Deep Energy Retrofit of Court Low-Rise Residence Buildings

Final Report

Prepared by: EMBODY Consulting
Prepared for: University of Waterloo

April 1st, 2022

200 University Avenue West
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April 1st, 2022

Dr. Bruce Hellinga
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Dear Dr. Hellinga:

This final report, entitled "Deep Energy Retrofit of Court Low-Rise Residence Buildings Final Report" was prepared for our client in accordance with the requirements of Deliverable 5 for CivE 401. This report outlines the approach that our team took to develop the best design for the deep energy retrofit project.

EMBODY Consulting specializes in building science, specifically the efficiency of building enclosures. We perform research on rising trends in the industry and provide consultation services to clients wishing to build new energy efficient buildings or to improve the performance of existing buildings. Our projects are completed in accordance with various building energy performance guidelines.

The team has completed Phase II of this project in accordance with the client's objectives and a high performing building enclosure design was produced. EMBODY Consulting is now prepared to deliver the detailed design to the client for implementation.

This report was written entirely by team 10, EMBODY Consulting, and has not received any previous academic credit at the University of Waterloo or any other academic institution. We would like to acknowledge Professor Costa Kapsis, who advised us when making technical decisions and reviewed our report. We received no other help with this proposal.

Best Regards,

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Summary

EMBODY Consulting was hired by the University of Waterloo to perform a deep energy retrofit of the Courts residence buildings. These buildings have reached the end of their enclosure service life and they demonstrate very poor performance. They waste a significant amount of energy, and the indoor conditions can be uncomfortable for occupants. This project will play an important role in meeting the university's goal of carbon neutrality by 2050.

EMBODY Consulting designed an exterior enclosure retrofit based on the following objectives: (1) reduce energy consumption and achieve Net-Zero-ready performance targets, (2) perform a brief analysis on integrated renewable energy resources to achieve Net-Zero Energy performance and, (3) enhance occupant comfort and maximize thermal resiliency. This project was split into two phases; in Phase I, a preliminary enclosure design was developed and in Phase II a detailed design solution was formulated for the retrofit project. In Phase I, three enclosure design alternatives were generated and energy modeling was performed to select the design with the most optimal thermal resistance values and costs. In Phase II materials were selected to achieve the thermal resistance values selected in Phase I. Hygrothermal and thermal modeling were performed to confirm the effectiveness of the design and the whole building energy model from Phase I was updated for the completed assembly designs. Next a future climate analysis was performed to confirm the durability of the design as climate change progresses. A solar potential analysis was also completed to ensure Net-Zero performance can be reached.

The final design has the following upgraded components: window U-factor of 0.85 USI (U-0.15), wall R-value of 3.5 RSI (R-20), roof R-value of 7.0 RSI (R-40) and external shading on southeast and southwest-facing windows. It was found that the total energy use intensity of the building can be reduced by 70% and thermal autonomy was reduced by 23% compared to the existing building. This is a large enough reduction that the entire energy consumption of the building can be offset by onsite solar generation in the form of roof and ground mounted PV systems to achieve Net-Zero Energy performance.

Acknowledgements

EMBODY Consulting would like to recognize the external parties that assisted in the delivery of this project. Professor Costa Kapsis was the team's technical advisor, and he provided the team with guidance and reference materials. Two of the University of Waterloo facility managers, Reuben Grin and Wade MacAulay provided the team with drawings and additional information on the existing building. EMBODY Consulting is very grateful to these parties for their help.

Contents

List of Figures

List of Tables

List of Appendices

1 Introduction

Buildings account for 40% of greenhouse gas (GHG) emissions globally and 17% within Canada (Architecture 2030, 2021; Natural Resources Canada, 2017). Deep energy retrofits are essential to reduce GHG emissions of the aging building infrastructure in Canada and have the potential to save up to 60% in energy costs (Natural Resources Canada, 2019). The University of Waterloo (UW) has a plan to achieve carbon neutrality by 2050 and has committed to improving its buildings' energy efficiency through a climate action plan (University of Waterloo, 2018). Currently, the UW has several old, poor performing buildings that provide prime opportunities for deep energy retrofits and the reduction of energy consumption, peak demand and GHG emissions.

EMBODY Consulting is performing a deep energy retrofit analysis on the building enclosure of the Court low-rise residence buildings (hereinafter referred to as "Court buildings"). The goals are to (1) reduce energy consumption and achieve Net-Zero-ready performance targets, (2) perform a brief analysis on integrated renewable energy resources to achieve Net-Zero Energy performance and, (3) enhance occupant comfort and maximize thermal resiliency.

1.1 Background

The Court buildings are located on the southeast side of the UW campus. They are bounded by University Avenue to the North, Lester Street to the East, Seagram Drive to the South and Laurel Trail to the West as shown in Figure 1.

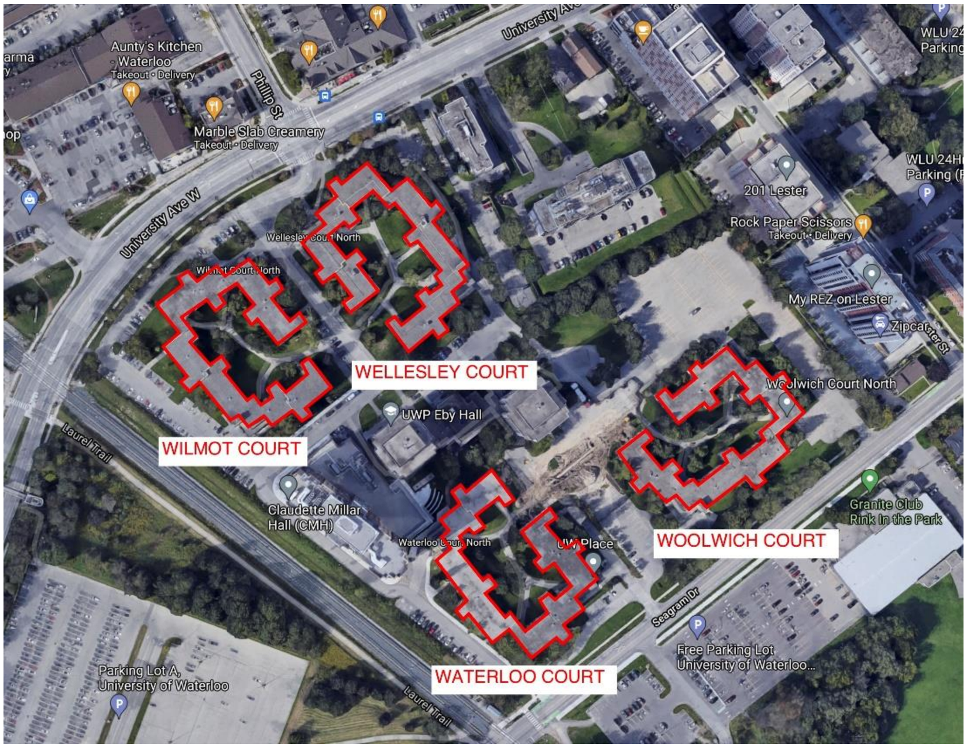

Figure 1: Location of court residence buildings

The four Court buildings are comprised of Wilmot Court, Wellesley Court, Waterloo Court and Woolwich Court. Each building contains 84 units with a capacity of three students per unit. The buildings were constructed in 1969 and renovated in 2000. The local climate consists of warm, humid summers and cold winters, categorized as Climate Zone 5A under ASHRAE standards (ASHRAE, 2019). An energy audit of the buildings was completed in December of 2020 by WalterFedy which highlighted the poor performance of the existing building. EMBODY Consulting was invited to perform a deep energy retrofit analysis and design, aiming to: (1) decrease the energy costs for the building, (2) reduce the maintenance requirements, (3) improve the interior environment to be more comfortable for the occupants and (4) reduce the environmental footprint of the building.

1.2 Scope

The project was split into two phases: **Phase I: Preliminary Enclosure Design; Spring 2021** and **Phase II: Detailed Enclosure Design and Renewable Energy Analysis; Winter 2022**. The scope of Phase I was to generate building enclosure design alternatives utilizing energy models and select the best design based on Key Performance Indicators (KPIs). The scope of Phase II – the focus of this report – was to design an enclosure to achieve the thermal resistances selected in Phase I and perform hygrothermal and thermal modelling on the assemblies. A brief analysis of solar PVs on the roof and in the parking lot was completed to ensure that a Net-Zero building is achievable. The present report focuses on Phase II of this project; for information regarding the preliminary enclosure design from Phase I, reference *Deep Energy Retrofit of Court Low-Rise Residence Buildings Phase I Final Report* (EMBODY Consulting, 2021). EMBODY Consulting has completed the following deliverables in Phase II:

Phase II: Detailed Enclosure Design and Renewable Energy Analysis:

1. A drawing package and installation procedures for components of the final design;
2. A final report detailing the features of the final enclosure design.

The analysis and design were performed for one of the four Court buildings, the Waterloo Court, and it is applicable to the other three buildings due to their similar layouts. There are no requirements for structural repair and only non-structural enclosure elements will be renovated. The UW plans to start the construction in the month of January and the project will take place over an eight-month time frame. While the building is under construction, students will not be residing in the buildings and due to lower enrollment in the winter and spring terms, the UW will be able to provide other accommodations for the students while the project is underway.

1.3 Objectives

This report will present an enclosure retrofit analysis of Waterloo Court that meets Net-Zero performance targets based on the enclosure design determined in Phase I. The KPIs were determined in Phase I to select the best enclosure design for the retrofit and were used to address the energy demand and thermal resilience (Architecture 2030, 2021). The KPIs that were considered in Phase I are listed below in Table 1. In Phase II, energy use intensity (EUI) and thermal autonomy were further analyzed.

Table 1: List of Key Performance Indicators

Objective	Key Performance Indicator	Standard Recommendations
Decrease energy demand (C. Kapsis, personal communication, July 5, 2021)	EUI	60 - 80 $\frac{kWh}{m^2\ yr}$
Maximize thermal resiliency (Kesik, O'Brien, & Ozkan, Thermal Resilience, 2019)	Passive habitability	Maximize
	Thermal autonomy	Maximize
Minimize Project Cost	Payback period	Minimize

The main objective of this report is to present the retrofitted enclosure details for the walls, roof, and windows. The materials used in each assembly are noted as well as how they will be installed during the construction phase of the project. Specific product specifications will not be provided. Building science fundamentals were applied and thermal and hygrothermal modelling were completed to inform the selection of materials, arrangement of control layers and connections within the final enclosure design. Solar panels were placed on the roof and in the parking lot to determine if the building's energy demand is within Net-Zero requirements. A simulation of the proposed retrofit building under future climate conditions was run to assess the building performance in 2050 to ensure that the design can withstand future conditions.

2 Assembly Selection

The proposed retrofit was designed to not only meet the thermal requirements of the enclosure determined in Phase I, but to also control other environmental loads such as moisture, air, and vapour to provide an energy efficient, comfortable, resilient enclosure while following the perfect wall concept (Lstiburek, 2007). The design factors considered when selecting the materials of the wall were performance, cost, embodied carbon, fire resistance, durability, and availability.

2.1 Roof Assembly

The existing roof of the building is in good condition, and it follows the perfect wall concept. It is an inverted warm roof, and the assembly has the following components (from inside to outside): gypsum board, metal furring channels, open web steel joists, a metal pan, concrete roof slab, a vapour barrier, an EPDM membrane, rigid insulation, a scrim sheet, and a gravel ballast. The existing detail drawing of this configuration can be found in Appendix A. The roof was renovated in 2000 and all the control layers are intact, however it is not well insulated. The insulation is only 2” thick and the roof has an effective R-value of 2 RSI (R-11). A 7 RSI (R-40) roof is required to achieve the performance objectives for this deep energy retrofit.

To improve the thermal resistance of the roof, it will be stripped down to the EPDM membrane and it will be inspected. If any discontinuities/damages are found, repairs will be required. Next, a 0.4” thick drainage mat will be added to the assembly to drain any water that passes through the insulation and prevent it from moving further through the assembly. The new insulation will be installed on top of the drainage mat. A comparison between five different types of rigid insulation board is shown below in Table 2 (Magwood, 2021).

Table 2 Insulation Comparison

Insulation Type	R-Value per Inch	Thickness Required for 7 RSI (R40)	Cost for 10 m^2 of 7 RSI (R40)	kg/CO2e for 10m^2 of 7 RSI (R40)
Mineral Wool	4.3	9.3	1871.48	204
EPS Foam	4.0	10.0	583.00	264
XPS Foam	5.0	8.0	1118.20	3948
Polyiso	6.5	6.2	977.28	200
GPS Foam	4.7	8.5	600.48	196

Graphite polystyrene insulation (GPS) was chosen to improve the thermal performance of this assembly due to its relatively high R-value per unit thickness that does not degrade over time, its low global warming potential, and its low cost. 9’’ of GPS insulation will be used to achieve a thermal resistance of 7.5 RSI (R42.3). A felt scrim sheet will be applied on top of the insulation, followed by the gravel ballast. The existing gravel ballast can be reused for this retrofit project. The updated roof assembly is shown in Figure 2.

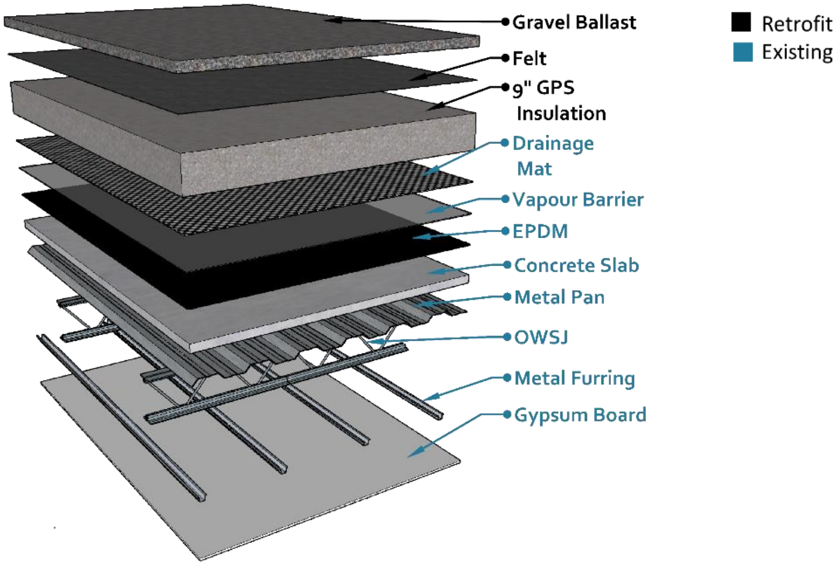

Figure 2: Retrofitted roof assembly

The existing roof assembly already followed the perfect wall concept, meaning it has all the necessary components for thermal, water, air, and vapour control, as well as a water shedding surface. The layers are identified as follows: the GPS insulation is the thermal control layer, the drainage mat is the water control layer, the EPDM membrane provides air control, the existing vapour barrier provides vapour control, and the GPS insulation is the water shedding surface. These control layers are shown on the roof assembly in Figure 3.

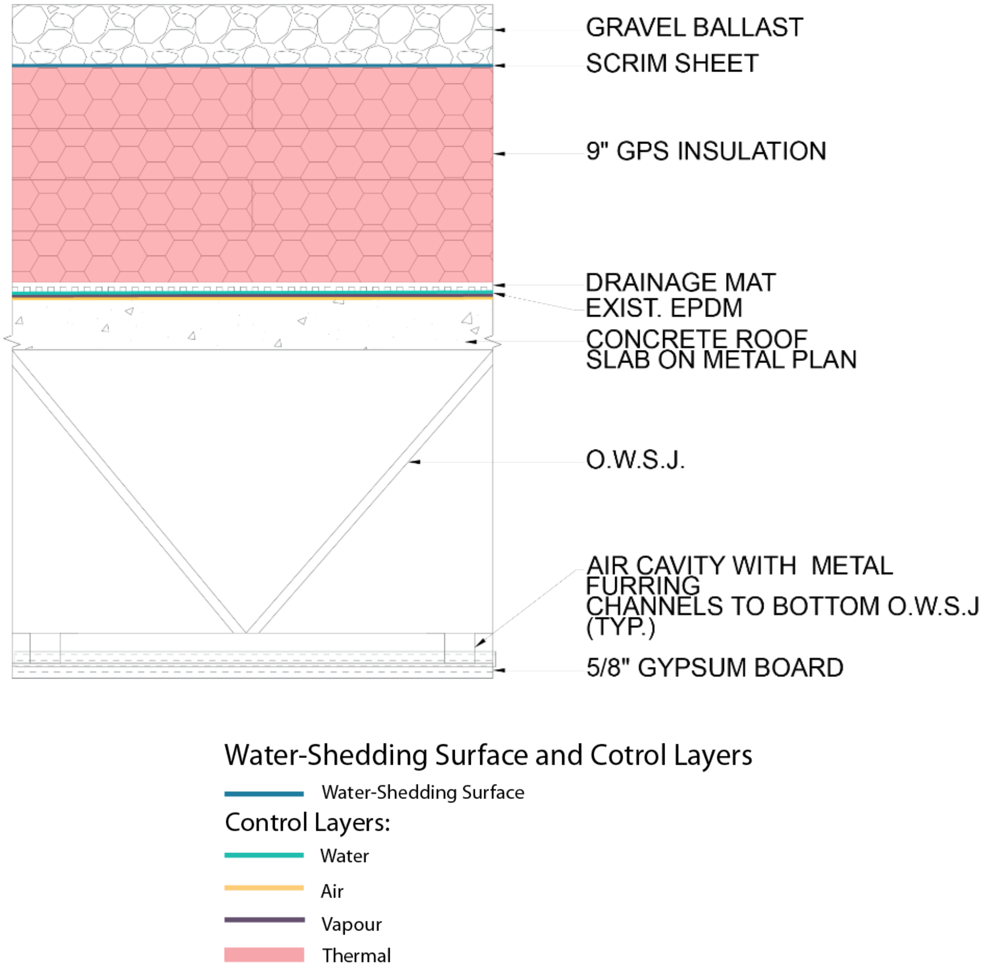

Figure 3: Control layers on retrofitted roof assembly

2.2 Above Grade Wall Assembly

The existing walls of the Courts building are poorly insulated with a thermal resistance value of 1 RSI (R-6). It consists of two parts: the original mass wall and an exterior insulated retrofit applied to the exterior of the original wall. The original construction of the wall (from inside to outside) consists of 0.5” of gypsum, wood strapping and 2” batt insulated service cavity, 4” of concrete block, and 4” of brick façade. A drawing of the existing wall layers can be found in Appendix A. The retrofit part involves adding rigid insulation and new metal cladding to the original brick structure.

The proposed design involves removing the cladding and the insulation to expose the original brick façade. A fluid applied vapour permeable air and water barrier will be directly applied on the brick, then 4.5” of rigid mineral wool insulation will be added to meet the required effective 3.5 RSI (R-20) target. A fluid applied membrane was chosen as it is best for masonry due to its roughness which will ensure it is fully adhered to the existing structure. XPS is the most common ridged insulation but for this project mineral wool was selected even though it has a higher cost due to its fire resistance, ability to dry out and lower embodied carbon; see Table 2. To attach the insulation to the brick, wood furring strips will be spaced at 24” on-centre using masonry screws. Insulation will then be placed into the cavities created between the furring strips and over top reaching a total thickness of 4.5” from the wall. The insulation will then be covered with an aluminum composite panel (ACM) cladding rainscreen system, which will be attached through the insulation to the wood furring strips. Metal hat channels will secure the insulation to the wood furring strips using 6” screws. The updated wall assembly is shown below in Figure 4.

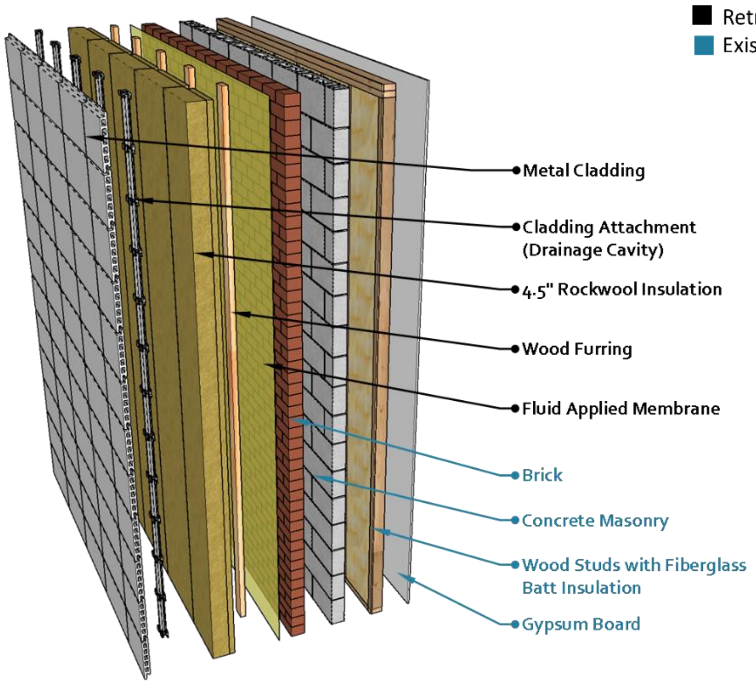

Figure 4: Retrofitted above grade wall assembly

Fiber cement siding and metal were the two material options for the cladding. ACM panels were selected because they are light weight, fire resistant and have a long lifespan. It is also cheaper and has a lower embodied carbon than fiber cement siding (Magwood, 2021). A rainscreen system was implemented for resilience and ease of installation. A rainscreen is beneficial as it keeps moisture away from the building and will allow the mineral wool to easily dry if it gets wet. Collectively the assembly will have an effective thermal resistance of 3.9 RSI (R-22).

The control layers are identified as follows: the mineral wool insulation is the thermal control layer, the fluid applied membrane is the water, air and vapour control layer, and the ACM cladding is the water shedding surface. These control layers are shown on the roof assembly in Figure 5.

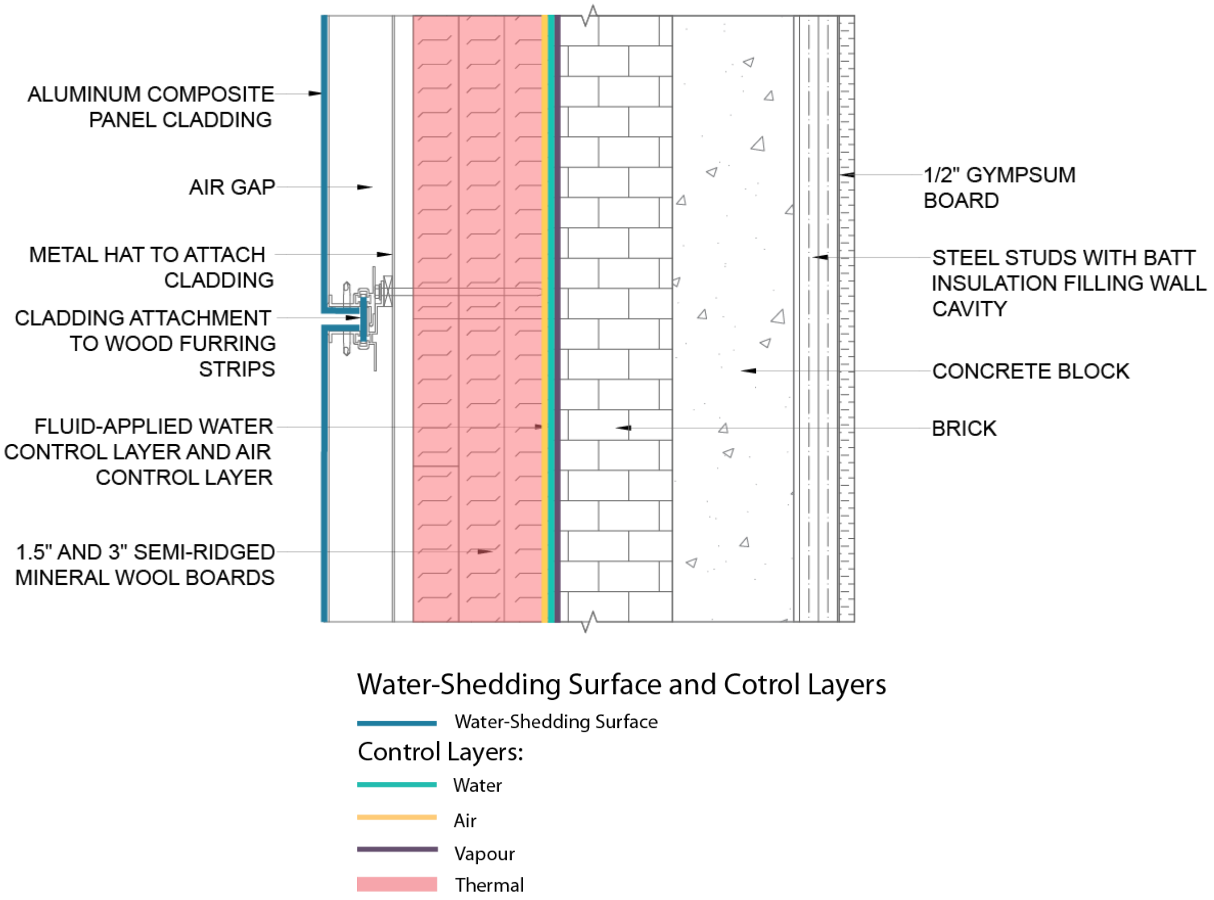

Figure 5: Above grade clear wall assembly control layers

2.3 Below Grade Walls

Currently, the existing foundation walls are insulated on the interior, however, to ensure optimal thermal performance and continuity in the new enclosure design, new control layers will be extended down to the existing footings and new footings for the enclosed balcony wall section. The new assembly will consist of a fluid applied membrane applied directly to the concrete, 4.5” of mineral wool insulation extending down to the footings, a drainage mat extending to the depth of the insulation and finally protection board that extends 6” below grade. Additionally new drainage pipes will be installed at the base of the footings embedded in gravel for adequate drainage. Each control layer in this assembly is highlighted in Figure 6.

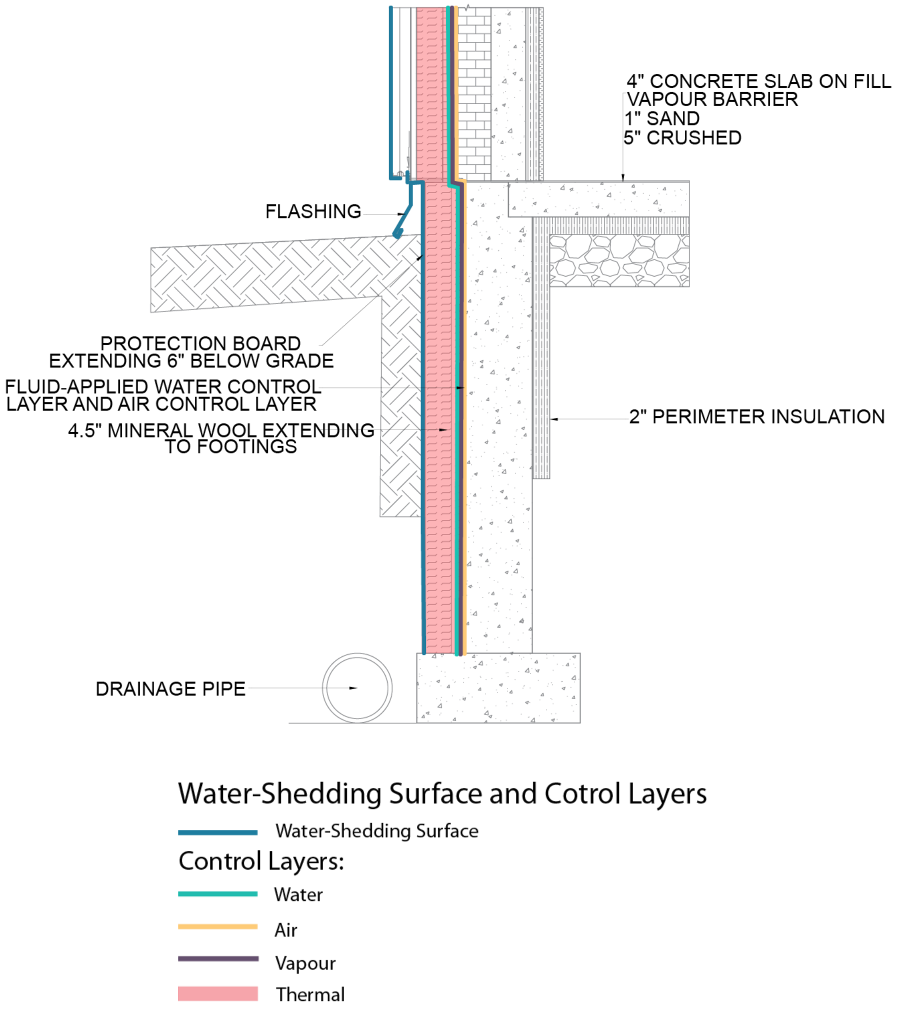

Figure 6: Below grade wall assembly control layers

2.4 Enclosed Balcony

In the Waterloo Court building, 35% of the units have balconies; although these balconies only take up a small percentage of the area of the building, they are a large source of heat loss. The floor construction is a continuous slab which extends to the balconies. This construction creates a thermal bridge as the concrete slab bisects the insulated wall (Finch, Higgins, & Hanam, 2014). To remediate this thermal bridge, the balconies will be enclosed by a new insulated wall that is flush with the adjacent walls and supported by a new foundation. It will be built to seamlessly integrate the new wall with the existing foundation wall.

In preparation of enclosing the balconies, the existing balcony railings and 5 ½" of the existing concrete topping will be removed. Then, a ¼" hot dipped galvanized steel plate will be installed that extends 4" outwards along the front of the balcony. This steel plate will support the new wall section and bring the new studs flush with the existing brick, thereby creating a continuous façade. New concrete topping will be poured over the steel plate to create continuity between the existing concrete balcony and the new wall.

The new wall consists of two sections: the interior structural section, and the exterior-retrofit section. The structural section consists of (from the interior) gypsum, a structural 2x6, 24" on-centre timber frame filled with fiber glass batt, and OSB sheathing. The exterior retrofit section is the identical retrofit applied to the existing mass masonry walls. Each control layer in this assembly is highlighted in Figure 7. Control layers for all details can be seen in Appendix B.

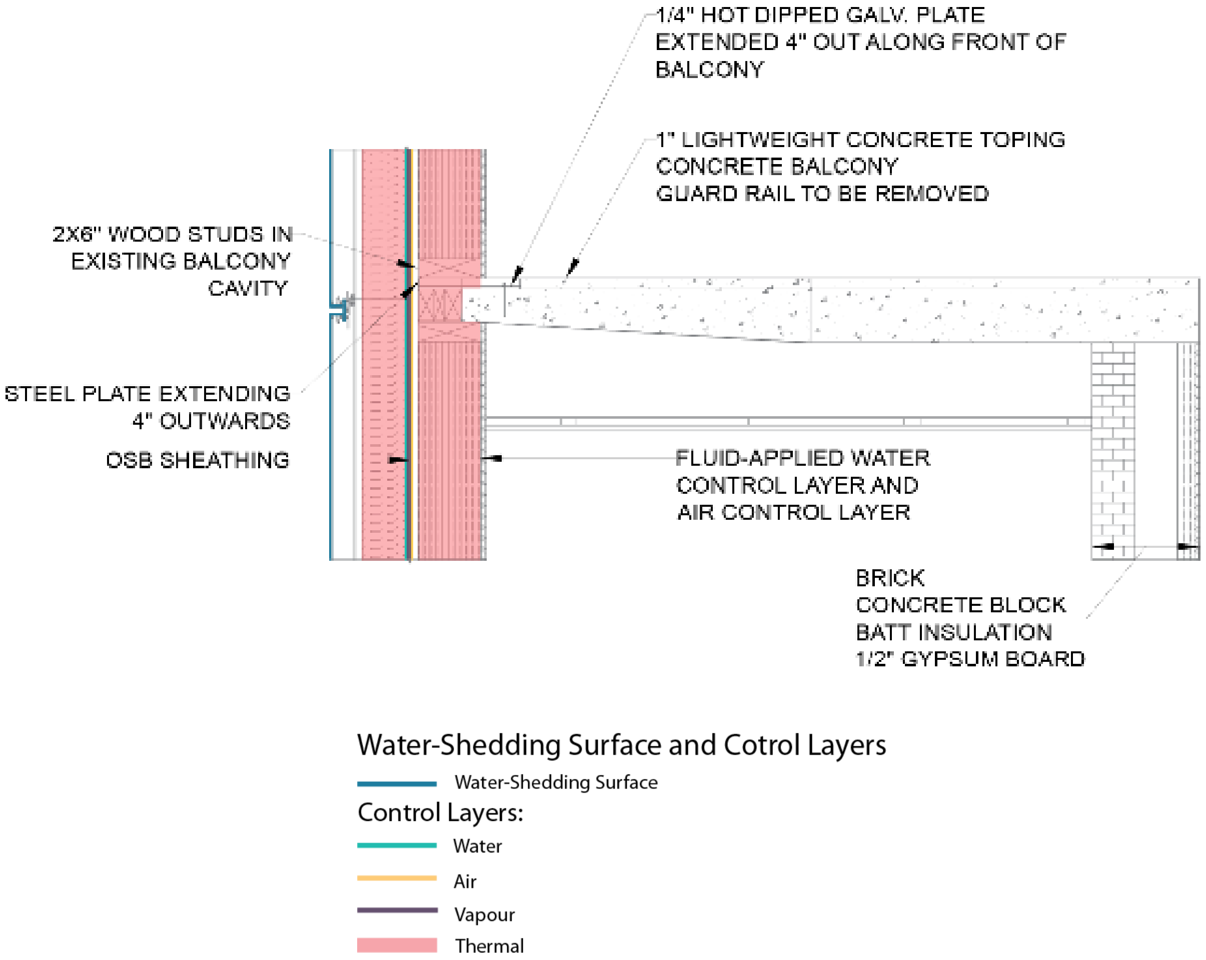

Figure 7: Balcony wall assembly control layers

2.5 Window Selection

The existing building has a window-to-wall ratio of 15%; there are single-glazed windows without any low emissivity (low-e) coatings and the gaps are only filled with air. These are very poor performing windows which resulted in a significant amount of air leakage and uncomfortable conditions inside the building. There are window products on the market that perform significantly better thermally and achieve low U-factor values with features such as three panes of glass, inert gas fills in the gaps and low-e coatings.

In Phase I, EMBODY Consulting determined that they would use windows with a U-factor of 0.8 USI (U-0.14) and a solar heat gain coefficient (SHGC) of approximately 0.40 (-). To minimize the embodied carbon associated with the window products, the team decided to select a window product manufactured in Canada. Natural Resources Canada (NRCan) has a searchable product list of all the Energy Star rated windows in Canada that was used to select the most suitable product for the Courts buildings (Natural Resources Canada, 2021).

An awning window was selected as they are a safe option for a university residence while still providing excellent natural air ventilation. The suites all have sprinklers, therefore according to the Ontario Building Code the window opening does not have to meet any size requirements (Ontario, 2020). A fiberglass window frame was chosen as fiberglass requires little maintenance, it is very durable, it has a moderate cost, and it has excellent thermal resistance properties (Badiei, 2016).

The team ultimately selected a Cascadia Universal Series triple-glazed fiberglass awning window. This product has three low-e coatings on surface 2, 4 and 6. There is a 90% argon gas fill and TriSeal Super Spacers in the cavities between the glass. This product has a SHGC of 0.32 (-) which is slightly below the target value chosen in Phase I and it has a total U-factor of 0.85 USI (U-0.15) (Cascadia Windows & Doors, 2021). The Cascadia window is shown in Figure 8.

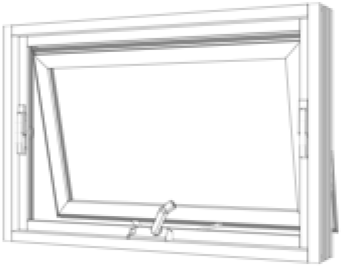

Figure 8: Cascadia Awning Window

2.6 Solar Shades

Solar shades can increase the energy efficiency of a building by controlling solar gains. In Phase I it was determined that horizontal external fixed shading devices can be added to the building exterior to reduce uncomfortable conditions due to direct radiation in the summer and maximize heat gain due to direct radiation in the winter. Shading devices will be placed above the windows and be an overhang depth of either 24” or 32” for a 3’ or 4’ window respectively. Maximum heat gain occurs through windows that face south, therefore external shades were only placed on southeast- and southwest-facing windows.

The solar shades will be louver style shading devices made from aluminum as it is lightweight and fire resistant. Louver style shading was selected to reduce snow loads on the shades and wind loads, as the snow and wind will pass through the spacing between the louver blades. The louvers are angled to wick moisture away from the building and prevent water damage. The blades will be spaced 4” apart at 25-degree angles to not let any additional sun pass through the louvers. The 24” sun shade will have five louver blades and the 32” sunshade will have seven louver blades. Figure 9 shows how the solar shade will block the sun in the summer and winter months, and the angle of the louver blades.

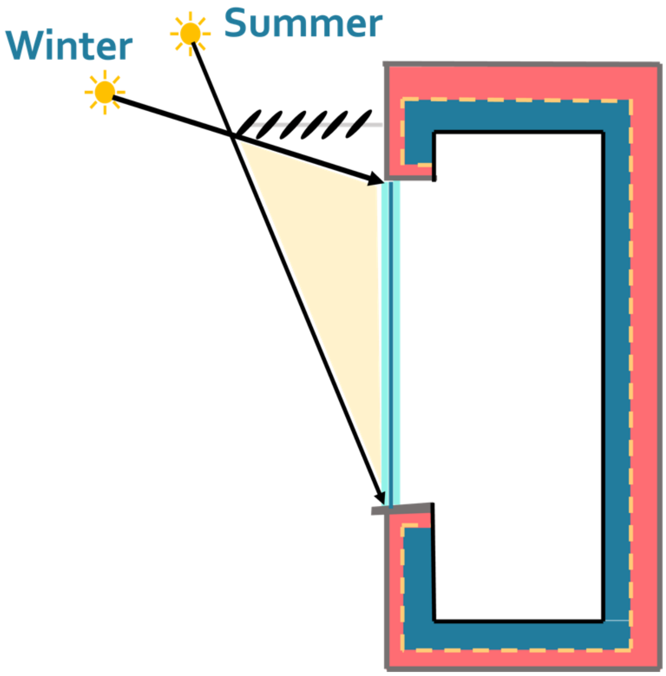

Figure 9: Typical solar shading on window

The external shades will be attached to the brick using 300 mm mounting brackets with an insulation material attached to the bracket to prevent thermal bridging. A profile view of the solar shades mounted to the retrofitted wall can be seen in drawing D1 in the detail drawing package.

3 Hygrothermal Modeling

The retrofit design will significantly increase the airtightness of the building which will make the building more comfortable and energy efficient, however, this might have a negative impact on the enclosure's resistance to moisture damage. Since the retrofitted enclosure will be able to maintain comfortable temperature and humidity levels inside the building, there are larger psychometric stresses driving moisture into the building (Morse & Acker, 2017). It is extremely important that the assemblies of the enclosure contain all the necessary control layers to prevent moisture from entering because the new design has a lower moisture storage capacity than the existing building.

The new wall and roof assemblies and the details of important connections were designed to have continuous air, water, vapour and thermal barriers as well as continuous water shedding surfaces. These control layers will effectively prevent condensation from forming in the assemblies. This is necessary because prolonged periods of condensation and the inability to dry out can cause mold to grow in the assembly. This will adversely impact the indoor air quality of the building and contribute to the deterioration of the building components (Morse & Acker, 2017).

To confirm that the enclosure design is durable, a hygrothermal analysis was performed to select the proper permeance value for the vapour barrier and check for a damaging level of moisture build-up. The new wall and roof assemblies were modeled in WUFI to determine if any condensation would occur. Condensation commonly occurs on the vapour barrier, therefore the relative humidity values on both sides of the vapour barrier were evaluated using WUFI. The relative humidity values for the roof and wall assemblies did not exceed 100%, which confirms that there will not be condensation. The water content graphs show periodic behaviour; therefore, the assemblies always dry themselves out when they get wet, and they are not accumulating water. These graphs are shown in Appendix C.

4 Thermal Modeling

After improving the thermal performance of the enclosure by adding insulation with higher thermal resistance values to the wall and roof assemblies and implementing high performing windows, it is very important to ensure that there is no heat leaking through the building enclosure. Heat is not likely to flow though the clear wall, however, there is concern in locations where the thermal insulation is interrupted such as wall-to-window connections, wall-to roof connections, wall-to-foundation connections, and wall-to-balcony slab connections (RDH Building Science, 2021). To confirm that there will not be increased heat flow in these locations, thermal modeling was performed using Lawrence Berkley National Laboratory’s THERM program. Thermal models were created and examined to determine if there were any thermal bridges where the interior of the building is at a colder temperature than expected. There were no thermal bridges found through this analysis which proves that the final design is effective. The THERM models of these connections are in Appendix D.

5 Whole Building Performance

The existing energy model was updated to represent the design modifications made during Phase II. These changes include updating the assemblies' and window’s thermal resistances, exterior shade placement, and enclosing the balconies, as discussed in previous sections. It should be noted that other energy conservation measures were also applied alongside the enclosure upgrades such as high efficiency lighting, equipment, domestic hot water (DHW) and a variable refrigerant flow (VRF) system for the heating and cooling loads.

To design a truly resilient retrofit that will last for its entire service life, the future climate performance of the retrofit must be considered. The climate is projected to warm quite significantly, transforming the climate from heating dominated to cooling dominated. This transition increases the necessity for cooling in the enclosure without increasing the energy demand or lowering the thermal autonomy or comfort (Environment and Climate Change Canada, 2019). The passive design strategies that have been incorporated such as operable windows, airtight construction, exterior shades, high performance windows, and increased insulation, as well as the inclusion of active strategies such as mechanical cooling will still be effective in the future climate conditions.

To ensure the design performs equally well in the future, a thermal analysis was performed on the design using climate data for a 2-degree warming scenario in 2050 based on the NRC climate change scenarios for Toronto (National Research Council Canada, 2021).

5.1 Energy

The resulting site EUI decreased by 70% from 235 kWh/m²yr to 73 kWh/m²yr under current climate conditions. Under future climate conditions the EUI is predicted to decrease from 73 kWh/m² yr to 68 kWh/m² yr. A breakdown of the EUI is shown below in Figure 10.

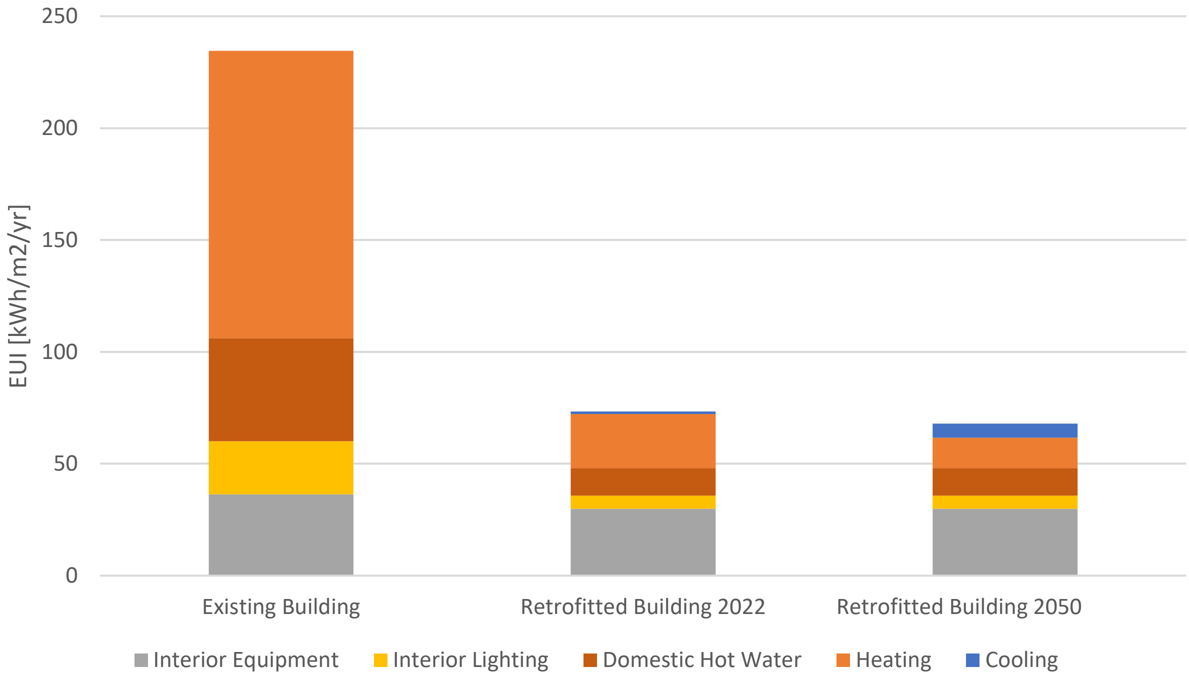

Figure 10: Site energy use intensity breakdown of the existing, retrofitted building in 2022 and retrofitted building in 2050

The most significant decrease in both the 2022 and 2050 scenarios is in the heating energy demand. This decrease in heating energy demand in the 2050 scenario is quite different than the decrease in the 2022 scenario as it is related to the changing climate and reduction of heating degree days. At the same time, there is an increase in cooling demand: the cooling load increase by 625% from 4 kWh/m² yr to 25 kWh/m² yr and the heating load decreased by 56%. The TEDI for the 2020 and 2025 retrofitted scenario broken down into the proportion of the demand from cooling and heating in Figure 11.

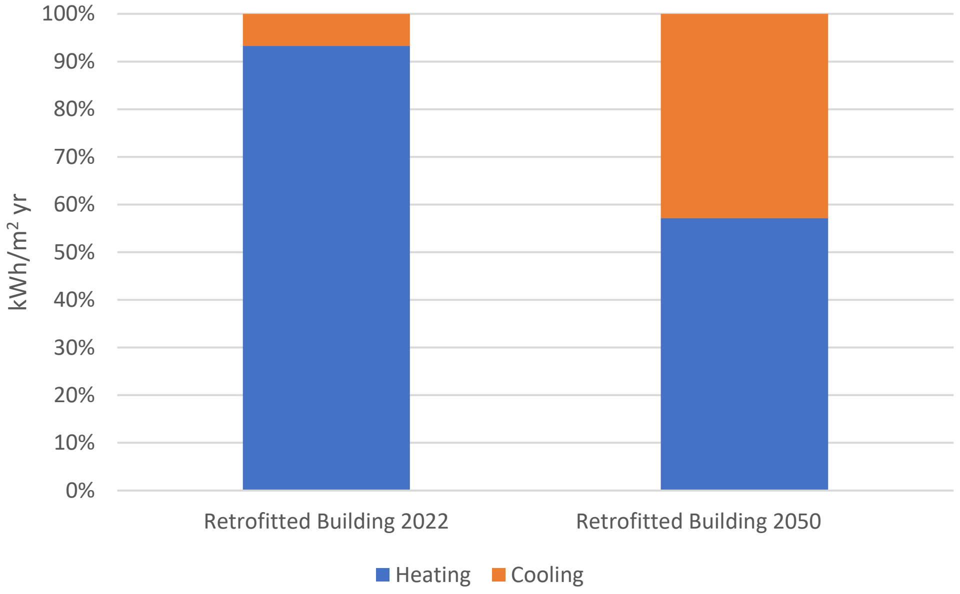

Figure 11: Thermal Energy Demand Intensity of the retrofitted building in 2022 and retrofitted building in 2050

These substantial increases in cooling demand are not as evident in the EUI due to the use of a VRF system; a high-performance VRF system can attain a cooling coefficient of performance (COP) of 4 (Padwal, 2022). Reliance on active systems to meet this increase in demand is not the desired approach as this leaves occupants in an uncomfortable or even deadly situation during extreme weather events when the grid goes down (Kesik, O'Brien, & Ozkan, Thermal Resilience, 2019).

5.2 Resilience and Comfort

Thermal resiliency and comfort were measured by running a free-run model; a free-run model is a model where all the active systems and occupancy are turned off. Thermal autonomy measures the percent of time a building can passively maintain comfortable conditions, between 18°C and 25°C, for students without active system energy inputs.

High thermal autonomy means that there is a lower percentage of time in the year spent outside the comfortable temperature range and therefore the building is less reliant on active systems. The existing building maintained a comfortable interior temperature 44% of the year; this was increased to 74% by applying the proposed retrofit design, as seen in Figure 12. This is a major increase in comfort and demonstrates the efficacy of the proposed retrofit strategies in the enclosure design without the addition of active strategies.

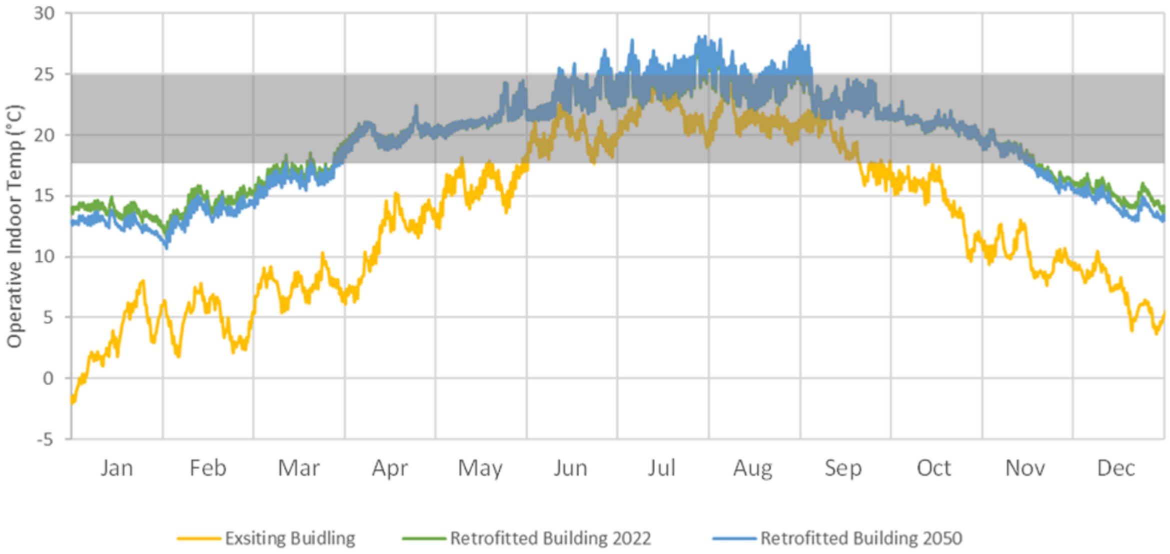

Figure 12: Thermal autonomy

Even though energy use was reduced under the future climate scenario, the thermal autonomy decreased to 67%. Although this is a minimal change in thermal autonomy it will become more important in the future as the probability of an extreme weather causing a blackout will become considerably higher and the ability to keep occupants comfortable and safe during these events will become even more important. It is recommended that a more in-depth energy analysis is performed to capture the full potential of energy efficiency measures on lighting, heating, cooling and ventilation. Full thermal model inputs and energy result can be found in Appendix E.

6 Onsite Energy Production

To meet the Net-Zero energy definition set out by the Canadian Home Builders Association a building must not only consume 80% less energy than typical buildings of the same typology, but they must also produce as much energy as it consumes on an annual basis (Canadian Home Builders' Association, 2022). The proposed enclosure design and active system upgrades have reduced the site energy demand of the building to a level that can be met by on-site energy systems. Renewable energy sources are the most sustainable option for onsite energy. Solar energy production was chosen for this site as its ample solar access, vacant roof and surrounding area make it a great candidate (BC Housing, 2018).

The scope of this project does not include a full renewable energy system design or cost analysis but does include the analysis of the potential of the building and its site to produce enough energy for Net-Zero energy performance. The maximum amount solar energy that could be produced by installing a roof-top photovoltaics (PV) system, ground-mounted PV or building-integrated PV (BIPV) system were evaluated. The solar irradiance was studied in ClimateStudio using typical solar modules placed upon the existing geometric model (Solemma, 2021). A summary of these results can be seen below in Table 3; the assumptions, calculations, and full results can be found in Appendix F.

Table 3: Solar Energy Potential for Various Possible PV Systems

PV Location	Type of System	Direction	Tilt (Degrees)	Percent of Demand Met
East parking lot	Ground-mounted	South-West	15	41
West parking lot	Ground-mounted	South-West	15	6
South parking lot	Ground-mounted	South-East	15	19
Roof	Roof-mounted	South-East	30	40
All outside faces	BIPV	Various	90	68
All Court faces	BIPV	Various	90	48
North faces	BIPV	North-West	90	14
East faces	BIPV	North-East	90	22
West faces	BIPV	South-East	90	33
South faces	BIPV	South-West	90	29

No single PV system can meet the full energy demand but by combining systems, Net-Zero Performance can be achieved. The chosen system comprises of a 200 kW roof-mounted PV system and a 340 kW ground-mounted PV array over several parking areas which collectively generate 105% of the energy demand annually. The layout is shown in Figure 13.

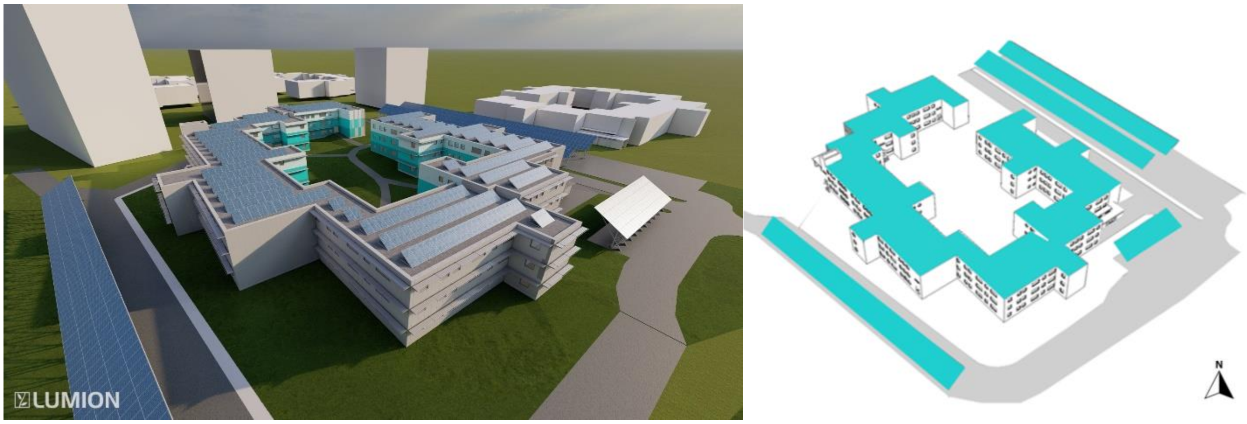

Figure 13: Display of PV Systems

Although, BIPV systems offer an equal or better opportunity for onsite solar energy production they are not currently price competitive with traditional PV modules (Natural Resources Canada, 2018). In the coming years, it is predicted that BIPV systems will become cheaper; when this occurs, it is recommended to evaluate them.

Net-zero energy performance increases the resilience of the building - through self-consumption and the reduction of peak power demand - by decreasing the reliance on the grid and therefore giving the ability to avoid blackouts.

7 Construction Documents

The modeling performed has confirmed that this enclosure design will be effective at insulating the building and preventing condensation from forming in the assemblies. There is still a risk that the building will face thermal and hygrothermal performance issues if it is not constructed correctly. The order of application of the control layers for the wall and roof assemblies matters and continuity must be maintained. There will be many different trades working independently on this project and it must be ensured that the work is done in the correct order and that there is continuity between the work of different trades. To mitigate these issues, EMBODY Consulting has completed a full set of construction drawings and thorough installation instructions for important connections.

The drawing package includes elevations, plans, and details of the following important interfaces and joints: wall-to-roof, wall-to-foundation, and a wall-to-window head/jamb/sill and the wall and roof assemblies. These details will assist the installers with precision and continuity at the interfaces and joints so the assembly can achieve the targeted thermal performance and durability. The detail drawings can be found in the drawing package.

Installation instructions were created for two specific details which are often wrongly constructed with discontinuities in their air, water, vapour or thermal control layers: the wall-to-roof connection (parapet) and the wall-to-window connection. These instructions show the order in which each component must be added to the assemblies to maintain continuity. Skilled professionals must be hired to install each specialized component. Additionally, each component must be installed according to the manufacturer's instructions. The installation instructions can be found in the installation drawing package.

8 Conclusion

In Phase II of this deep energy retrofit project the final enclosure design has been completed for the Waterloo Courts Residence building. The following criteria was considered in the design process: performance, cost, embodied carbon, durability, availability and fire safety. The resulting enclosure has a 7 RSI (R-40) roof, 3.5 RSI (R-20) walls and 0.85 USI (U-0.15) triple-glazed fiberglass awning windows with three low-e coatings and a SHGC of 0.32 (-). Additionally, large thermal bridges such as balconies were addressed and fully enclosed and exterior solar shading was added on the near south-facing façades. Within each assembly, layers have been introduced to ensure that vapour, air and water have been managed properly. The effectiveness of the assemblies was confirmed by performing thermal and hygrothermal modeling.

The enclosure design was able to achieve the initial objective of meeting Net-Zero performance targets by lowering the energy consumption by 70% to 73 kwh/m^2 yr when additional active measure such as high efficiency HVAC and lighting systems are installed. This is a large enough reduction that the entire energy consumption of the building can be offset by onsite solar generation in the form of roof and ground mounted PV systems. The second objective was also met as the same measures that have been implemented to meet the net-zero goal inherently enhance comfort and resilience. This can be seen though 23% increase in thermal autonomy.

Finally, to guarantee that the design will perform well during its entire service life a future climate analysis was performed using climate data for a 2-degree warming scenario in 2050. In terms of energy, it performed marginally better but in terms of resiliency and comfort it was not as optimal. The EUI was found to be 68 kwh/m^2 yr, and thermal autonomy was found to be 67%. The future climate performance is still significantly better than the existing building. Installation instructions and a full drawing package were created to guide the construction.

9 Recommendations

EMBODY Consulting has completed their deep energy retrofit design, however they recommend that additional analyses should be performed before implementing their design. Structural analysis is out of the scope of this enclosure retrofit, however the structural capacity of the roof should be analyzed to ensure that it can support the proposed PV roof system. Additionally, a complete economic analysis is recommended to determine the financial feasibility of the proposed solar PV systems and potential cost savings associated with it.

It is recommended that the client should strongly consider the application of mechanical energy efficiency measures in conjunction with the enclosure retrofit to reach the highest potential of energy savings. A mechanical engineer should be hired to perform this as mechanical design is outside of the scope of this project. It is also recommended to incorporate wind driven ventilation into the energy analysis as this can alleviate the cooling load and increase the comfort.

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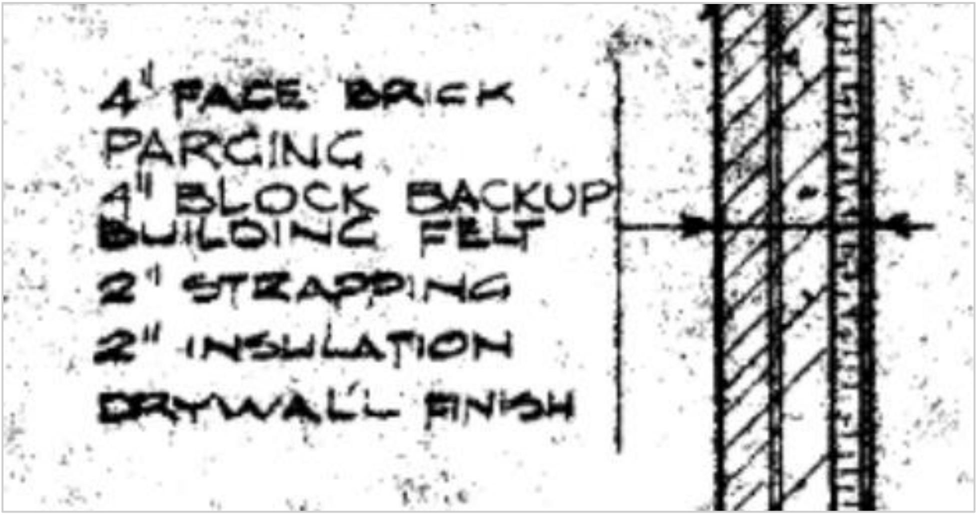
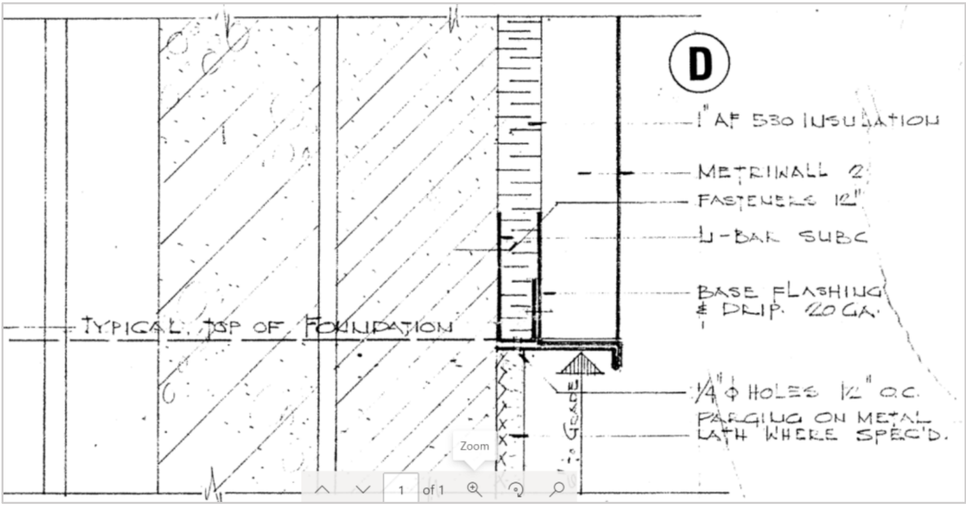
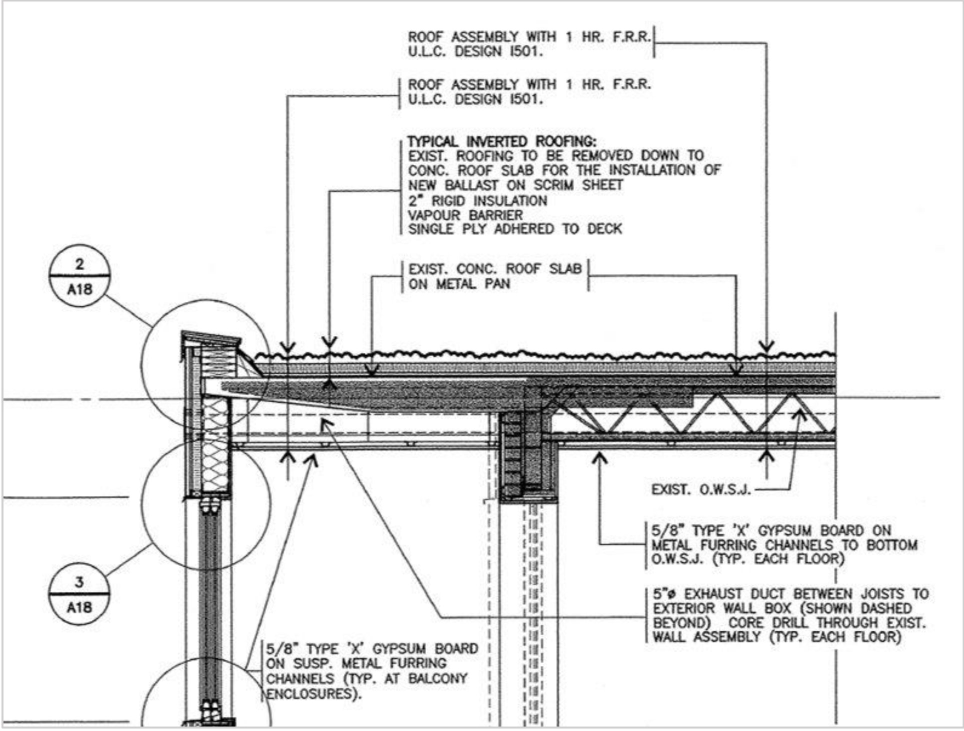
Appendix A: Drawings of Existing Building



Existing Wall

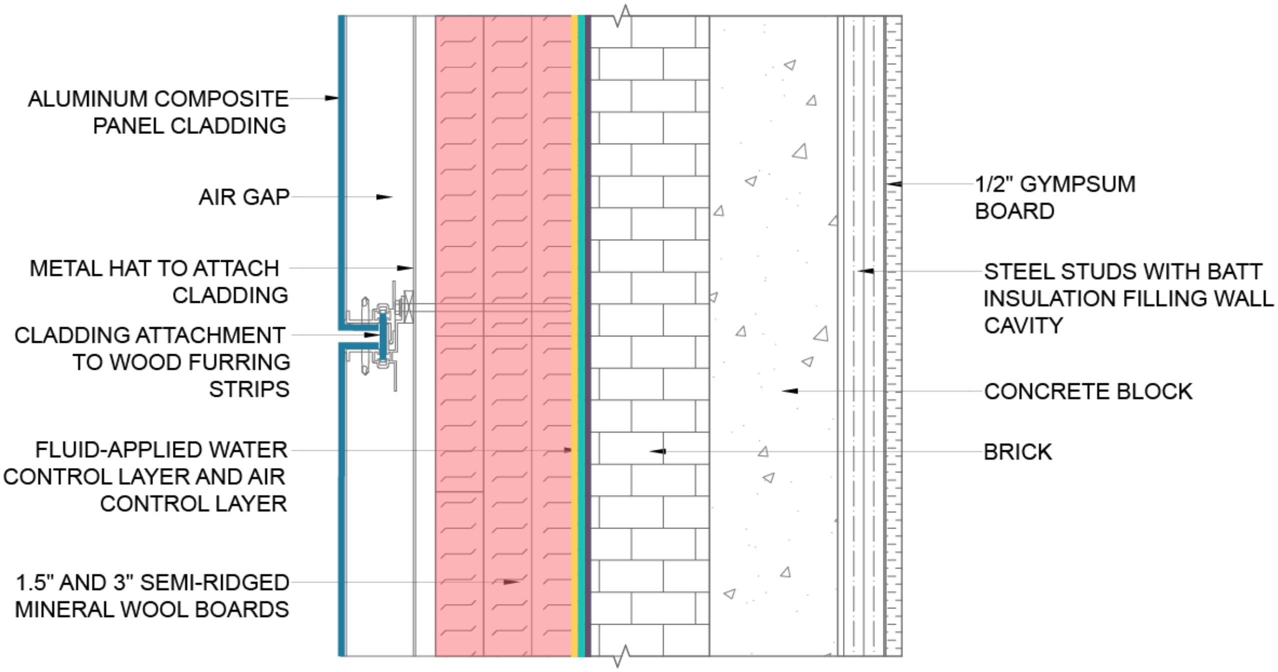


Existing Wall



Existing Roof

Appendix B: Control Layer Details



Water-Shedding Surface and Cotrol Layers

▬ Water-Shedding Surface

Control Layers:

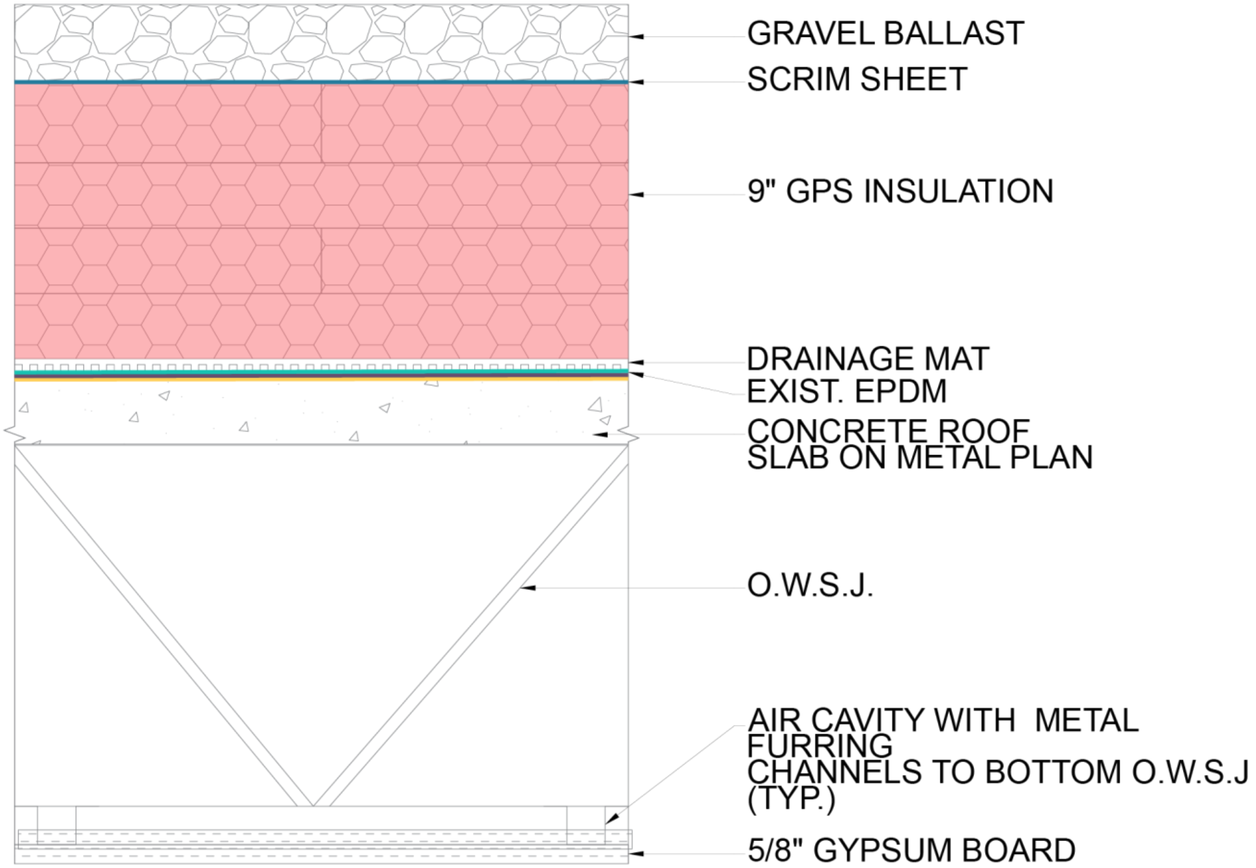
▬ Water

▬ Air

▬ Vapour

▬ Thermal

Clear Wall Control Layers



Water-Shedding Surface and Cotrol Layers

▬ Water-Shedding Surface

Control Layers:

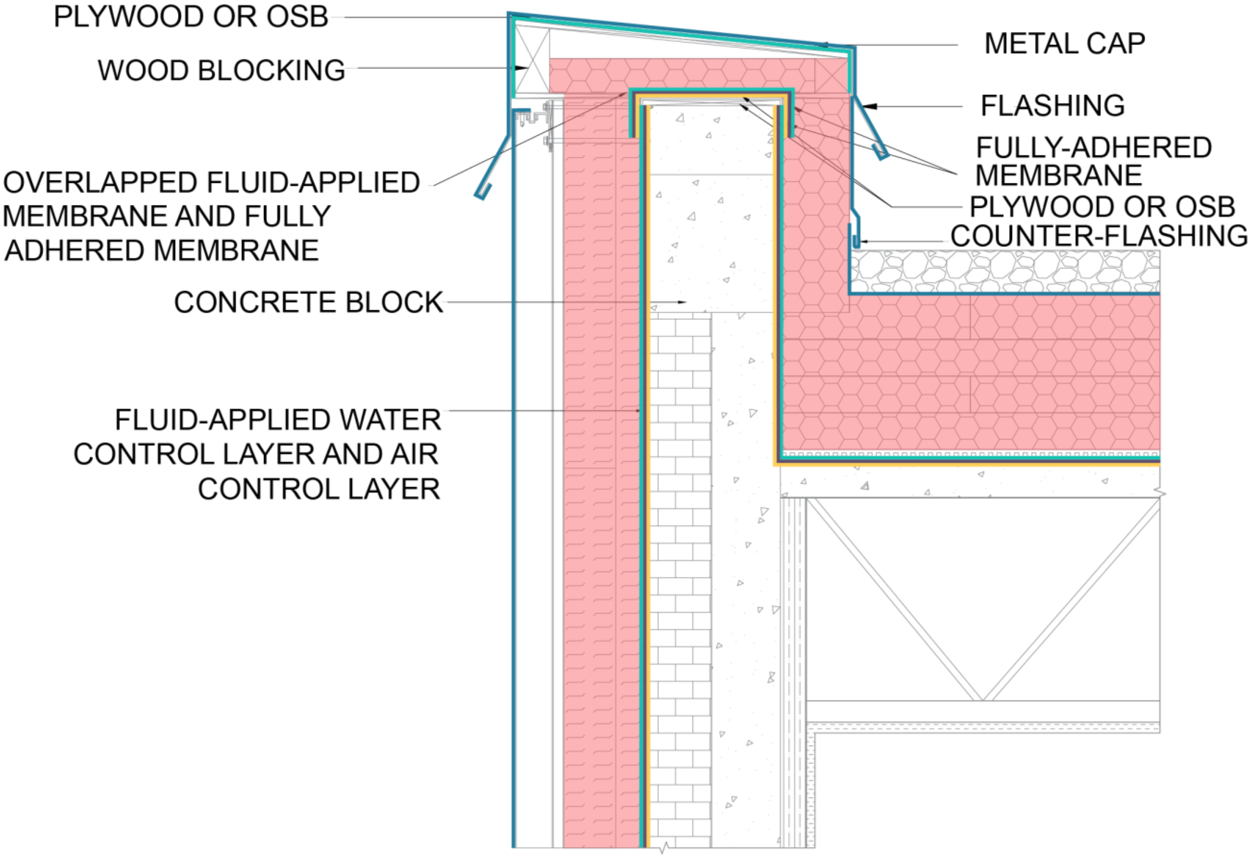
▬ Water

▬ Air

▬ Vapour

▬ Thermal

Clear Roof Control Layers



Water-Shedding Surface and Cotrol Layers

▬ Water-Shedding Surface

Control Layers:

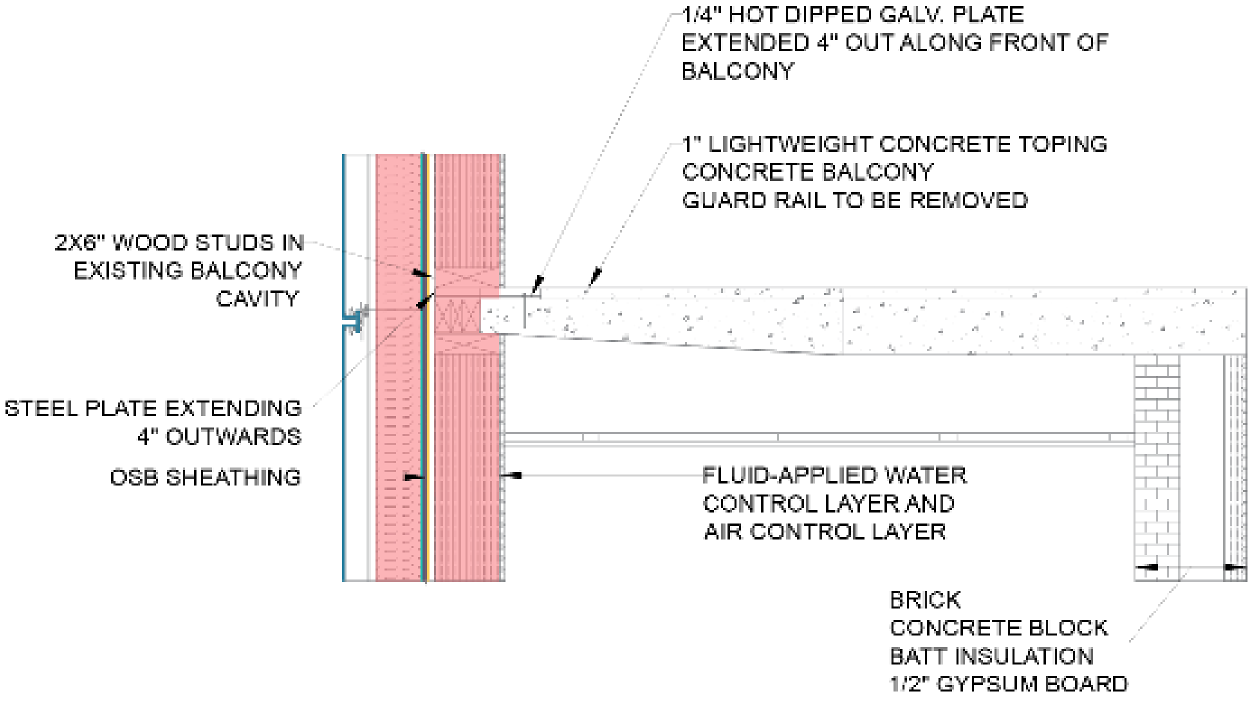
▬ Water

▬ Air

▬ Vapour

🟥 Thermal

Wall-to-Roof Control Layers



Water-Shedding Surface and Cotrol Layers

▬ Water-Shedding Surface

Control Layers:

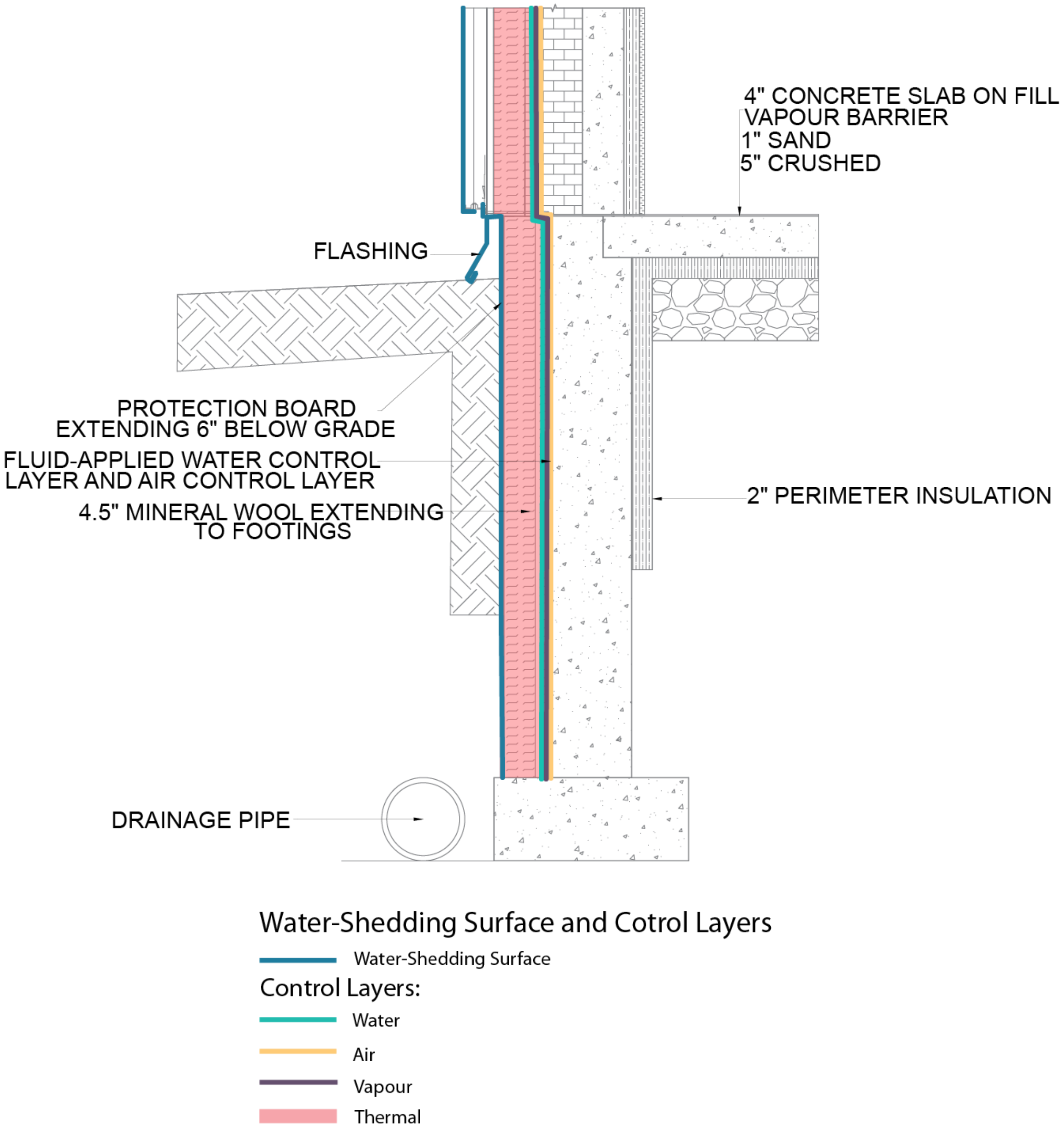
▬ Water

▬ Air

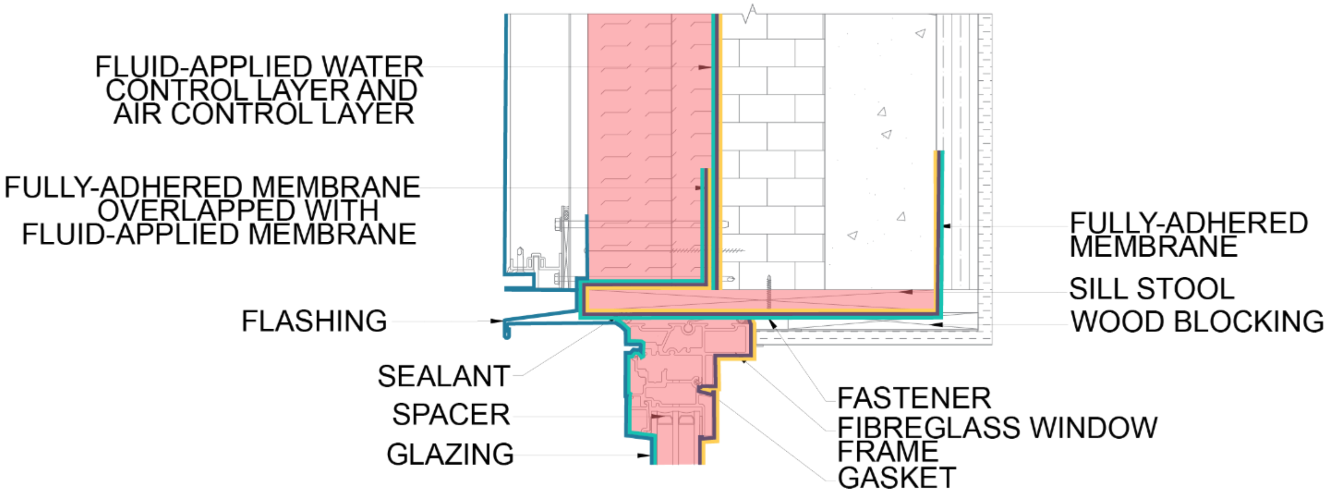
▬ Vapour

▬ Thermal

Wall-to-Balcony Control Layers



Wall-to-Foundation Control Layers



Water-Shedding Surface and Cotrol Layers

Water-Shedding Surface

Control Layers:

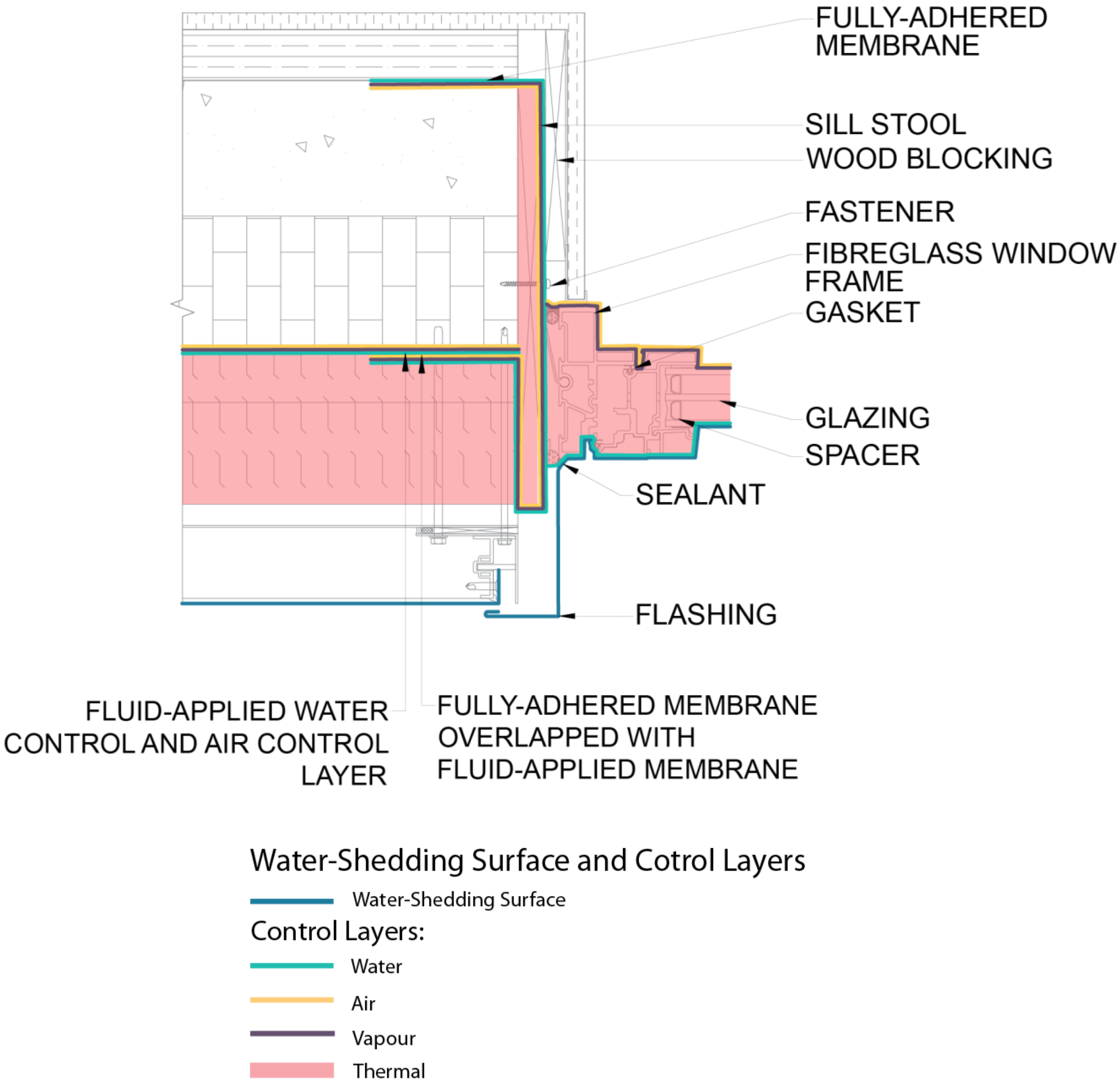
Water

Air

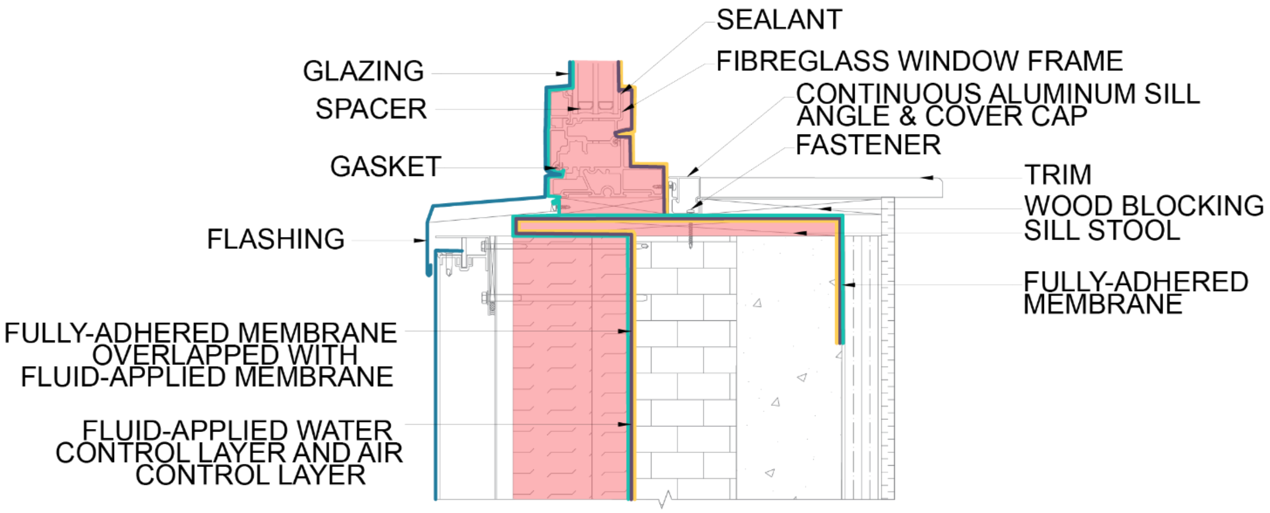
Vapour

Thermal

Wall-to-Window Head Control Layers



Wall-to-Window Jamb Control Layers



Water-Shedding Surface and Cotrol Layers

🟦 Water-Shedding Surface

Control Layers:

🟩 Water

🟨 Air

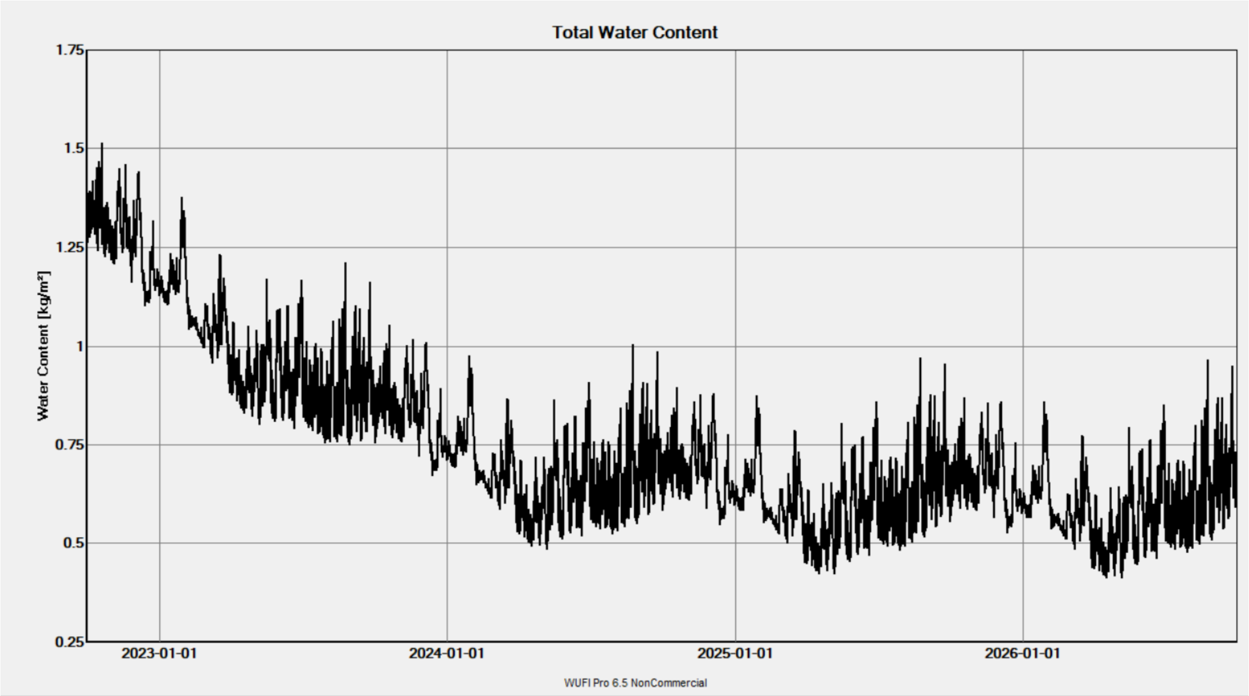
🟪 Vapour

🟥 Thermal

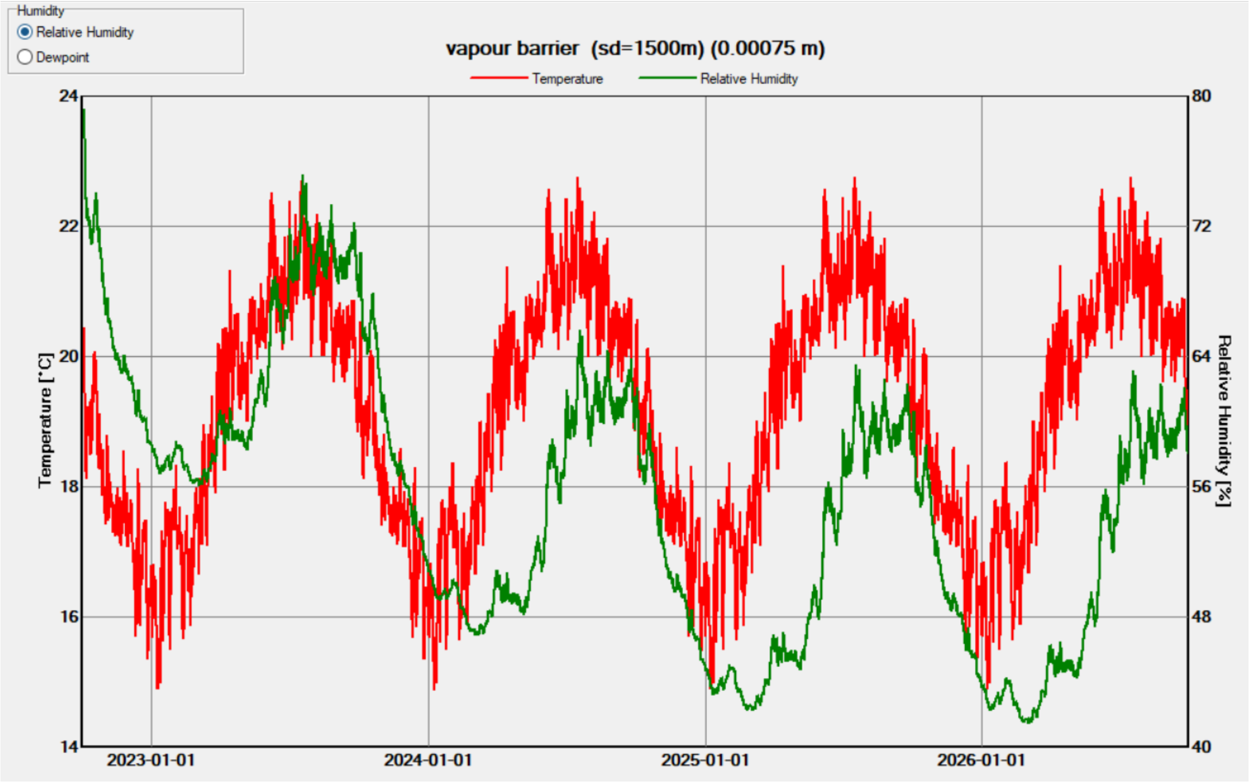
Wall-to-Window Sill Control Layers

Appendix C: WUFI Results

Roof: Total Water Content

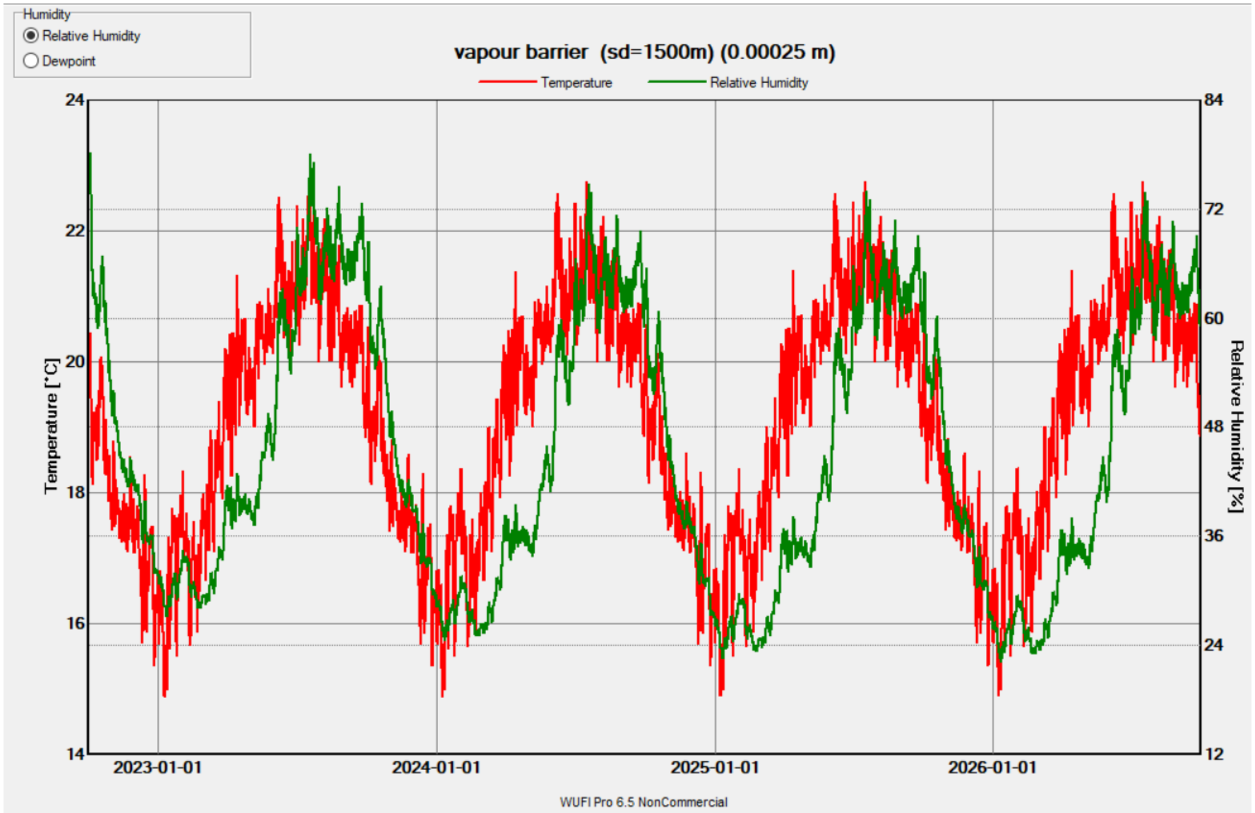


Roof: Relative Humidity Measured on Interior Facing Interface of Vapour Barrier

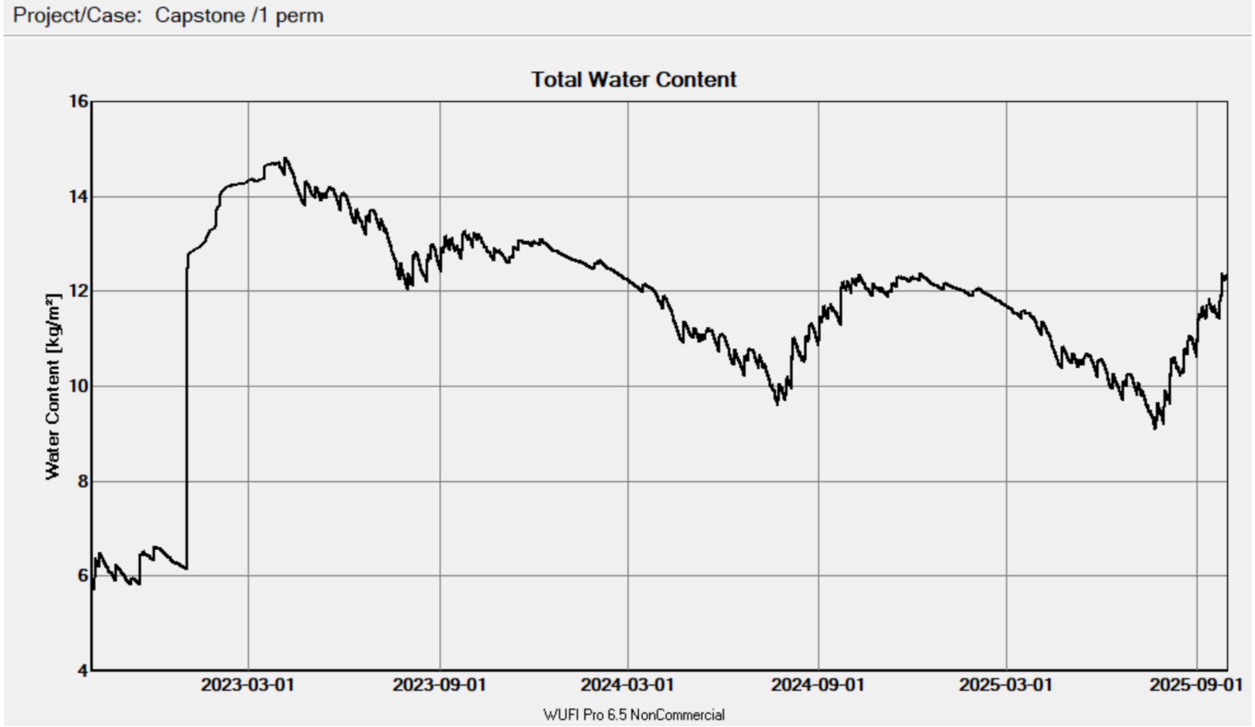


Humidity
● Relative Humidity
○ Dewpoint

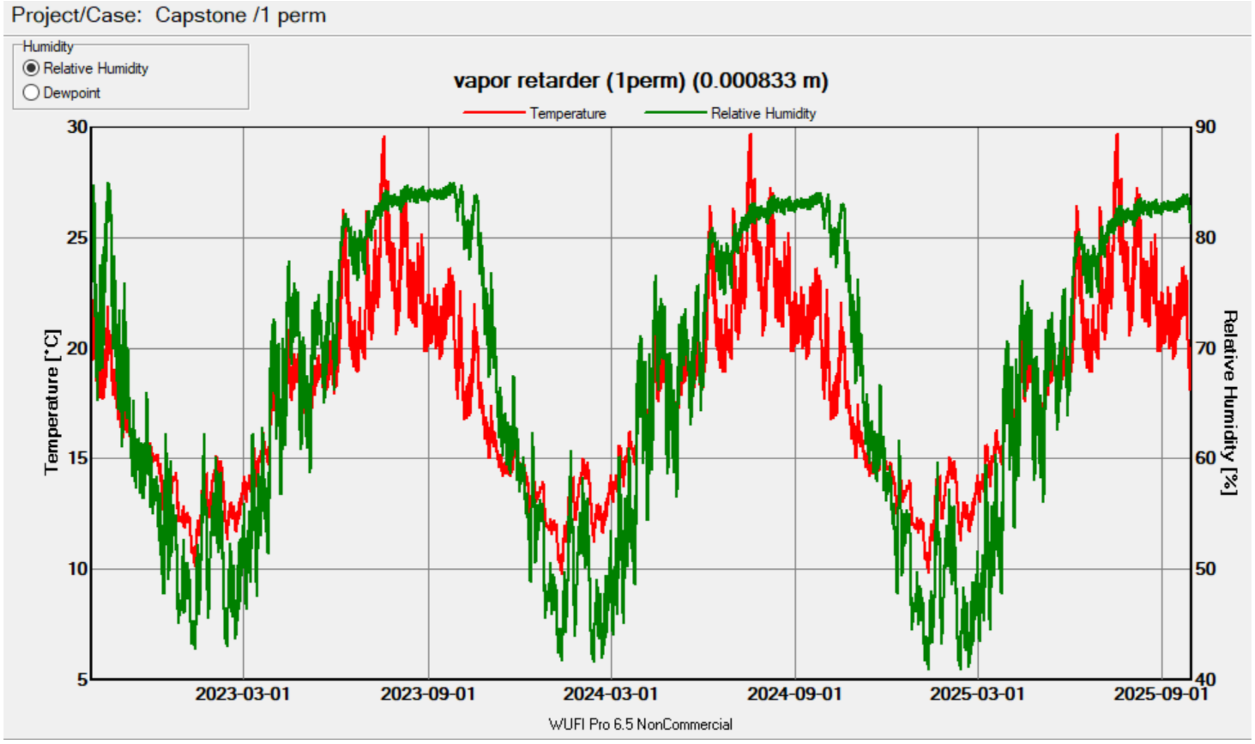
Roof: Relative Humidity Measured on Exterior Facing Interface of Vapour Barrier



Wall: Total Water Content



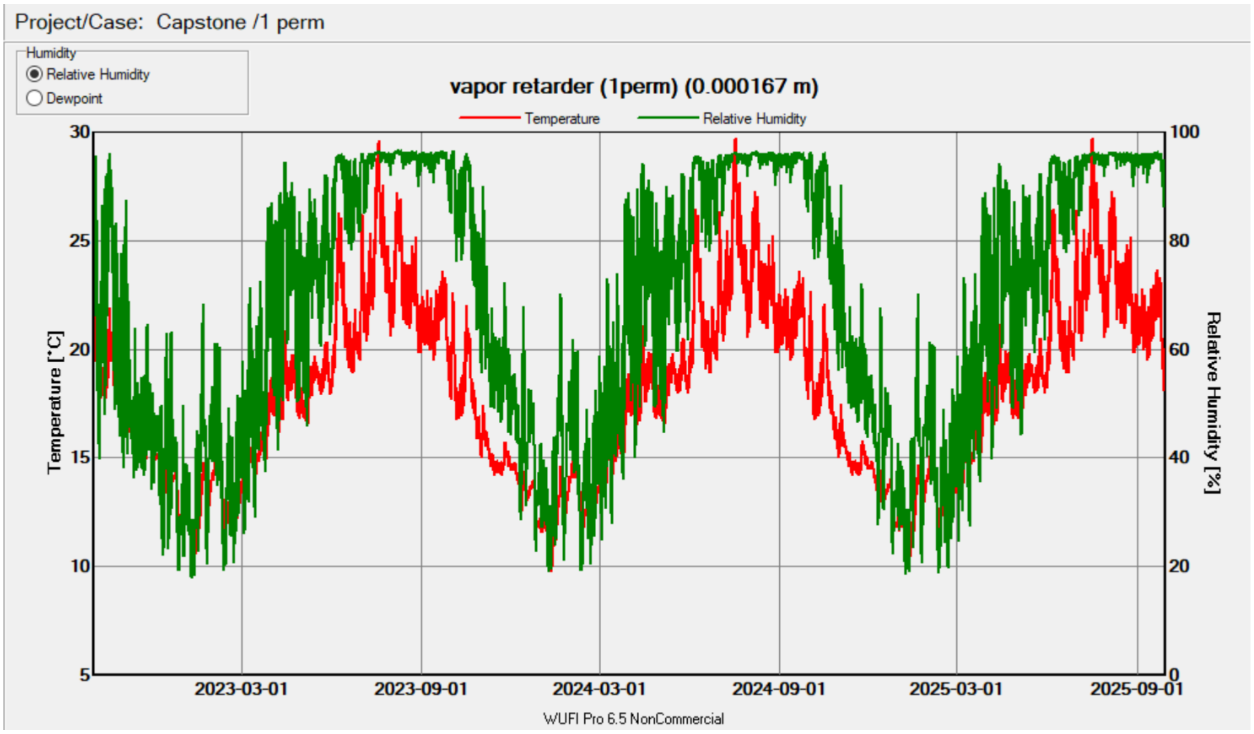
Wall: Relative Humidity Measured on Interior Facing Interface of Vapour Barrier



Project/Case: Capstone /1 perm

Humidity
● Relative Humidity
○ Dewpoint

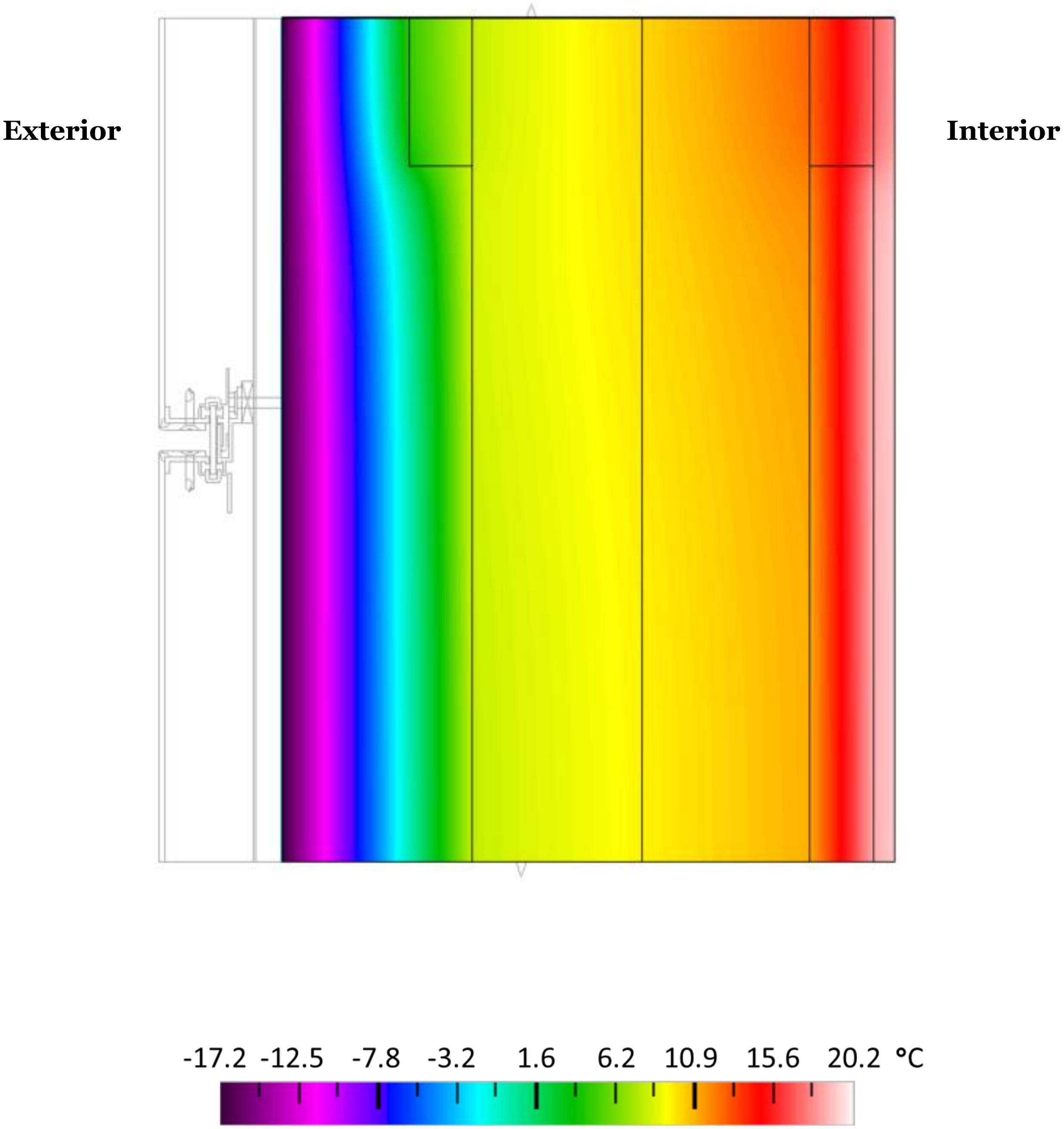
Wall: Relative Humidity Measured on Exterior Facing Interface of Vapour Barrier



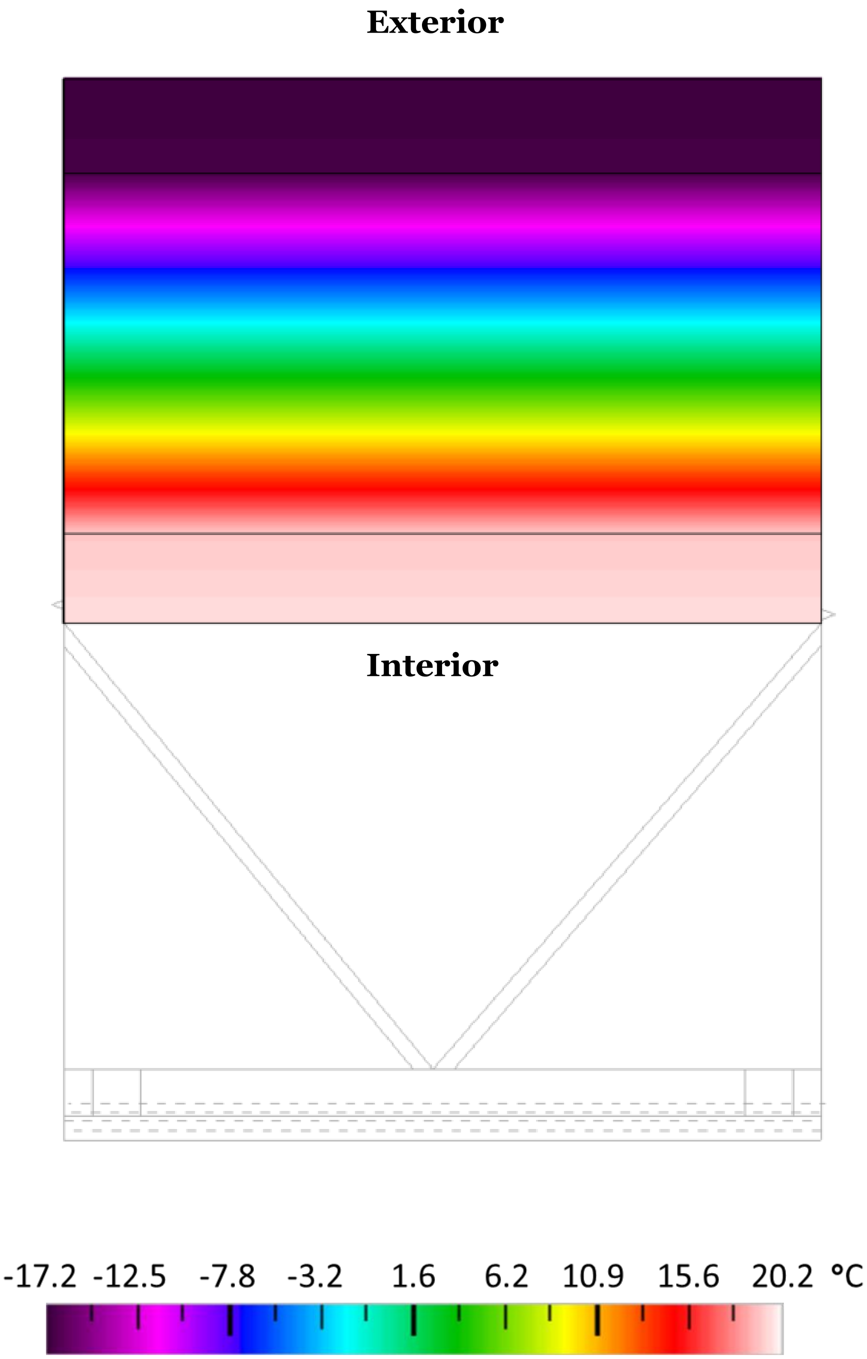
Project/Case: Capstone /1 perm

Humidity
● Relative Humidity
○ Dewpoint

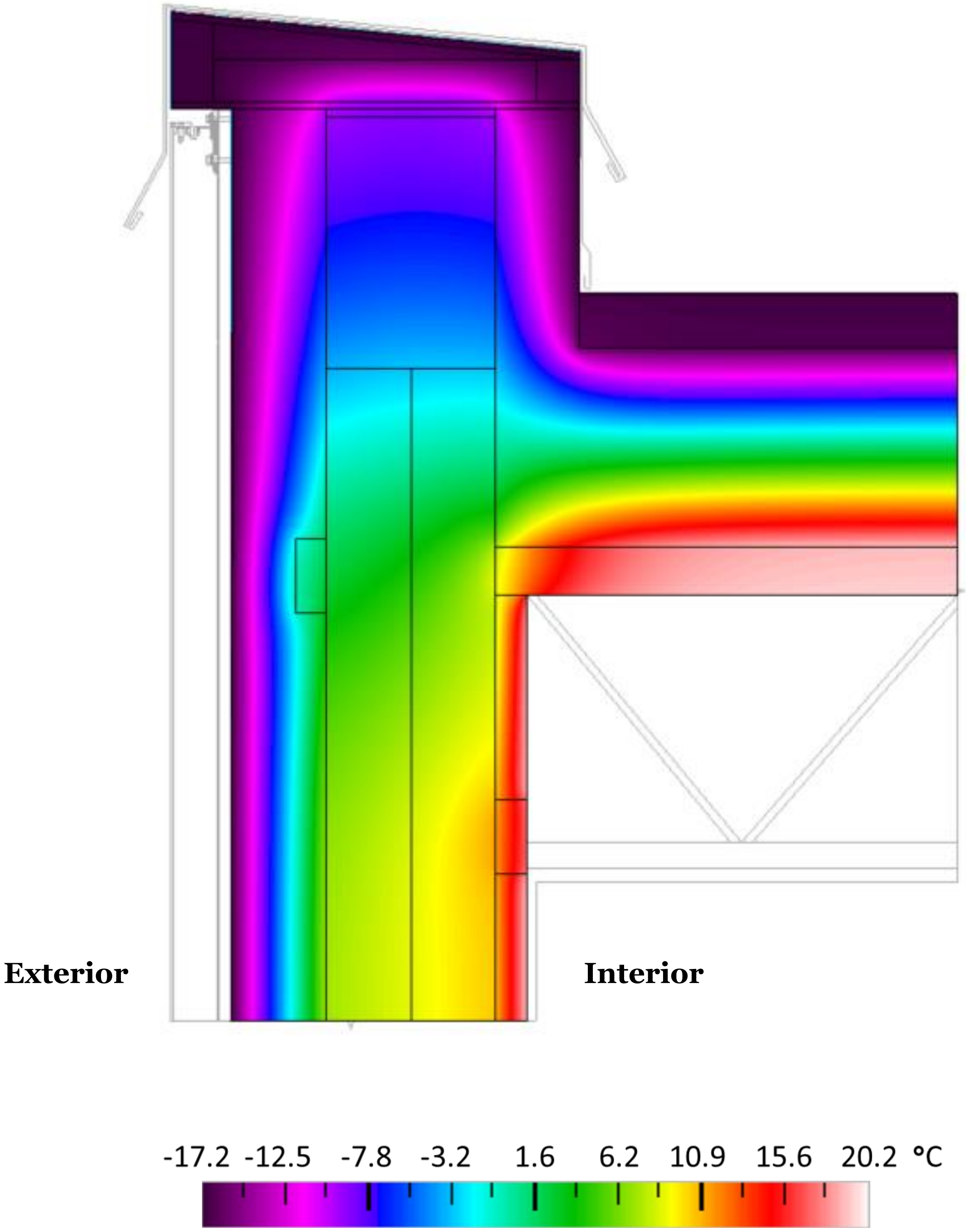
Appendix D: THERM Models



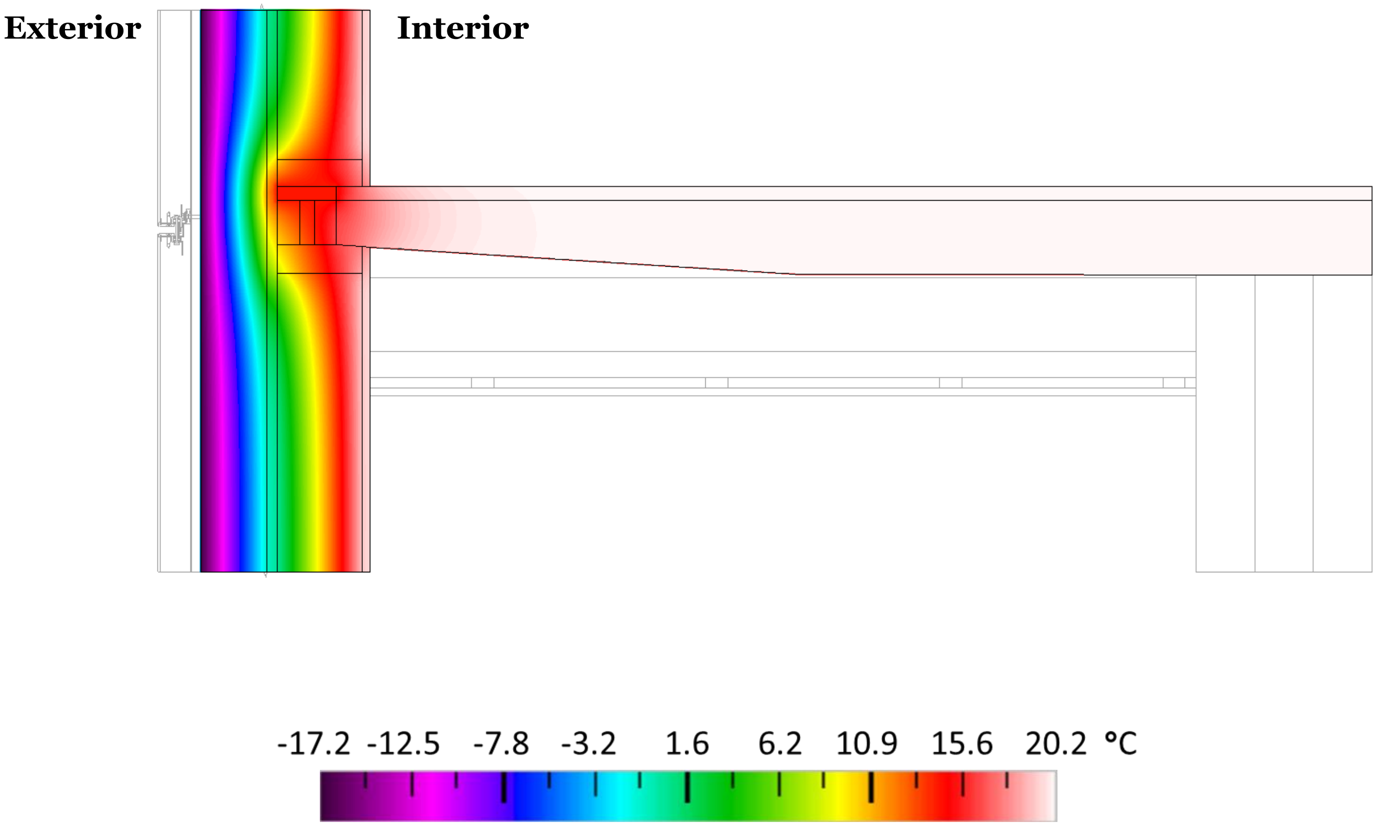
Clear Wall Assembly



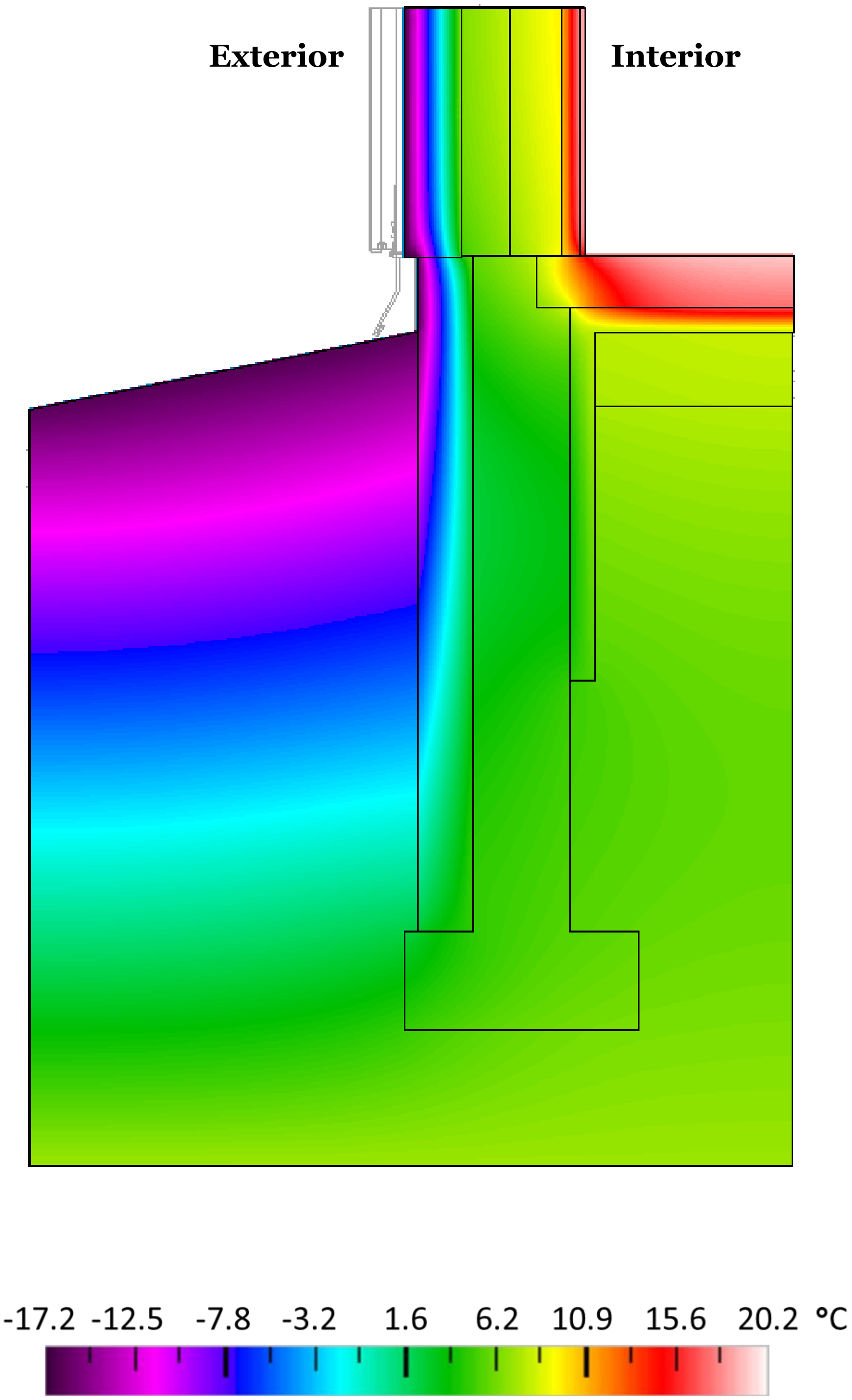
Clear Roof Assembly



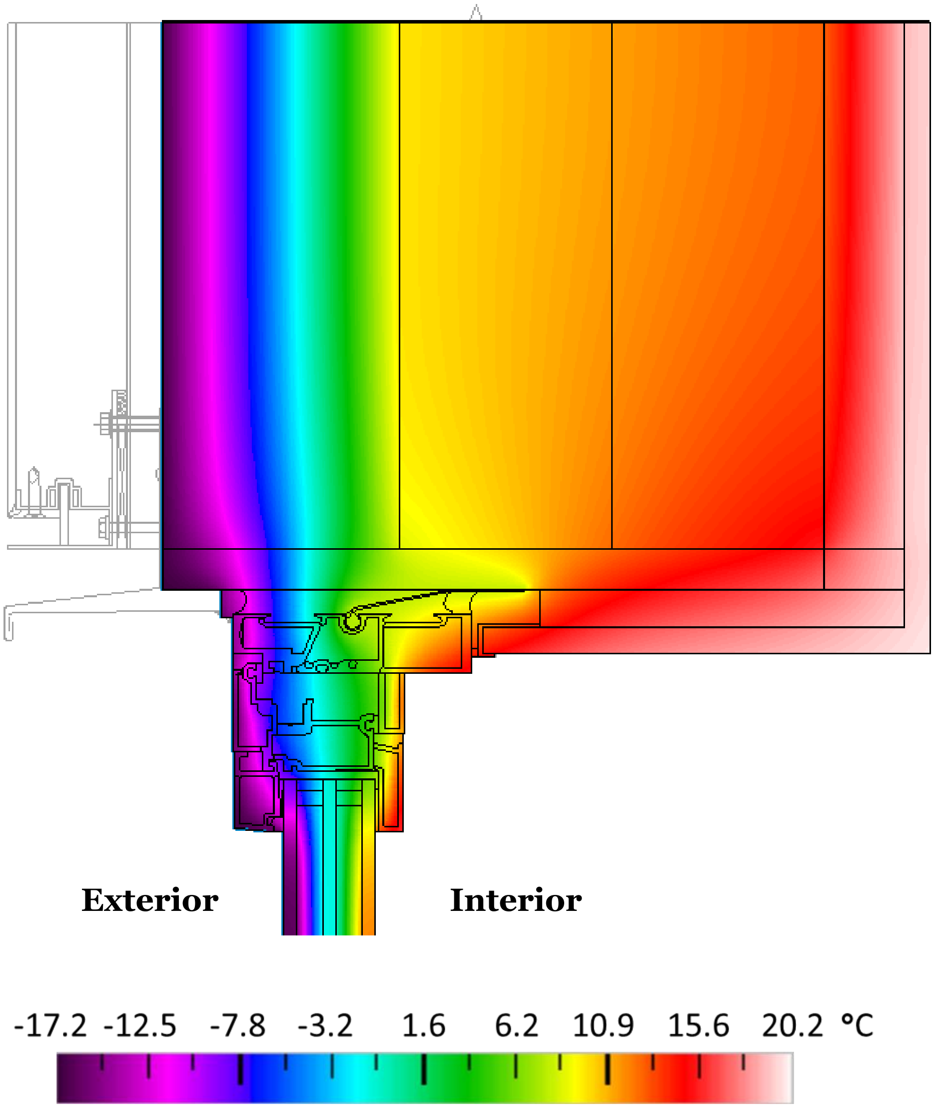
Wall-to-Roof Connection



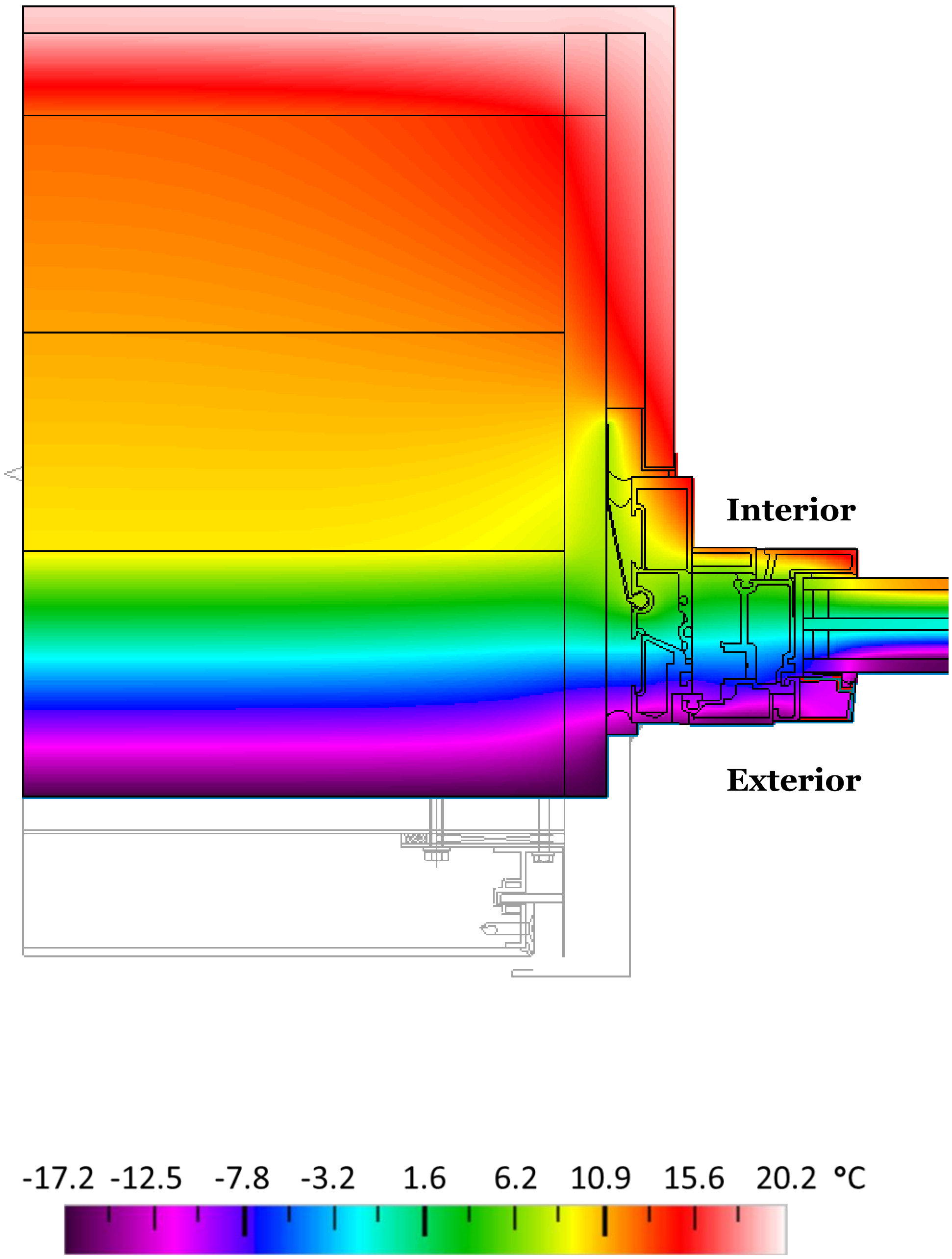
Wall-to-Balcony Connection



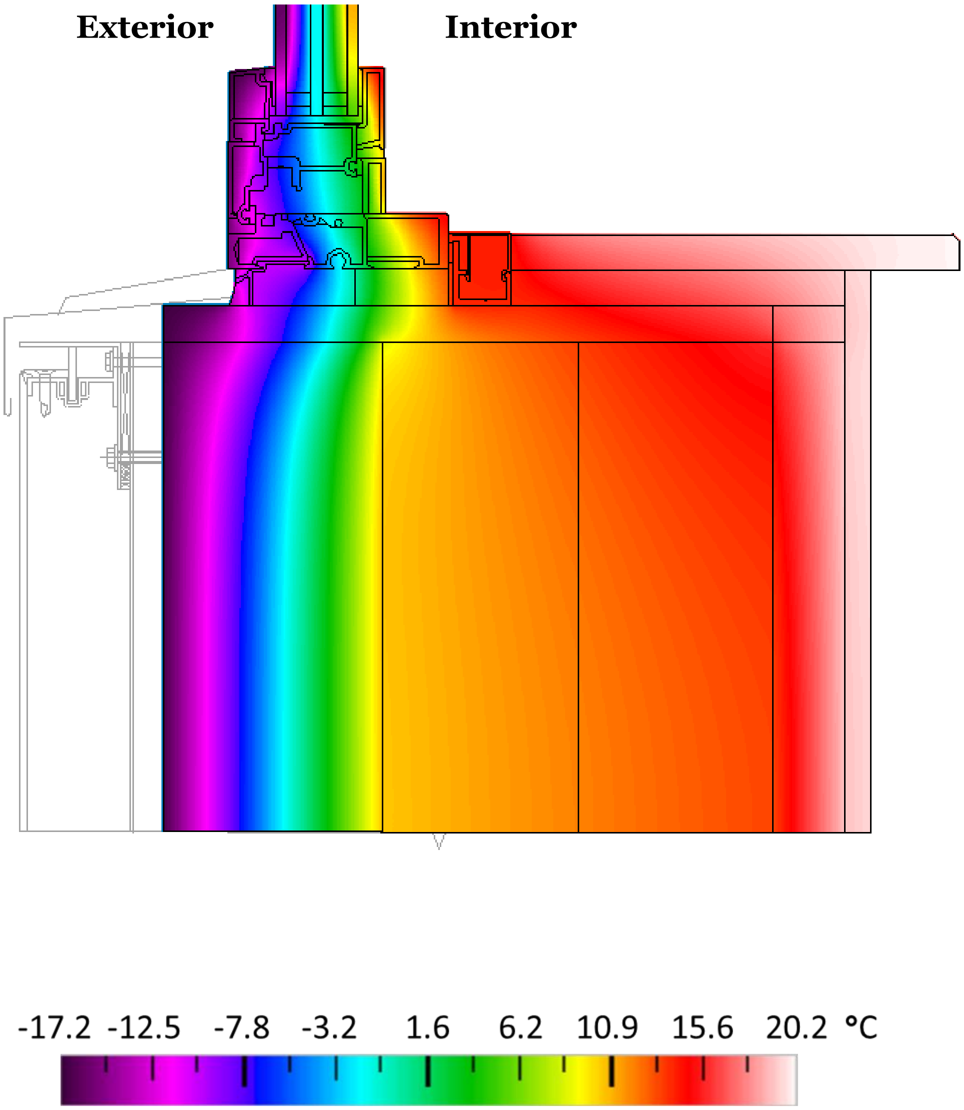
Wall-to-Foundation Connection



Wall-to-Window Head Connection



Wall-to-Window Jamb Connection



Wall-to-Window Sill Connection

Appendix E: Energy and Thermal Autonomy

Thermal Model Inputs

Climate File Location: Toronto

Loads	
Use Type	ResidenceHallDormitory
People	
People Density [p/m2]	0.027802
Metabolic Rate	1.2
Occupancy Schedule	MidriseApartment-5A_APT_OCC_SCH_Year
Airspeed Schedule	Airspeed 0
Equipment	
Equipment Power Density [W/m2]	6.935887781 (**CORE** = **OFF**)
Equipment schedule	MidriseApartment-5A_APT_EQP_SCH_Year
Lights	
Lighting Power Density [W/m2]	2.260495156
Lights Availability Schedule	MidriseApartment-5A_APT_LIGHT_SCH_Year
Illuminance Target	200
Dimming Type	Off
HVAC	
Heating	
Schedule	MidriseApartment-5A_APT_HTGSETP_SCH_Year
Availability Schedule	AllOn
Max supply air temp C	30
Limit	No Limit
Heating Limit	100
Flow Limit	100
Heating COP	2.5
Cooling	
Schedule Setpoint	MidriseApartment-5A_APT_CLGSETP_ SCH_Year
Availability schedule	AllOn
Limit	No limit
Cooling Limit	100
Flow Limit	100
Cooling COP	4
Humidity Control	
Off	
Mechanical Ventilation	
Fresh air / person	2.5
Fresh air /zone area	0.3
Availability Schedule	AllOn
Heat Recovery	None
Sensible Recovery Ratio	NA
Latent Recovery Ratio	NA
Economizer	NoEconomizer

Fan Energy using EMS	
Off	
Ventilation	
Scheduled Ventilation	
Off	
Natural Ventilation	
Off	
Setpoint	NA
Min Outdoor Temp	NA
Max Outdoor Temp	NA
Max Rel Humidity	NA
Schedule	NA
Infiltration	
Infiltration (ACH)	0.3
Constant Term Coeff	1
Temperature Term Coeff	0
Velocity Term Coeff	0
Velocity squared term Coeff	
AirMassFlow Coeff	0.001
Hot Water	
Peak Flow [l/h/person]	5.66667
Supply Temp	60
Mains Temp	10
Schedule	MidriseApartment-5A_APT_DHW_SCH_Year
Hot Water COP	2
Settings	
Carbon and Cost Factors	
Heating Fuel CO2 [kg/kwh]	0.178843767
Heating Fuel Cost [$/kwh]	0.010150047
Cooling Fuel CO2 [kg/kwh]	n/a
Cooling Fuel Cost	n/a
Hot Water Fuel CO2 [kg/kwh]	0.178843767
Hot Water Fuel Cost	0.010150047
Electricity CO2	0.04
Electricity Cost	0.113
Zone Behaviour	
Partition assembly order	1
Inside Convection Alg	TARP
Outside Convection Alg	DOE2
Roof tilt angle	10
Ext floor tilt angle	180
Grid Height	0.8
Grid Spacing	1

Energy Performance Results

Existing Building

		End Use			Site Use	
	GJ	kWh	EUI	COP	kWh	EUI
Heating	3347.8	930693.8	102.68	0.8	1163367	128.35
Cooling	0.0	0	0	0.0	0	0
Interior Lighting	775.5	215642.1	23.791	1.0	215642.1	23.791
Interior Equipment	1184.9	329404.7	36.342	1.0	329404.7	36.342
Domestic Hot Water	1200.4	333701	36.816	0.8	417126.3	46.02

Retrofitted Building 2022

		End Use			Site Use	
	GJ	kWh	EUI	COP	kWh	EUI
Heating	1977	549720	61	2.5	219888	24
Cooling	143	39801	4	4.0	9950	1
Interior Lighting	190	52798	6	1.0	52798	6
Interior Equipment	977	271564	30	1.0	271564	30
Domestic Hot Water	797	221683	24	2.0	110841	12

Retrofitted Building 2050

		End Use			Site Use	
	GJ	kWh	EUI	COP	kWh	EUI
Heating	1105	307590	34	2.5	123036	14
Cooling	830	230818	25	4.0	57704	6
Interior Lighting	190	52798	6	1.0	52798	6
Interior Equipment	977	271564	30	1.0	271564	30
Domestic Hot Water	797	221683	24	2.0	110841	12

Comparison of energy KPIs

Scenario	TEDI [kWh/m2 yr]	TEDI Reduction over Existing [%]	EUI []	EUI Reduction over Existing [%]
Existing Building	103	NA	235	NA
Retrofitted Building 2022	65	37	73	69
Retrofitted Building 2050	59	42	68	71

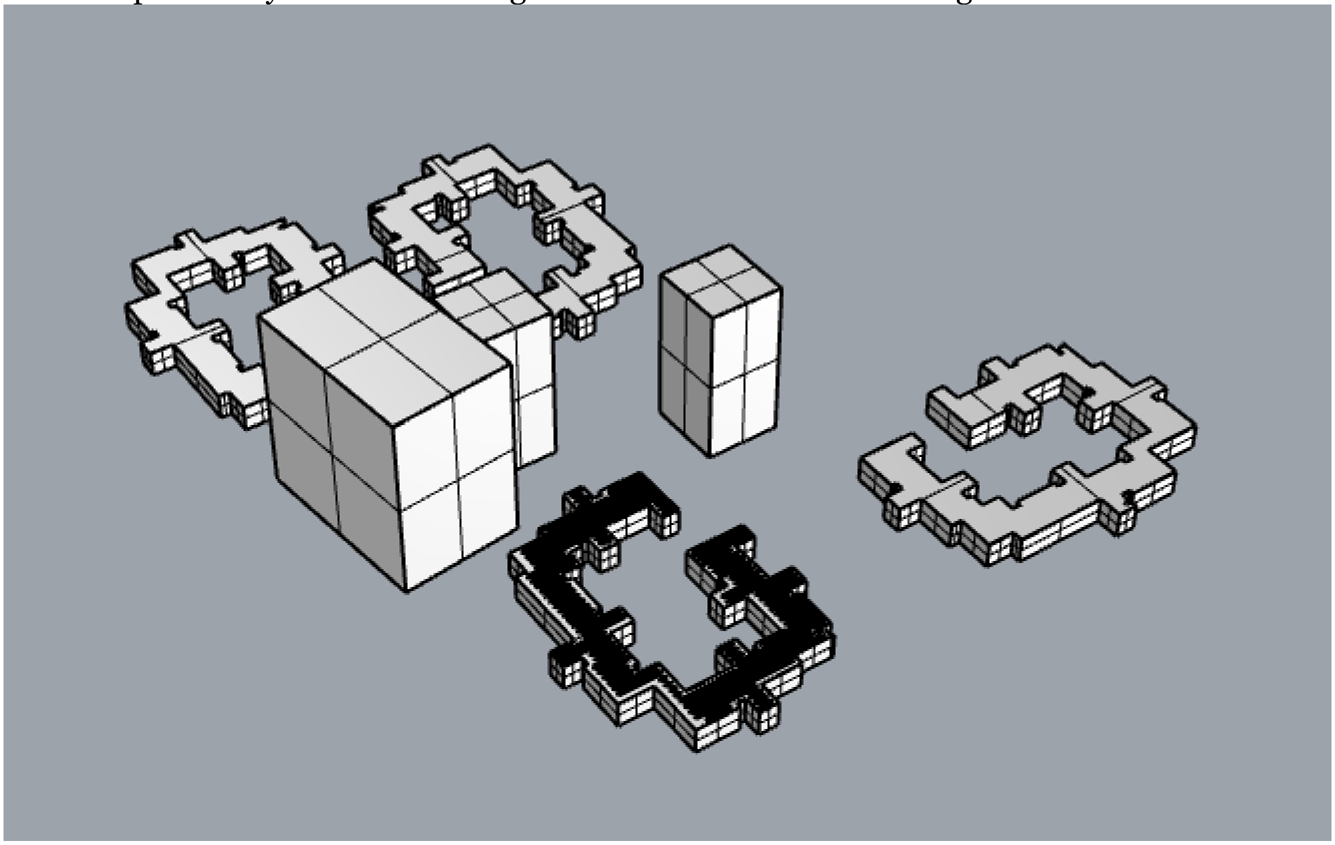
Thermal Autonomy

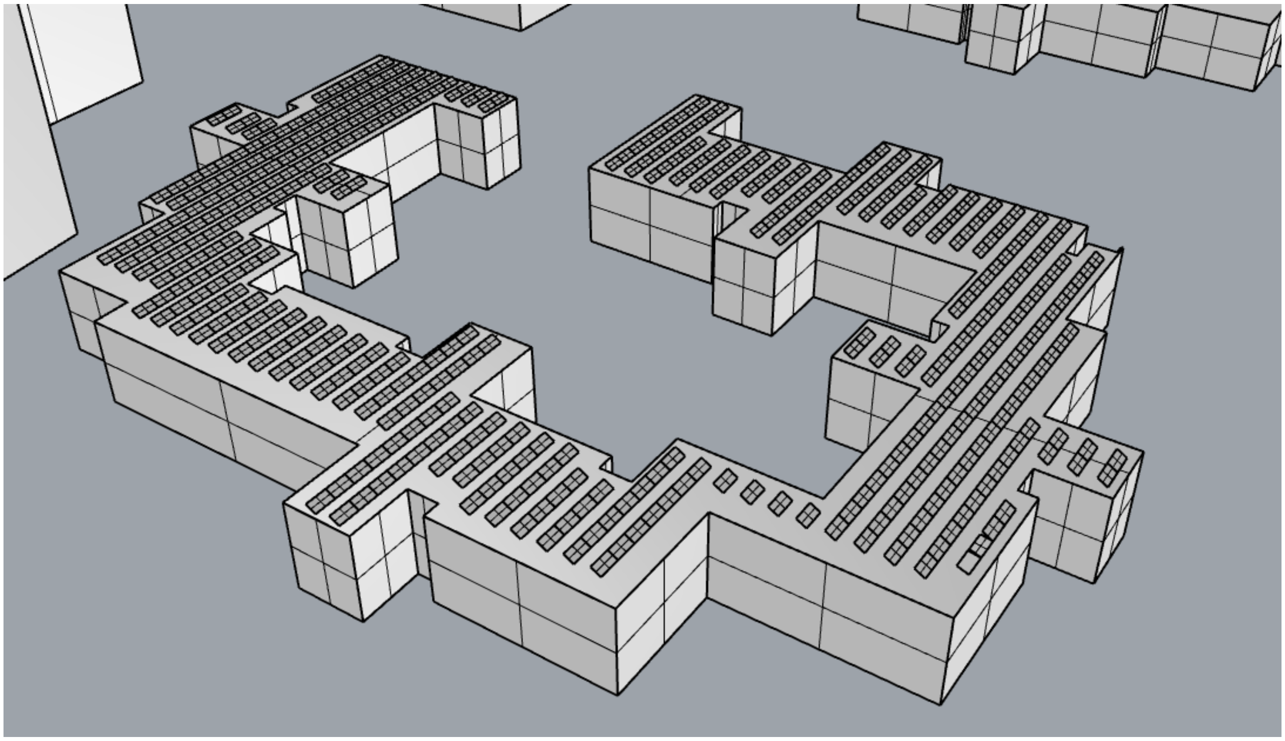
	Existing Building	Retrofitted Building 2050	Retrofitted Building 2022
hours under 18 degrees	4839	2028	1570
hours over 25 degrees	0	827	730
% Thermal not autonomous	0.556	0.328	0.264
% Thermal autonomous	44.321	67.149	73.535
% different from existing	NA	-22.828	-29.214

Appendix F: Solar Energy Potential

Solar Radiance Potential

ClimateStudio Radiation Map used to analyze direct solar exposure. See renders below of roof top PV array and surrounding site that was used for modeling.





Site EUI [kWh/m2/yr]	70.9
Building area [m2]	9064
Site Total energy use [kWh/yr]	642639
Panel efficiency	20%
Panel Size [m2]	2
Inverter efficiency	96%

PV location	Type of system	Direction	Tilt	Number of Panels	Area	Annual Solar Radiation [kwh/m2/yr]	Total Annual Solar Radiation [kwh/m2/yr]	Percent of demand met
East Parking Lot	ground-mounted	South-West	15	1014.1	1346.0	518.3	262081.4	40.8
West parking lot	ground-mounted	South-West	15	464.2	1346.0	518.3	119967.8	6.0
South parking lot	ground-mounted	South-East	15	144.6	1400.0	129.8	38856.63	18.7
Roof	Roof-mounted	South-East	30	476.0	952.0	1417	259004.9	40.3
All outside faces	BIPV	Various	90	na	2922.0	777	435915.6	67.8
All Court faces	BIPV	Various	90	na	2110.0	762	308701.4	48.0
North Faces	BIPV	North-West	90	na	997.3	465	89041.04	13.9
East faces	BIPV	North-East	90	na	1194.9	610	139941.1	21.8
West Faces	BIPV	South-East	90	na	1189.4	925	211233.1	32.9
South faces	BIPV	South-West	90	na	969.9	1000	186221.9	29.0

Calculations for wind load uplift on roof solar PV arrays. (Canadian Commision on Building and Fire Codes, National Research Council of Canada, 2018)

Building dimensions		PV Dimensions		Net pressure coefficient	
h (m)	8.45	h (m)	2	γp	0.9355
hpt (m)	0.3	l (m)	1	γc	0.8
				Eex	1.5
				Eunex	1

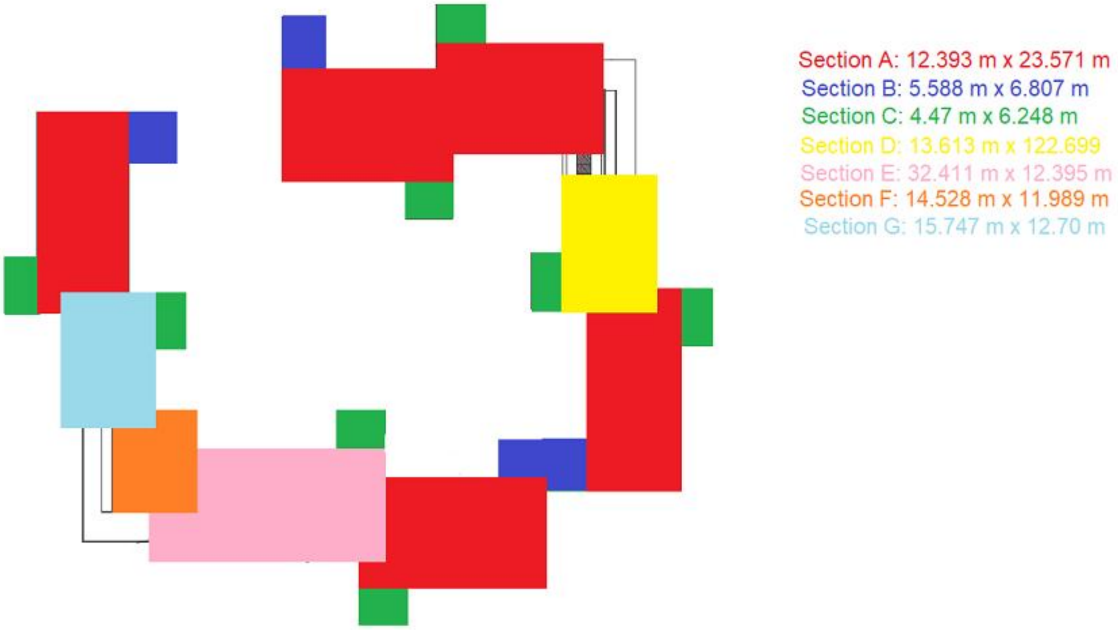
	Roof		Size of roof zones			Tributary area for array		(CgCp)n (0-5 deg)[1]	(CgCp)n (15-30 deg)[1]	0-5 deg			15-30 deg			0-5 deg[2]			15-30 deg[2]		
Area	Ws (m)	Wl (m)	Zone 1	Zone 2	Zone 3	Lb	AN (m^2)			Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3	P1	P2	P3	P1	P2	P3
			-10.2	-21.407	16.9			1.32	1.9	Exposed			Exposed			Exposed			Exposed		
										1.482	1.965	2.223	2.133	2.975	3.480	0.345	0.458	0.518	0.497	0.694	0.811
A	12.4	24				5.65	62.76	1.75	2.65	Unexposed			Unexposed			Unexposed			Unexposed		
			-21.4	16.9	16.9			1.98	3.1	0.988	1.310	1.482	1.422	1.983	2.320	0.230	0.305	0.345	0.332	0.462	0.541
			-27	-28.212	16.9			1.25	1.8	Exposed			Exposed			Exposed			Exposed		
										1.403	1.796	2.021	2.021	2.694	3.256	0.327	0.419	0.471	0.471	0.628	0.759
B	5.59	6.8				3.03	80.00	1.6	2.4	Unexposed			Unexposed			Unexposed			Unexposed		
			-28.2	16.9	16.9			1.8	2.9	0.936	1.197	1.347	1.347	1.796	2.170	0.218	0.279	0.314	0.314	0.419	0.506
			-27.6	-29.33	16.9			1.25	1.8	Exposed			Exposed			Exposed			Exposed		
										1.403	1.796	2.021	2.021	2.694	3.256	0.327	0.419	0.471	0.471	0.628	0.759
C	4.47	6.2				2.91	80.00	1.6	2.4	Unexposed			Unexposed			Unexposed			Unexposed		
			-29.3	16.9	16.9			1.8	2.9	0.936	1.197	1.347	1.347	1.796	2.170	0.218	0.279	0.314	0.314	0.419	0.506
			-20.2	-21.101	16.9			1.25	1.8	Exposed			Exposed			Exposed			Exposed		
										1.403	1.796	2.021	2.021	2.694	3.256	0.327	0.419	0.471	0.471	0.628	0.759
D	12.7	14				4.29	80.00	1.6	2.4	Unexposed			Unexposed			Unexposed			Unexposed		
			-21.1	16.9	16.9			1.8	2.9	0.936	1.197	1.347	1.347	1.796	2.170	0.218	0.279	0.314	0.314	0.419	0.506
			-1.39	-21.405	16.9			1.45	2	Exposed			Exposed			Exposed			Exposed		
										1.628	2.189	2.470	2.245	3.199	3.817	0.379	0.510	0.576	0.523	0.746	0.890
E	12.4	32				6.62	45.64	1.95	2.85	Unexposed			Unexposed			Unexposed			Unexposed		
			-21.4	16.9	16.9			2.2	3.4	1.085	1.459	1.646	1.497	2.133	2.545	0.253	0.340	0.384	0.349	0.497	0.593
			-19.3	-21.811	16.9			1.25	1.8	Exposed			Exposed			Exposed			Exposed		
										1.403	1.796	2.021	2.021	2.694	3.256	0.327	0.419	0.471	0.471	0.628	0.759
F	12	15				4.43	80.00	1.6	2.4	Unexposed			Unexposed			Unexposed			Unexposed		
			-21.8	16.9	16.9			1.8	2.9	0.936	1.197	1.347	1.347	1.796	2.170	0.218	0.279	0.314	0.314	0.419	0.506
			-18.1	-21.1	16.9			1.25	1.8	Exposed			Exposed			Exposed			Exposed		
										1.403	1.796	2.021	2.021	2.694	3.256	0.327	0.419	0.471	0.471	0.628	0.759
G	12.7	16				4.61	80.00	1.6	2.4	Unexposed			Unexposed			Unexposed			Unexposed		
			-21.1	16.9	16.9			1.8	2.9	0.936	1.197	1.347	1.347	1.796	2.170	0.218	0.279	0.314	0.314	0.419	0.506

[1] Taken from Chart I-8 of NBC 2015 Commentary

[2] Net pressure at zones and exposure condtion (kPa) @ different angles

Required thickness of roof gravel ballast based on previous wind uplift calculations

Maximum wind uplift pressure:	0.89	kPa	(Taken from Area E, exposed section P3)
Density of loose dry gravel:	1522	kg/m^3	(Walker, 2016)
	14.93	kN/m^3	
Required thickness	0.06	m	
	or 2.35	"	


Section A: 12.393 m x 23.571 m
Section B: 5.588 m x 6.807 m
Section C: 4.47 m x 6.248 m
Section D: 13.613 m x 122.699
Section E: 32.411 m x 12.395 m
Section F: 14.528 m x 11.989 m
Section G: 15.747 m x 12.70 m