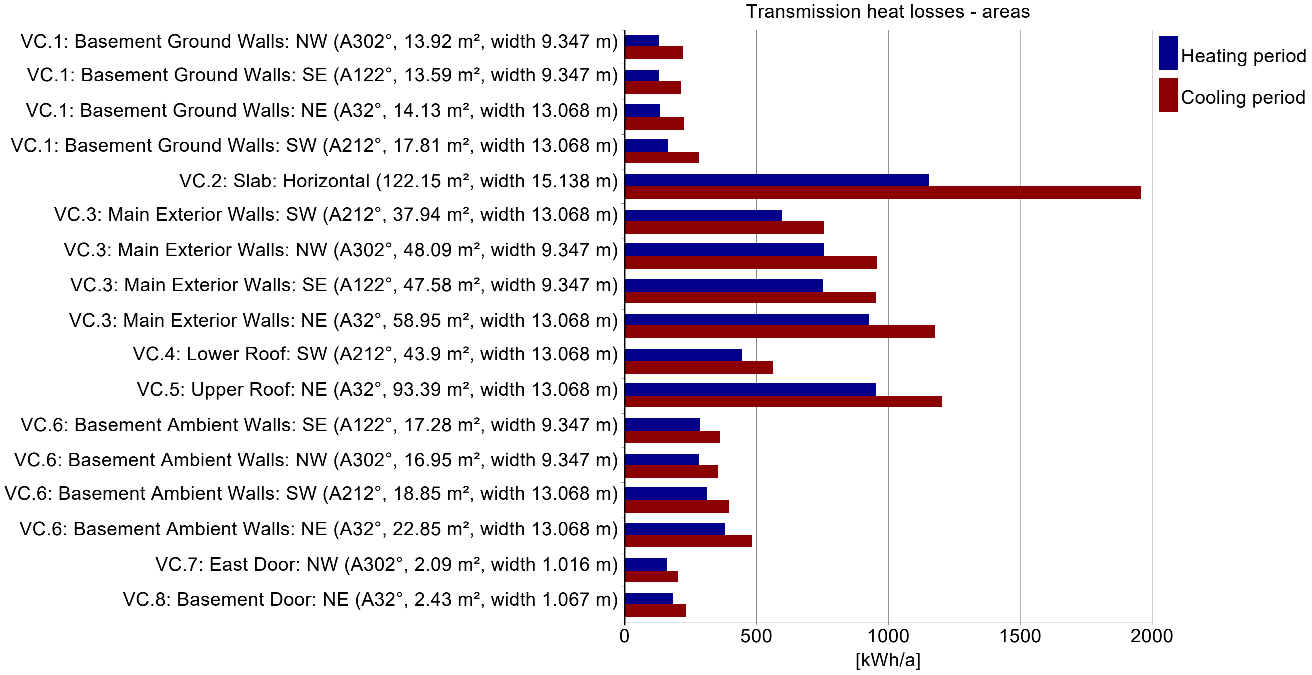
AREAS

Transmission heat losses - areas

Name	Area [m²]	Average U-value [W/m²K]	Absorption coefficient	Emission coefficient	Reduction factor shading [%]	Transmission losses heating [kWh/a]	Transmission losses cooling [kWh/a]
VC.1: Basement Ground Walls: NW (A302°, 13.92 m², width 9.347 m)	13.9	0.154	0	0	0	131.3	222.6
VC.1: Basement Ground Walls: SE (A122°, 13.59 m², width 9.347 m)	13.6	0.154	0	0	0	128.2	217.3
VC.1: Basement Ground Walls: NE (A32°, 14.13 m², width 13.068 m)	14.1	0.154	0	0	0	133.4	226
VC.1: Basement Ground Walls: SW (A212°, 17.81 m², width 13.068 m)	17.8	0.154	0	0	0	168	284.8
VC.2: Slab: Horizontal (122.15 m², width 15.138 m)	122.2	0.154	0	0	0	1157	1961
VC.3: Main Exterior Walls: SW (A212°, 37.94 m², width 13.068 m)	37.9	0.145	0.4	0.9	100	598.7	757.8
VC.3: Main Exterior Walls: NW (A302°, 48.09 m², width 9.347 m)	48.1	0.145	0.4	0.9	100	758.8	960.5
VC.3: Main Exterior Walls: SE (A122°, 47.58 m², width 9.347 m)	47.6	0.145	0.4	0.9	100	750.8	950.3
VC.3: Main Exterior Walls: NE (A32°, 58.95 m², width 13.068 m)	59	0.145	0.4	0.9	100	930.2	1177.5
VC.4: Lower Roof: SW (A212°, 43.9 m², width 13.068 m)	43.9	0.094	0.4	0.9	100	446.6	565.3
VC.5: Upper Roof: NE (A32°, 93.39 m², width 13.068 m)	93.4	0.094	0.4	0.9	100	950.1	1202.6
VC.6: Basement Ambient Walls: SE (A122°, 17.28 m², width 9.347 m)	17.3	0.153	0.4	0.9	100	287.3	363.6
VC.6: Basement Ambient Walls: NW (A302°, 16.95 m², width 9.347 m)	16.9	0.153	0.4	0.9	100	281.8	356.7
VC.6: Basement Ambient Walls: SW (A212°, 18.85 m², width 13.068 m)	18.9	0.153	0.4	0.9	100	313.5	396.8
VC.6: Basement Ambient Walls: NE (A32°, 22.85 m², width 13.068 m)	22.9	0.153	0.4	0.9	100	380	481
VC.7: East Door: NW (A302°, 2.09 m², width 1.016 m)	2.1	0.703	0.4	0.9	100	159.9	202.4
VC.8: Basement Door: NE (A32°, 2.43 m², width 1.067 m)	2.4	0.703	0.4	0.9	100	185.5	234.8

Degree hours [kKh/a]

	Heating	Cooling
Ambient heating	108.8	137.7
Ground heating	61.3	104



THERMAL BRIDGES

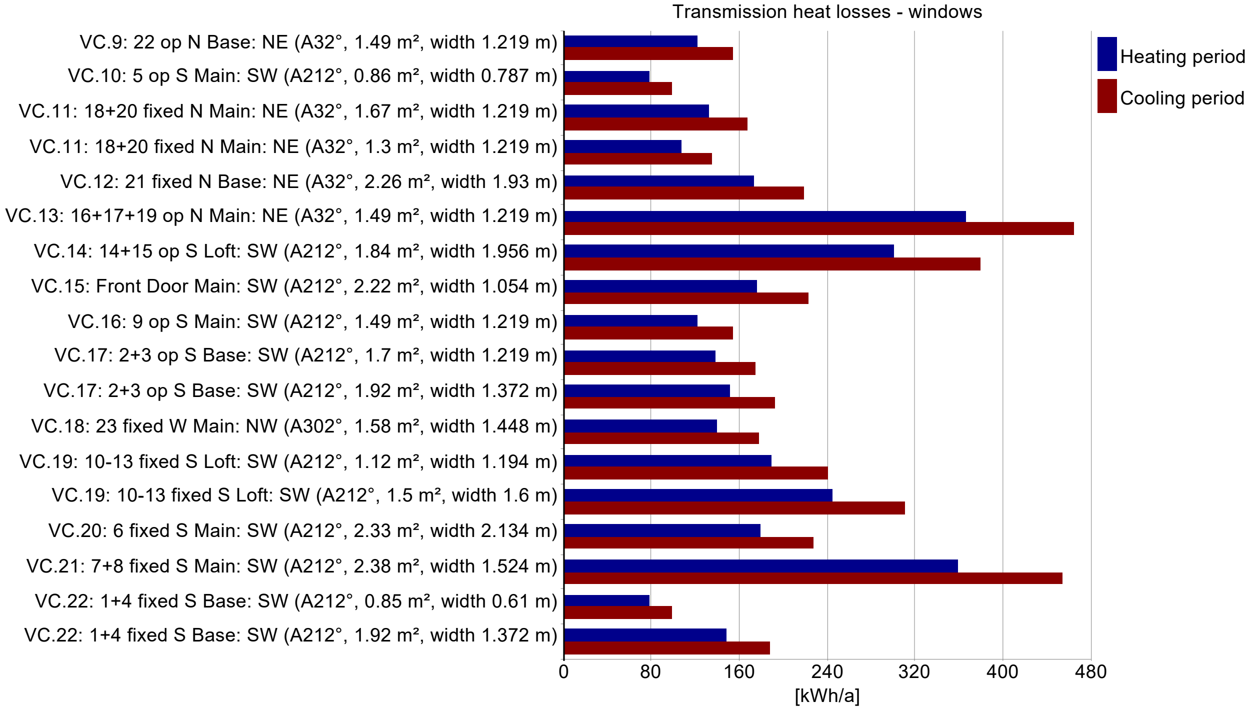
Transmission heat losses - thermal bridges

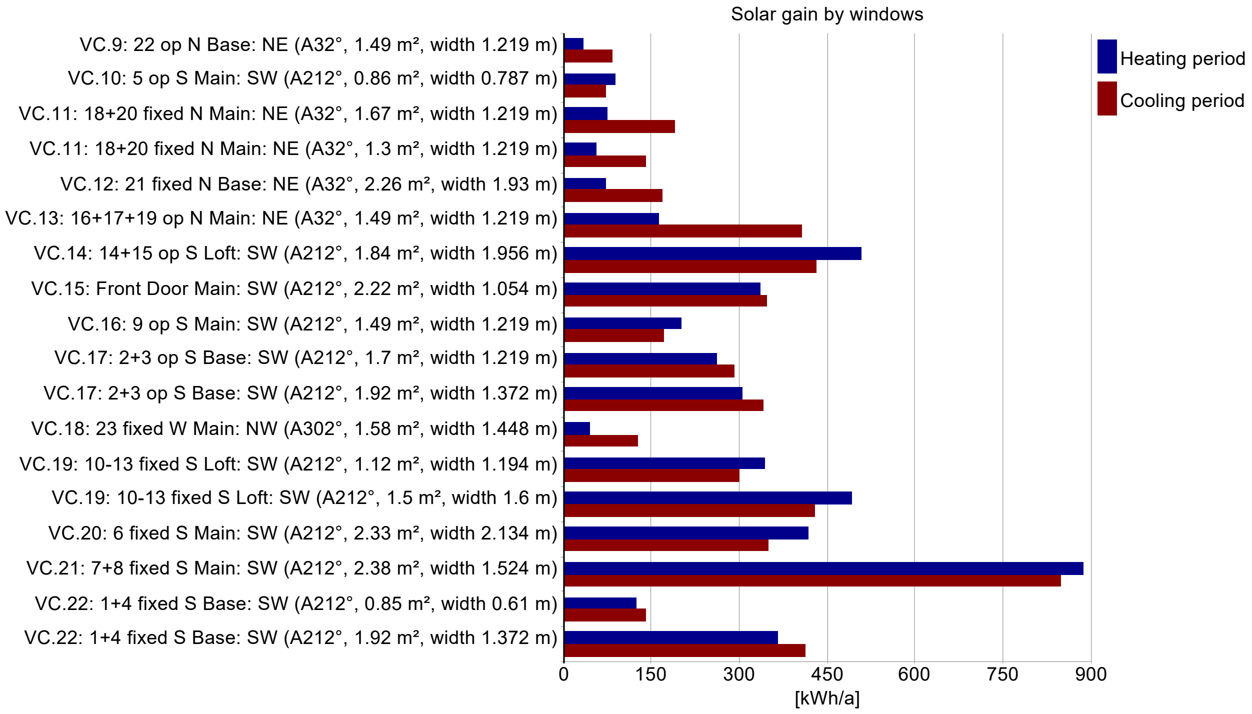
Name	Length [m]	Psi-value [W/mK]	Transmission losses [kWh/a]	Transmission losses cooling [kWh/a]

WINDOWS

Transmission heat losses - windows

Name	Quan-tity	Incli-nation [°]	U-value total [W/m²K]	SHGC (perpen-dicular)	Reduction factor shading [%]	Reduction factor shading summer [%]	Solar gain heating [kWh/a]	Solar gain cooling [kWh/a]	Transmission losses heating [kWh/a]	Transmission losses cooling [kWh/a]
VC.9: 22 op N Base: NE (A32°, 1.49 m², width 1.219 m)	1	90	0.757	0.5	54.8	55.6	34.8	82.6	122.3	154.8
VC.10: 5 op S Main: SW (A212°, 0.86 m², width 0.787 m)	1	90	0.832	0.5	73.1	50.3	89.7	73.3	77.8	98.5
VC.11: 18+20 fixed N Main: NE (A32°, 1.67 m², width 1.219 m)	1	90	0.729	0.5	86.1	92.3	76.4	191.3	132.6	167.8
VC.11: 18+20 fixed N Main: NE (A32°, 1.3 m², width 1.219 m)	1	90	0.758	0.5	84.6	91.3	56.1	141.7	107.2	135.7
VC.12: 21 fixed N Base: NE (A32°, 2.26 m², width 1.93 m)	1	90	0.705	0.5	57.9	58.1	71.4	167.5	172.9	218.9
VC.13: 16+17+19 op N Main: NE (A32°, 1.49 m², width 1.219 m)	3	90	0.757	0.5	84.7	91.4	161.7	407.4	367	464.5
VC.14: 14+15 op S Loft: SW (A212°, 1.84 m², width 1.956 m)	2	90	0.75	0.5	78.7	56.2	507.6	430.8	300	379.7
VC.15: Front Door Main: SW (A212°, 2.22 m², width 1.054 m)	1	90	0.728	0.5	81.9	71.2	336.3	347.1	175.9	222.6
VC.16: 9 op S Main: SW (A212°, 1.49 m², width 1.219 m)	1	90	0.757	0.5	78.2	56	201.2	171.2	122.3	154.8
VC.17: 2+3 op S Base: SW (A212°, 1.7 m², width 1.219 m)	1	90	0.742	0.5	85.5	80.2	260.8	290.7	137.4	174
VC.17: 2+3 op S Base: SW (A212°, 1.92 m², width 1.372 m)	1	90	0.729	0.5	86.3	80.9	305.2	339.9	151.9	192.2
VC.18: 23 fixed W Main: NW (A302°, 1.58 m², width 1.448 m)	1	90	0.813	0.6	28.5	38.1	44.3	127.1	139.8	177
VC.19: 10-13 fixed S Loft: SW (A212°, 1.12 m², width 1.194 m)	2	90	0.778	0.5	76.2	56.1	343.7	300.7	189.9	240.3
VC.19: 10-13 fixed S Loft: SW (A212°, 1.5 m², width 1.6 m)	2	90	0.749	0.5	78.5	57.6	493	430.1	245.2	310.3
VC.20: 6 fixed S Main: SW (A212°, 2.33 m², width 2.134 m)	1	90	0.707	0.5	81	57.3	416.8	350.2	179.1	226.7
VC.21: 7+8 fixed S Main: SW (A212°, 2.38 m², width 1.524 m)	2	90	0.693	0.5	82.9	66.7	887	847.5	359	454.4
VC.22: 1+4 fixed S Base: SW (A212°, 0.85 m², width 0.61 m)	1	90	0.843	0.5	80.1	76.6	124.5	141.6	78.1	98.8
VC.22: 1+4 fixed S Base: SW (A212°, 1.92 m², width 1.372 m)	1	90	0.714	0.5	87.3	82.8	365.7	412.3	148.9	188.4





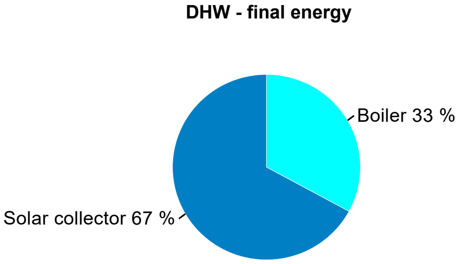
Summary building envelope

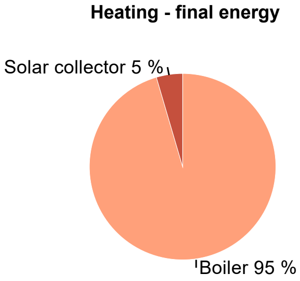
	Total area / length	Average U-value / Psi value	Transmission losses
Exterior wall ambient:	**273** m²	**0.156** W/m²K	**4,646.4** kWh/a
Exterior wall ground:	**59.4** m²	**0.154** W/m²K	**560.9** kWh/a
Basement:	**122.2** m²	**0.154** W/m²K	**1,157** kWh/a
Roof:	**137.3** m²	**0.094** W/m²K	**1,396.7** kWh/a
Windows:	**39.7** m²	**0.742** W/m²K	**3,207.3** kWh/a
Doors:	**0** m²	**0** W/m²K	**0** kWh/a
Thermal bridge ambient:	**0** m	**0** W/mK	**0** kWh/a
Thermal bridge perimeter:	**0** m	**0** W/mK	**0** kWh/a
Thermal bridge floor slab:	**0** m	**0** W/mK	**0** kWh/a

Shading

	Heating	Cooling
Reduction factor North:	**75.2** %	**79.5** %
Reduction factor East:	**100** %	**100** %
Reduction factor South:	**81.2** %	**65.3** %
Reduction factor West:	**28.5** %	**38.1** %
Reduction factor Horizontal:	**100** %	**100** %

System	DHW			Heating			Total		
	Covered DHW demand [%]	Estimated solar fraction [%]	Final energy demand [kWh/a]	Covered heating demand [%]	Estimated solar fraction [%]	Final energy demand [kWh/a]	Performance ratio	CO2 equivalent emissions [kg/a]	Source energy demand [kWh/a]
Boiler, Example Boiler	100	70.4	2,517.7	100	4.6	3,481.4	1.1	1,499.8	6,599.1
Solar collector, Example Solar Collector	0	0	5,131.6	0	0	165.6	0	0	0
Σ	100	70.4	7,649.3	100	4.6	3,647		1,499.8	6,599.1





Boiler

Boiler type: **Gas**

Condensing: **yes**

In thermal envelope: **yes**

Boiler output: **10** kW

Efficiency at 30% load: **99** %

Efficiency at normal output: **93** %

Heatloss at 70°C standby: **1.7** %

VENTILATION

Infiltration pressure test ACH50:	**0.3** 1/h
Total extract air demand:	**300** m³/h
Supply air per person:	**30** m³/h
Occupancy:	**6**

Average air flow rate:	**168** m³/h
Average air change rate:	**0.19** 1/h
Effective ACH ambient:	**0.03** 1/h
Effective ACH ground:	**0.01** 1/h
Energetically effective air exchange:	**0.04** 1/h
Infiltration air change rate:	**0.02** 1/h
Infiltration air change rate (heating load):	**0.05** 1/h

Type of ventilation system:	**Balanced PH ventilation**
Wind screening coefficient (e):	**0.07**
Wind exposure factor:	**15**
Wind shield factor:	**0.05**

Ventilation heat losses: **1,044.76** kWh/a

Devices

Name	HRV / ERV efficiency [-]	Electric efficiency [Wh/m³]	Heat recovery efficiency SHX [-]	Effective recovery efficiency [-]
Main Floor HRV	0.9	0.42	0.3	0.9
Basement Suite HRV	0.9	0.42	0.3	0.9
Altogether	0.9	0.42	0.1	0.9

Ducts

Name	Length (total) [m]	Clear cross-section [m²]	U-value [W/m²K]	Assigned ventilation units
Supply / outdoor air duct	2	0.0324	9.14	Main Floor HRV, Basement Suite HRV
Extract / Exhaust air duct	2	0.0324	9.14	Main Floor HRV, Basement Suite HRV
Σ	4			

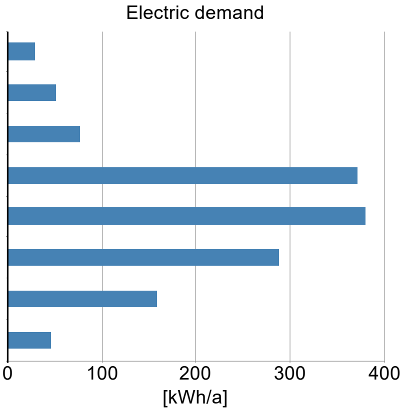
*length * quantity ** thermal conductivity / thickness

SUMMER VENTILATION

ACH night ventilation:	**0.3** 1/h
ACH natural summer:	**0.03** 1/h
Mechanical ventilation summer:	**0.3** 1/h
Mechanical ventilation summer with HR:	**no**
Preferred minimum indoor temperature for night ventilation:	**20** °C
Overheating temperature:	**25** °C

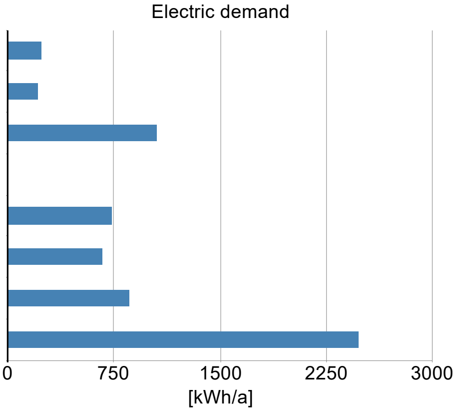
ELECTRICITY DEMAND - AUXILIARY ELECTRICITY

Type	Quantity	Indoor	Norm demand	Electric demand [kWh/a]	Source energy [kWh/a]
Boiler DHW system auxiliary energy	1	yes	136 W	29.4	92.9
Boiler heating auxiliary energy	1	yes	45 W	51.4	162.3
Solarcollector auxiliary energy	1	no	44 W	77	243.3
Ventilation winter	1	yes	0.4 Wh/m³	371.7	1174.6
Ventilation summer	1	yes	0.4 Wh/m³	380.4	1202.1
Heating system circulation pump	1	yes	73.4 W	288.5	911.5
DHW circulating pump	1	yes	29.7 W	157.6	497.9
DHW storage load pump	1	yes	63.7 W	46.5	146.8
Σ				1402.4	4431.6



ELECTRICITY DEMAND RESIDENTIAL BUILDING

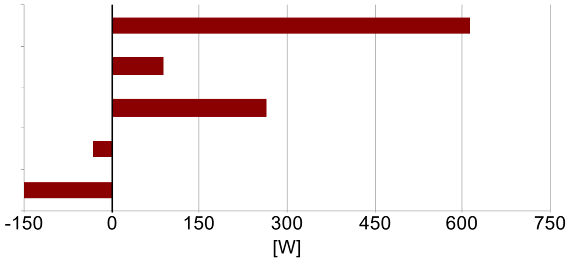
Type	Quantity	Indoor	Norm demand	Electric demand [kWh/a]	Non-electric demand [kWh/a]	Source energy [kWh/a]
Kitchen dishwasher	1	yes	1.2	234	146.8	901
Laundry - washer	1	yes	1.1	206.9	85.8	748.2
Laundry - dryer	1	yes	3.5	1047.4	0	3309.7
Energy consumed by evaporation	0	yes	3.1	0	213.1	234.4
Kitchen fridge/freeze combo	2	yes	1	730	0	2306.8
Kitchen cooktop	1	yes	0.2	660	0	2085.6
PHIUS+ 2015 Interior lighting	1	yes	856	856	0	2704.9
PHIUS+ 2015 Misc electric loads	1	yes	2,476.5	2476.5	0	7825.9
Σ	8			6210.8	445.7	20116.5



INTERNAL HEAT GAINS

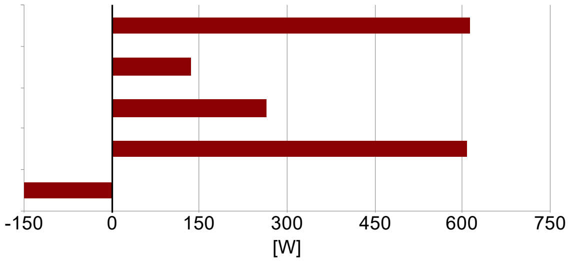
Heating season

Electricity total:	**614** W
Auxiliary electricity:	**89.7** W
People:	**264** W
Cold water:	**-31.6** W
Evaporation:	**-150** W
Σ:	**791.5** W
Specific internal heat gains:	**3.2** W/m²



Cooling season

Electricity total:	**614** W
Auxiliary electricity:	**134.2** W
People:	**264** W
Cold and hot water:	**608.6** W
Evaporation:	**-150** W
Σ:	**791.5** W
Specific internal heat gains:	**3.2** W/m²



DHW AND DISTRIBUTION

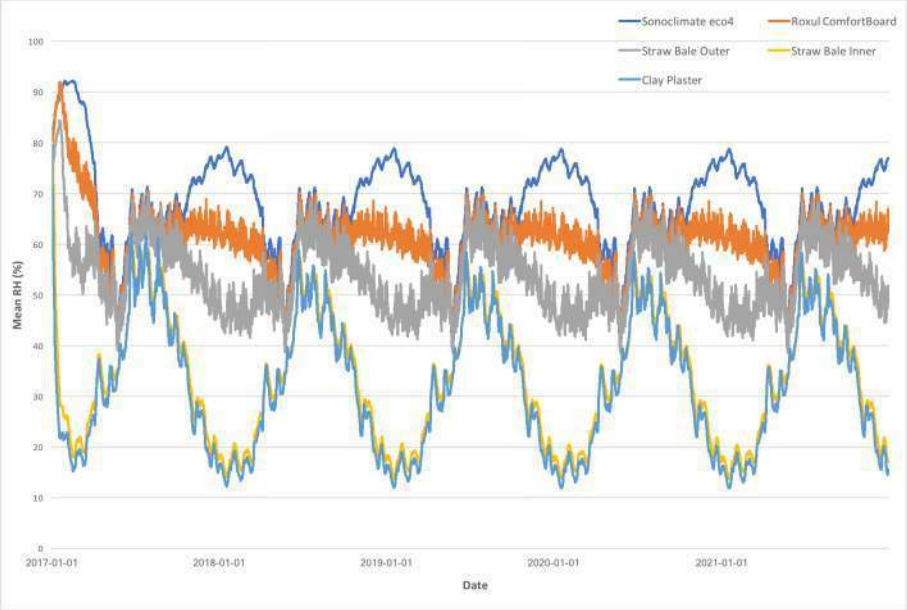
DHW consumption per person per day:	**25** Ltr/Person/day
Average cold water temperature supply:	**5.4** °C
Useful heat DHW:	**3,949.6** kWh/a
Specific useful heat DHW:	**16.1** kWh/m²a
Total heat losses of the DHW system:	**3,344.1** kWh/a
Specific losses of the DHW system:	**13.6** kWh/m²a
Performance ratio DHW distribution system and storage:	**1.8**
Utilization ratio DHW distribution system and storage:	**0.5**
Total heat demand of DHW system:	**7,293.7** kWh/a
Total specific heat demand of DHW system:	**29.7** kWh/m²a
Total heat losses of the hydronic heating distribution:	**310.8** kWh/a
Specific losses of the hydronic heating distribution:	**1.3** kWh/m²a
Performance ratio of heat distribution:	**109.5** %

Region	Length [m]	Annual heat loss [kWh/a]
Hydronic heating distribution pipes		
In conditioned space	39.6	310.8
Σ	39.6	310.8
DHW circulation pipes		
In conditioned space	99.1	2198.6
Σ	99.1	2198.6
Individual pipes		
In conditioned space	49.5	497.7
Σ	49.5	497.7
Water storage		
Device 5 (Water storage: DHW)		647.8
Σ		647.8

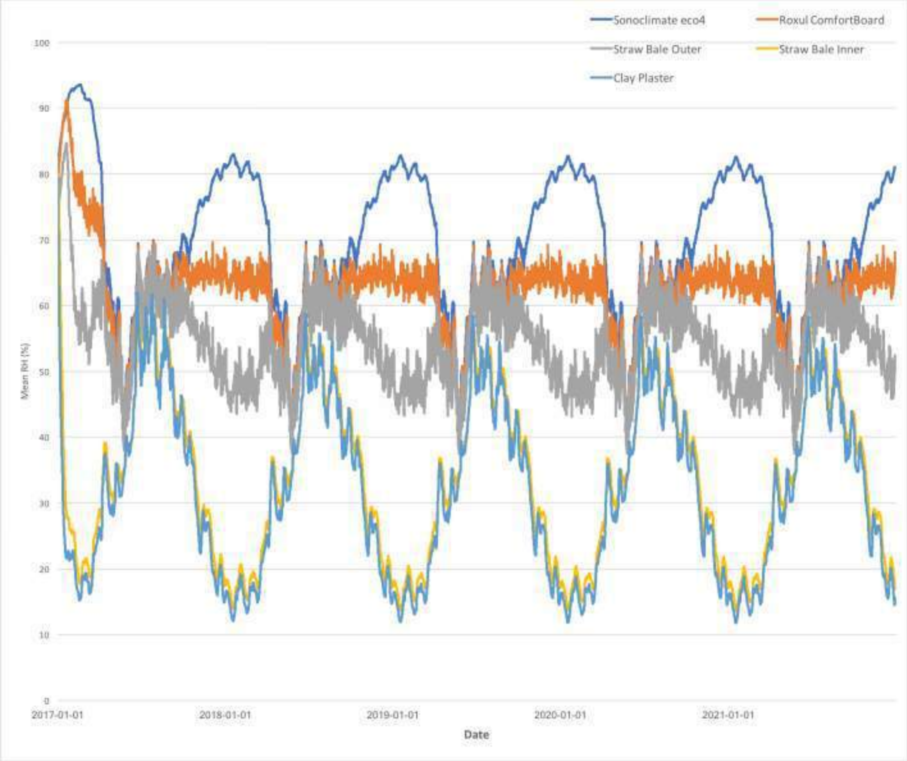
SOLAR DHW

Name	Area of solar thermal array [m²]	Solar thermal yield [kWh/m²a]	Useful storage capacity [Liter]	Optimal storage capacity [Liter]	Reduction factor shading [-]	Estimated solar fraction of DHW [-]	Contribution to useful heat [kWh/m²a]
Device 4 (Solar collector: Heating, DHW): Example Solar Collector	11	546	700	825	1	0.704	5,131.56
Σ	11	546	700	825		0.7	5131.6

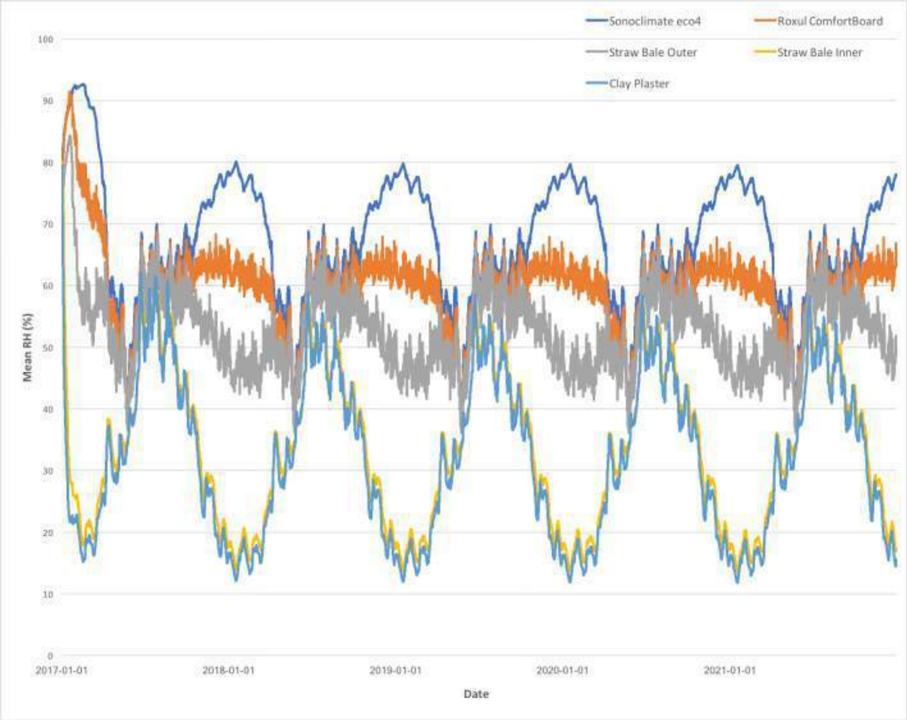
Appendix IV: Plots from Hygrothermal Analysis



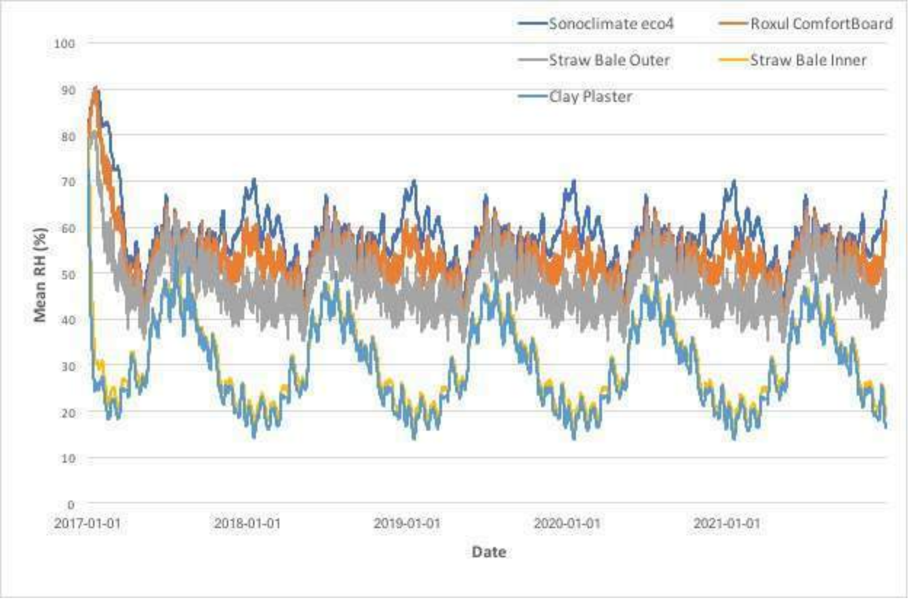
Saskatoon SW Wall



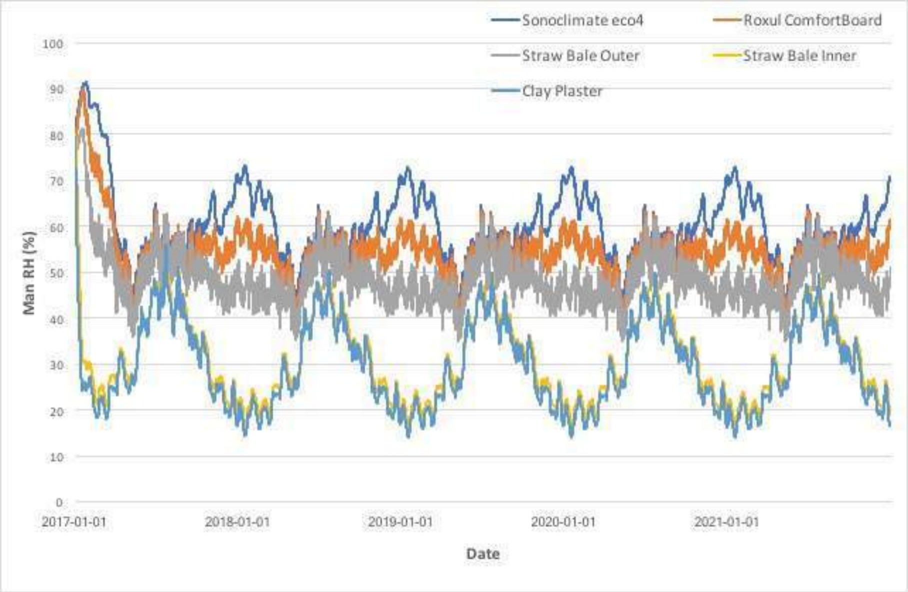
Saskatoon NW Wall



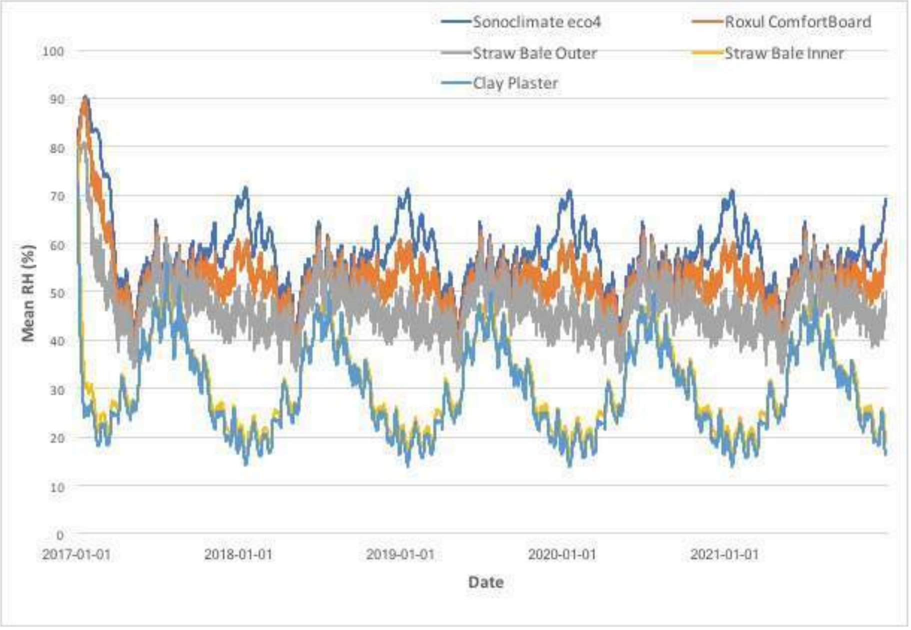
Saskatoon SE Wall



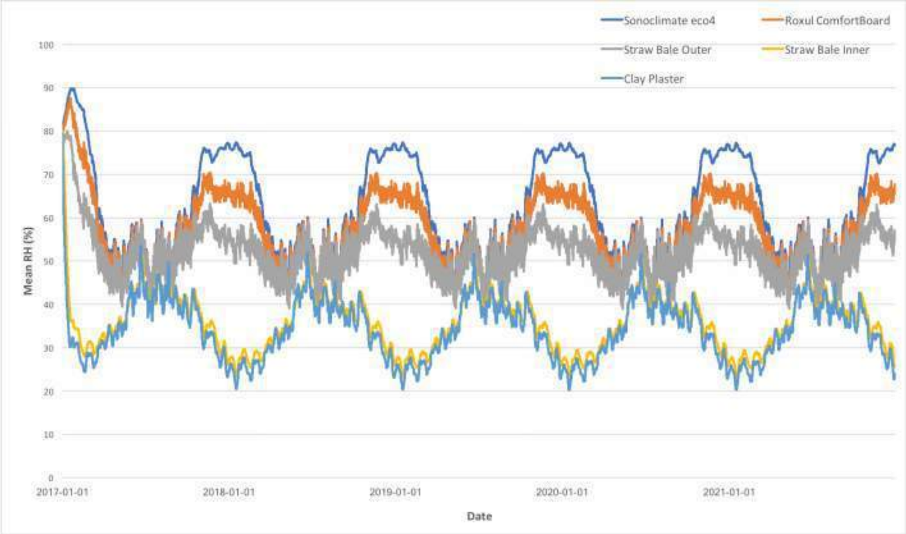
Calgary SW Wall



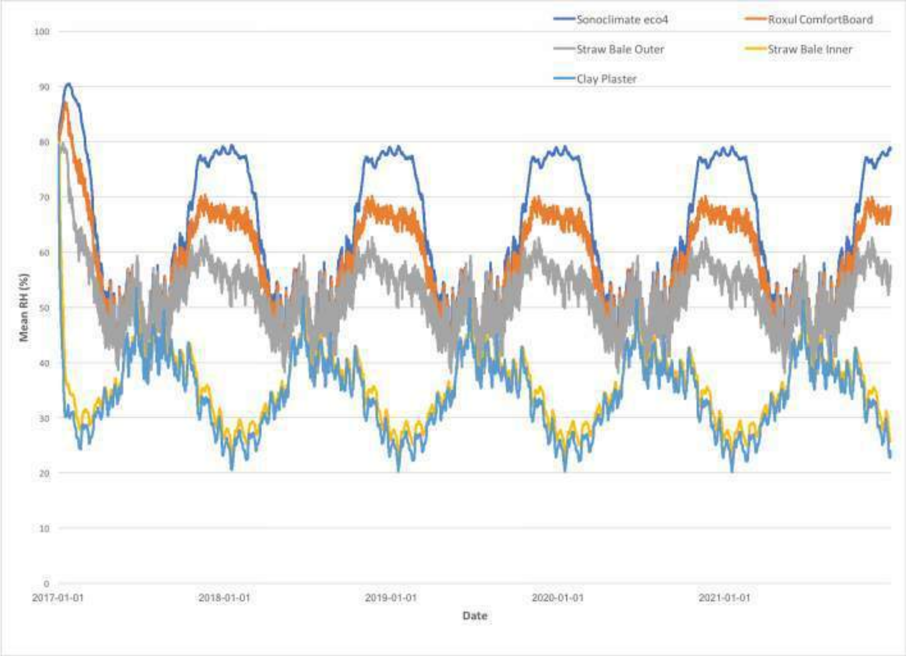
Calgary NW Wall



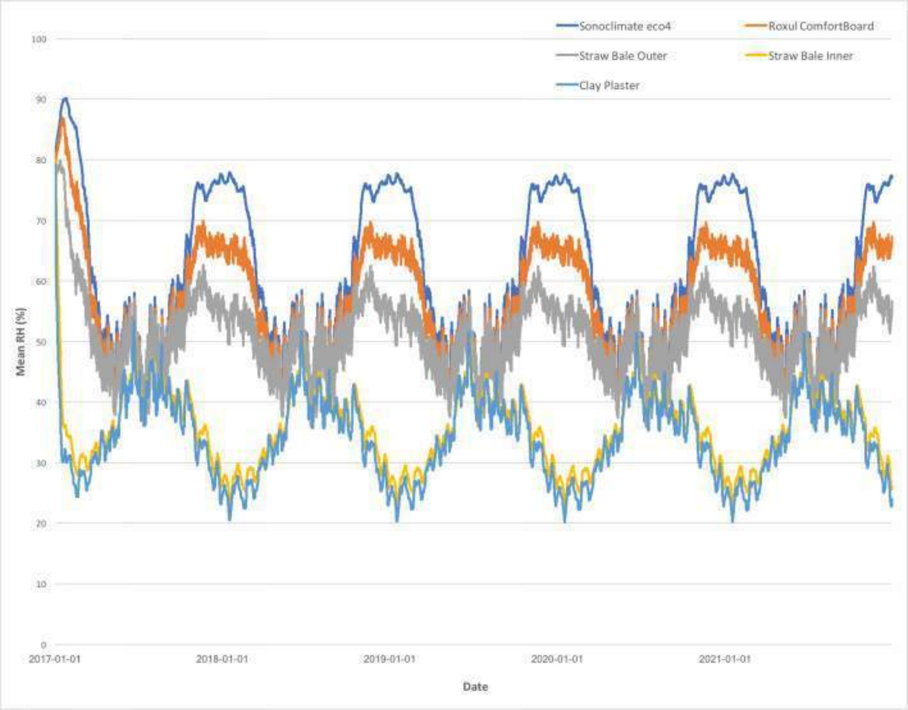
Calgary SE Wall



Kelowna SW Wall



Kelowna NW Wall



Kelowna SE Wall

Appendix V: WUFI PASSIVE OUTPUT WITH ADJUSTED OCCUPANCY

WUFI Passive output showing impact of the proposed straw bale assembly adapted to reference house for two occupancy scenarios (6 occupants corresponds to the ‘as-designed’ home with the secondary suite, while 5 occupants corresponds to the same home without a secondary suite - the additional kitchen and HRV unit were removed, and occupant loads were adjusted to reflect the change) for the select cities (compared to the ‘as designed’ and PHIUS+ 2015 targets). Targets that are not satisfied are highlighted.

Saskatoon					
Metric	Target	Straw bale 6 occupants		Straw bale 5 occupants	
		Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	28.39	27.3	4.0	28.96	-2.0%
Annual Cooling Demand (kWh/m^{2}a)	3.15	2	57.5	1.72	83.1%
Peak Heating Load (W/m^2)	19.24	17.71	8.6	17.80	8.1%
Peak Cooling Load (W/m^2)	11.67	4.45	162.2	4.07	186.7%
Source Energy Demand (kWh/person•yr)	6,200	5605	10.6	6275	-1.2%
Calgary					
Metric	Target	Straw bale 6 occupants		Straw bale 5 occupants	
		Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	27.13	16.63	63.1	20.45	32.7
Annual Cooling Demand (kWh/m^{2}a)	3.15	2.16	45.8	1.69	86.4
Peak Heating Load (W/m^2)	19.24	15.86	21.3	15.93	20.8
Peak Cooling Load (W/m^2)	10.41	2.86	264.0	2.17	379.7
Source Energy Demand (kWh/person•yr)	6200	5892	5.2	5874	5.5
Kelowna					
Metric	Target	Straw bale 6 occupants		Straw bale 5 occupants	
		Output	% Below Target	Output	% Below Target
Annual Heating Demand (kWh/m^{2}a)	21.77	13.35	63.1	14.68	48.3
Annual Cooling Demand (kWh/m^{2}a)	3.15	2.91	8.2	2.52	25.0
Peak Heating Load (W/m^2)	15.77	11.89	32.6	11.95	32.0
Peak Cooling Load (W/m^2)	11.99	5.2	130.6	4.80	149.8
Source Energy Demand (kWh/person•yr)	6200	5109	21.4	5653	9.7

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