Final Report | Project 21007.000

UBC - Designing Climate Resilient Multifamily Buildings

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0 Summary

0.1 Introduction and Methodology

The primary objective of this study is to assess the implications of increasing outdoor air temperatures due to climate change on the thermal comfort of multifamily residential buildings in the Lower Mainland, and to identify cost-effective design measures that will maintain thermal comfort under future climate conditions.

A variety of climate adaptation and mitigation measures (CAMMs) suitable for both new and existing, high and low rise multifamily residential buildings are explored using future climate projections. Ideally, solutions are identified that improve thermal comfort without sacrificing parallel societal objectives to reduce energy consumption and greenhouse gas emissions. It is also desirable that identified solutions improve the resiliency of buildings to maintain comfort during increasingly common extreme weather events such as unusually high temperatures, wildfire-induced poor air quality, or power outages.

The results of this study will support development of design guidelines, policies and standards that ensure new building provide residents with thermally comfortable environments, as well as programs that improve the thermal comfort of existing residential buildings. This study will also guide best practises for incorporating projections of warmer future climate conditions into building energy modelling and design.

The study evaluated four primary archetypes, representative of the development typologies in UBC's residential neighbourhoods and across the Lower Mainland:

1. New Building: Low Rise
2. New Building: High Rise
3. Existing Building: Low Rise
4. Existing Building: High Rise

To assess future climate impacts, the archetypes were modelled using future climate files specific to UBC, provided by the Pacific Climate Impact Consortium (PCIC). The future climate files are based on the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 8.5 scenario for 2020s, 2050s, and 2080s. The RCP-8.5 pathway represents the 'business as usual' greenhouse gas concentration scenario (i.e. the projected future climate if we take no committed action to reducing carbon emissions).

The following metrics are reported for each archetype and each climate scenario:

→ Number of overheated hours per year, defined according to the 80% acceptability limit outlined in ASHRAE 55-2010 Section 5.3, and the modelled hourly peak operative[1] temperatures (°C) for representative thermal zones within each building. The threshold of 200-hours above the 80% acceptability limit, defined in the City of Vancouver Energy Modelling Guideline (and referenced by the BC Energy Step Code) is used as a reference point in this study since it is the only

[1] Operative temperature is often used as a measure of human thermal comfort. Operative temperature considers the air temperature and the temperature of the surfaces in the space (mean radiant temperature).

currently used standard within BC, although it may not prove acceptable by occupants on a consistent basis, and even less so as outdoor temperatures increase over time.

- → Annual heating and total building energy consumption, including BC Energy Step Code (BC ESC) metrics; thermal energy demand intensity (TEDI) (kWh/m²a), and total energy use intensity (TEUI) (kWh/m²a)
- → Annual cooling energy demand intensity (CEDI) (kWh/m²a) and peak cooling load (W/m²)
- → Greenhouse gas intensity (GHGI) ($kgCO_2e/m^2a$), using City of Vancouver metric as defined in the City of Vancouver's Green Buildings Policy for Rezoning[2]
- → Peak annual heating and cooling demand (W/m²)

The BC ESC and City of Vancouver energy and emission metrics (TEDI, TEUI, GHGI), as well as peak heating and cooling demand, are reported at the building level, whereas the results for thermal comfort are reported at the zone level.

Costing was completed to gauge cost-effectiveness, and sensitivity analysis was completed to evaluate the resilience of proposed solutions to power outages, high internal gains, loss of natural ventilation, and higher than predicted temperatures.

0.2 Recommendations for Methods and Standards

Drawing on the study results, a number of design strategies and modelling recommendations are offered, with the intent of informing future analysis, program and policy development.

0.2.1 Design Strategies

*For **new** multi-family residential buildings:*

- → Designing for reduced WWR and SHGC are both promising strategies given that they reduce the risk of overheating with either a negligible or positive impact on incremental costs. It is recommended that these be considered as core design considerations in the near term. However, both strategies may reduce winter solar gains and increase thermal energy demand, and as such, each strategy must be evaluated within the context of a specific project and its other performance metrics.
- → Dramatically improving window thermal performance (e.g. to Passive House level) without also addressing solar heat gain, via a reduced SHGC and/or shading measures, can put the building at risk of overheating. This leads the team to recommend that as building designs progress toward the highest steps of the BC ESC that solar heat gain reduction measures also be required. Reduced SHGC targets beyond what is already required by code would be one way to address this, or inclusion of exterior shading.
- → For the low-rise new archetype, the results indicate that upgrading the ventilation system to include a high efficiency HRV (with boost and bypass modes), plus a cooling

[2] City of Vancouver, Green Buildings Policy For Rezoning – Process and Requirements, June 25, 2014

coil downstream of the HRV, meets the thermal comfort criteria based on RCP-8.5 2050s climate. This suggests that a separate mechanical cooling system is not generally required for this archetype in the 2050s climate, provided we accept the 200-hr 80% acceptability limit.

- → If not constrained to use a district heating system, heat pumps could also be installed at the time of construction to efficiently provide both heating and cooling. The modeling results for an electric baseboard baseline showed that adding partial or full cooling *in combination with passive measures* significantly increases the thermal comfort when modelled with the RCP-8.5 2050s climate scenario, with no or minimal negative impact on GHG emissions, total energy use, or the operating energy cost of the building.
- → If centralized HRVs are used, distribution ducts could be oversized during design to allow additional capacity for cooling in the future. Current best practice for high efficiency HRVs is to size at 150-160% capacity, which enables boost airflow and additional cooled air to be circulated when needed.
- → Combined in-suite HRV heat pumps are an emerging technology that may be suitable for condominium buildings that have individual suite metering and ownership.
- → Further work could include the development of design guidelines for a range of cooling (or 'partial' cooling) strategies as we prepare buildings for future climate conditions.
- → In order to meet thermal comfort in the current and future climate without sacrificing energy demand reduction targets, it is recommended that any building that includes partial or full mechanical cooling also include design elements to mitigate solar heat gain (such as exterior shading and/or low SHGC) and thereby manage cooling equipment loads. This will also reduce annual energy costs, electricity demand charges and provide greater resiliency to power outages and poor air quality events such as forest fires.
- → A well-insulated, airtight enclosure, paired with passive cooling strategies, is shown to be beneficial for mechanically cooled archetypes in terms of reducing peak cooling demand and annual cooling demand. It is also shown to be beneficial for non-mechanically cooled buildings in terms of improving thermal comfort. A high performance enclosure also reduces the total building energy use, greenhouse gas emissions and annual energy cost.
- → A Cooling Energy Demand Intensity (CEDI) metric is used in this study to quantify the cooling demand in the current and future climate scenarios. Peak cooling demand is also used. The Passive House Institute cooling demand intensity metric is included as a theoretical reference point for the CEDI[3]. As our climate shifts from heating dominated to cooling dominated, a target for cooling demand intensity and/or peak cooling demand will likely be desired. These targets will guide design professionals toward cooling strategies that consider not just comfort, but also overall energy reduction and resiliency goals.

[3] PHI's cooling demand intensity requirement is not climate specific, while Passive House Institute US (PHIUS) varies its target based on location, building size, and occupant load.

*For **existing** buildings:*

→ Generally speaking, for upgrades to existing building assets, the most cost-effective time to accommodate CAMMs is during a planned renewal. For example, adding exterior shading during a comprehensive cladding and window renewal means that the work can be designed at the same time for a cohesive appearance and proper detailing, and can make use of the same site mobilization such as scaffolding and on-site trades that can accomplish multiple scopes of work. The bundles were selected and costed with this approach in mind, and where applicable, basic renewal with like-for-like components was assumed as a starting point for the incremental costing.

→ As a corollary to the first point, if we *do not* address climate adaptation and mitigation at the time of renewal, there is a lost opportunity cost, as major building assets such as windows and siding are typically only renewed once every 40 or 50 years. There is therefore some urgency with which programs and policies may be developed to support this type of work for existing buildings.

→ A primary focus for retrofitting existing buildings (both low and high rise) in the near term should be on mitigating direct solar heat gain through existing high solar gain windows. Any passive measures that reduce solar heat gain are shown to significantly improve thermal comfort performance with this archetype and should be encouraged at every opportunity. If resources are limited, such efforts could focus on the south and west facing elevations where the solar heat gains are most impactful.

→ Further to the first point, it is recommended that any existing building that is considering adding full mechanical cooling also incorporate passive solar heat gain mitigation measures (e.g. exterior shading). This will increase the likelihood that an added cooling system will actually be able to meet the peak cooling load. This will also reduce the likelihood that the existing electrical capacity is exceeded with the addition of new equipment. While not evaluated in this study, it is possible that the cost of adding passive heat gain mitigation measures would be less than the cost to upgrade a building's electrical service.

→ Combined in-suite HRV heat pumps are an emerging technology that may be suitable for existing condominium buildings that have individual suite metering and ownership. This type of equipment would enable existing buildings, which typically have neither mechanical cooling nor mechanical ventilation, to address efficient heating, cooling and ventilation needs in a single piece of equipment, although passive measures would likely also be required (similar to the HRV + cooling coil case). Additional analysis is recommended to evaluate the best applications, available products, and demand reduction measures for this technology.

0.2.2 Modelling considerations and recommendations

→ Current modelling guidelines prescribe the use of CWEC 2016 weather files, which are based on historical data. As this study has shown, the use of future climate models dramatically changes the modelled results for the key overheating metrics. With the understanding that the climate will continue to change throughout a building's lifetime, it is strongly recommended that the modeling and design of new buildings incorporate future climate considerations.

- → The historical CWEC files upon which the future climate files are built, are provided in TMY format and are created by combining twelve statistical median months chosen from a continuous 15-30-year period of historical data. This approach results in a file that represents the average climate and does not include events such as cold snaps or heat waves. There is currently no requirement to use climate files that represents warmer (or colder) conditions than average, to stress test archetypes for Step Code compliance.

  As such, it is recommended that further analysis is conducted to identify a reasonable set of current and future climate files that modellers can use to test the resilience of new building designs to extreme temperature events.

- → The definition of overheating outlined in the City of Vancouver Energy Modelling Guideline v.2.0. was followed in this study for non-mechanically cooled buildings. The upper temperature limit used to determine an overheated hour is a function of the mean outdoor air temperature. In this analysis, the upper temperature limit was calculated based on each climate file. As such, the upper temperature limit increases as the climate warms and the number of overheated hours is lower than if the upper temperature limit would have been held constant throughout (based on the CWEC file). Further scope could focus on developing a consistent approach and metrics around overheating design limits.

- → The sensitivity analysis around internal heat gains suggests that higher than expected internal gains can have a significant impact on overheating. Further investigation may be warranted to validate current modelling standard practice and/or designers need to be aware of projects that are likely to have higher occupant loads or other internal gains and accommodate those in the modelling.

- → There is currently no standard available for modelling of natural ventilation. For consistency within the industry, further scope is recommended to focus on developing a guideline for modelling of natural ventilation as overheating studies becomes more common.

0.3 Key Findings – Archetype Modeling

0.3.1 Low Rise New Building

- → The Step 4 low rise baseline archetype performs better from a thermal comfort perspective than the Step 3 low rise archetype.

- → Both Step 3 and Step 4 baseline archetypes are vulnerable to overheating under the 2050s scenario. This suggests that some deliberate design strategies beyond simply meeting the current BC ESC metrics are required to address future thermal comfort.

- → Reduced Window to Wall Ratio and glazing with a reduced Solar Heat Gain Coefficient are two essentially zero incremental cost design measures with a beneficial impact on reducing the risk of overheating.

- → For the Step 4 archetype, all modelled passive and combined (passive and active) bundles meet the thermal comfort criteria based on the RCP-8.5 2050s climate, though only the bundles including partial or full mechanical cooling meet the thermal comfort criteria for the Step 3 archetype.

→ For both the Step 3 and Step 4 archetypes, adding partial or full mechanical cooling is shown to increase the annual energy cost (due to an increase in electricity consumption). However, both solutions show that all overheated hours can be eliminated when modelled under the RCP-8.5 2050s climate scenario, without increasing the GHG emissions. The increase in utility cost is due to the baseline assumption of district heating, which is currently less than half the cost of grid electricity. If the baseline heating system had been, for example, electric baseboards, considerable annual energy cost savings would have been realized in the bundles.

→ The results for both Step 3 and Step 4 archetypes indicate that upgrading the ventilation system to include a high efficiency HRV that can operate in boost and bypass mode as needed, plus a cooling coil downstream of the HRV, meets the thermal comfort criteria based on the 2050s climate file. This suggests that full mechanical cooling is not required for this archetype in the RCP-8.5 2050s climate, provided we accept the 200-hr 80% acceptability limit.

→ The addition of passive measures to the mechanically cooled bundles is shown to reduce the cooling energy consumption and peak cooling demand. The addition of passive cooling measures can also result in lower energy costs due to lower cooling energy use, and may allow for reduced cooling equipment size as a result of decreased peak cooling loads.

→ The peak cooling demand and CEDI are both lower for the fully mechanically cooled Step 4 archetype compared to Step 3, demonstrating the benefit of a high performance enclosure toward reducing mechanical cooling equipment size, cooling energy demand and associated operating costs.

→ A high performing enclosure also increases the likelihood that an emerging technology like combined heat recovery ventilator heat pumps can satisfy heating, cooling and ventilation system needs in a single piece of equipment.

→ It should be noted that the low incremental cost for full mechanical cooling results from the baseline system assumption, which for UBC is hydronic radiant heating with code minimum HRVs. A different type of baseline system would result in a considerably higher incremental cost to change to full mechanical cooling. An additional analysis was completed to understand the cost associated with this measure for a low rise new building with a more common baseline heating system. The archetype in the additional analysis is heated via electric baseboards, while all other characteristics are unchanged. The results of the additional analysis are provided in Appendix D.

Summary graphics of the Step 3 and Step 4 low rise archetype results are shown below.

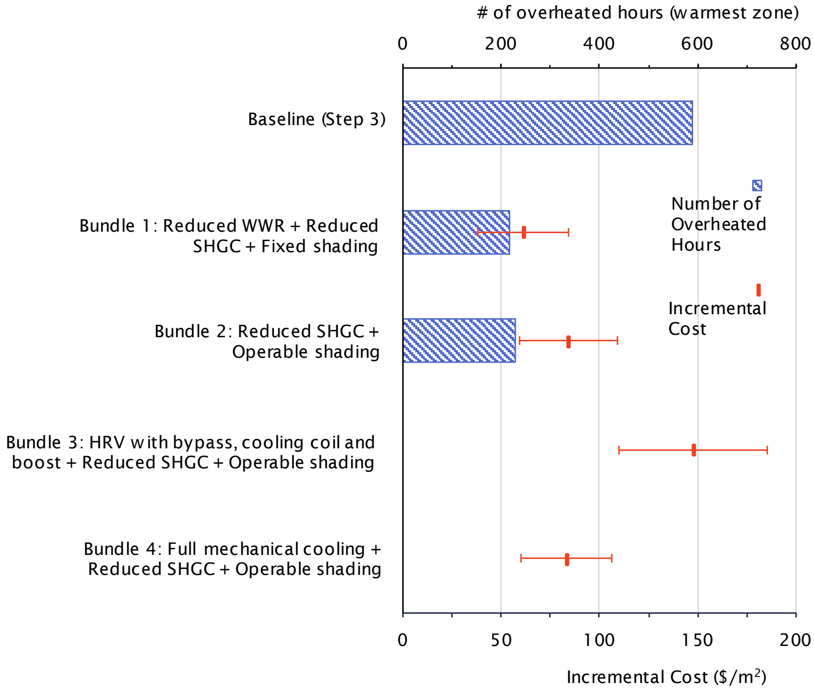

Figure 0.1 Incremental cost ($/m²) for the Step 3 bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

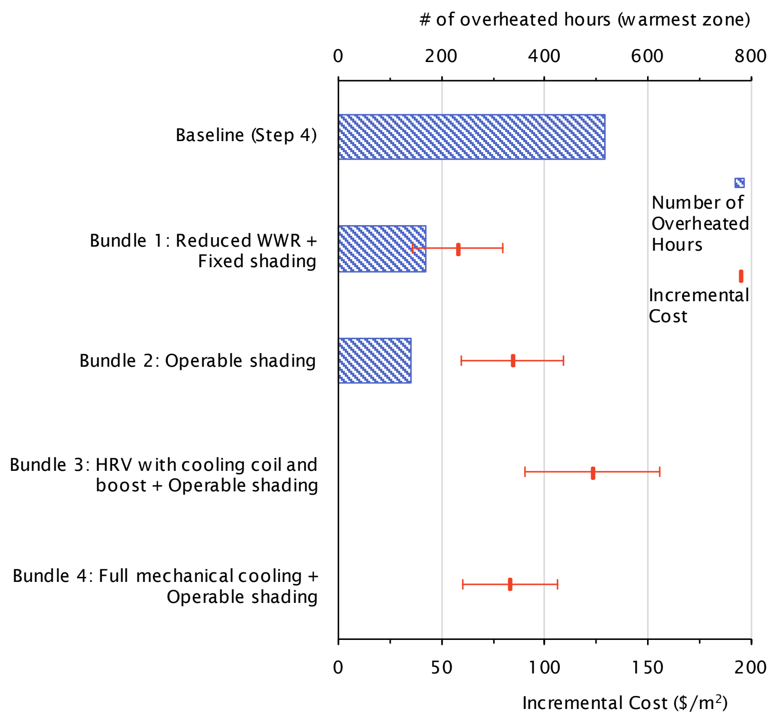

Figure 0.2 Incremental cost ($/m²) for the Step 4 bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

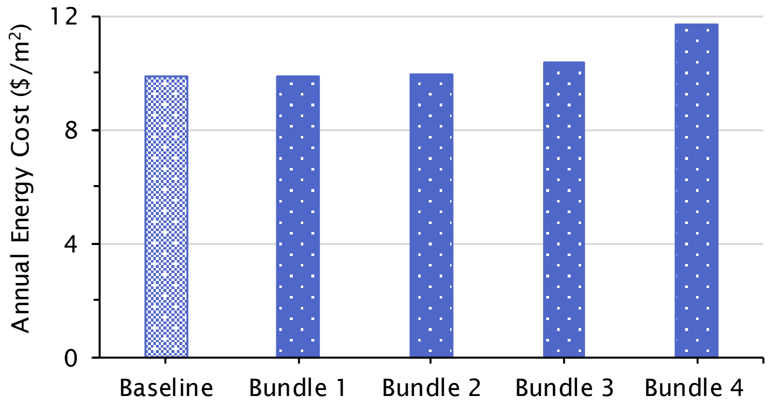

Figure 0.3 Annual energy cost ($/m²) for the Step 3 baseline and bundles.

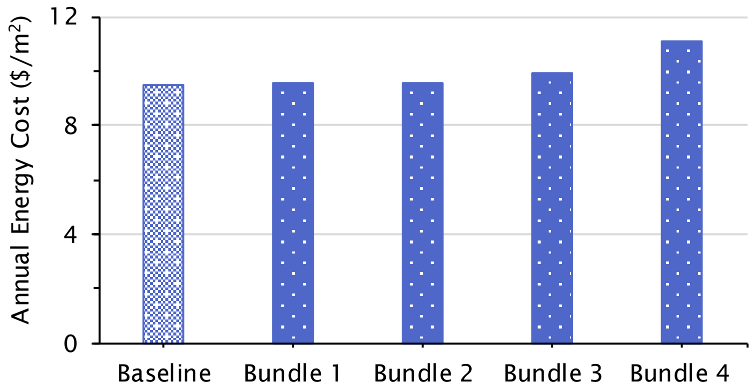

Figure 0.4 Annual energy cost ($/m²) for the Step 4 baseline and bundles.

TABLE 0.1 ENERGY COST SAVINGS COMPARED TO THE BASELINE (STEP 3)				
	Bundle 1	Bundle 2	Bundle 3	Bundle 4
Energy Cost Savings (%)	0%	0%	-5%	-19%

TABLE 0.2 ENERGY COST SAVINGS COMPARED TO THE BASELINE (STEP 4)				
	Bundle 1	Bundle 2	Bundle 3	Bundle 4
Energy Cost Savings (%)	0%	0%	-4%	-16%

0.3.2 High Rise New Building

→ Reduced Window to Wall Ratio and glazing with a reduced Solar Heat Gain Coefficient are two essentially zero incremental cost design measures with a considerable impact on annual cooling energy demand and peak cooling load. However, both strategies may reduce winter solar gains and increase thermal energy demand, and as such, each strategy must be evaluated within the context of a specific project and its other performance metrics.

→ Since there is currently no target established in the BC ESC for annual cooling energy demand (on building level), the Passive House Institute (PHI) criteria of 15 kWh/m²a has been used a reference point. The results show that neither the Step 3 or Step 4 baselines meet this target, while all modelled bundles meet the target.

→ Besides reducing the annual cooling energy consumption, the addition of passive cooling measures is also shown to reduce the peak cooling load and may allow for smaller cooling equipment size.

→ The addition of passive cooling measure also reduces the peak cooling demand on the electricity grid and hence the annual energy cost.

→ The Step 3 and Step 4 bundles consist of the same passive cooling measures, though the Step 4 bundles achieve higher reductions in annual cooling energy demand and peak cooling demand than the Step 3 bundles. The Step 4 baseline includes a higher performing building enclosure. The results therefore illustrate the benefit of a higher performing building enclosure for mitigating peak cooling demand and managing comfort while also meeting energy and emission reduction targets.

→ The peak cooling demand for the building in the Step 4 baseline case is 133 kW, which in itself is a 27 kW reduction over the Step 3 baseline case. With the Step 4 Bundle 2 (Reduced WWR, reduced SHGC and fixed shading), the peak cooling demand is reduced to 80 kW, which represents a 40% reduction over the Step 4 baseline and a 50% reduction over the Step 3 baseline.

→ The Step 4 bundles also result in a 5% decrease in total energy use (TEUI) compared to the Step 4 baseline, due to the reduction in cooling energy consumption. The Step 3 bundles do not result in a reduction in TEUI.

→ The Step 4 bundle archetypes are shown to be favourable compared to the Step 3 bundle archetypes in terms of energy performance, demand on electricity grid, GHG emissions, energy cost, and equipment size.

Summary graphics of the Step 3 and Step 4 high rise archetype results are shown below.

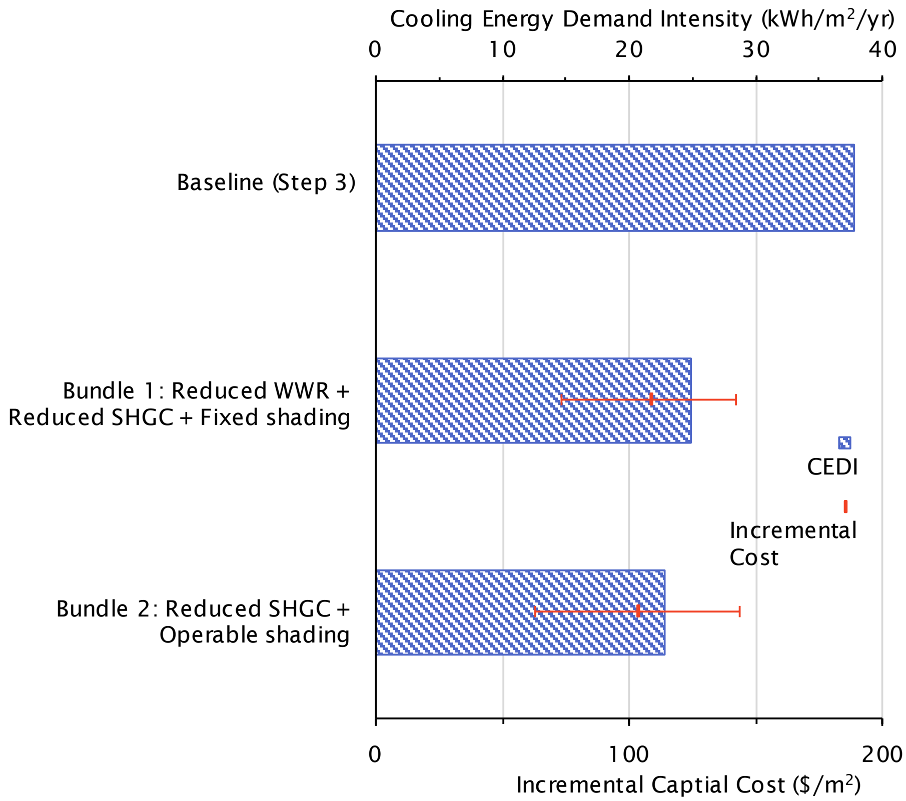

Figure 0.5 Incremental cost ($/m²) for the Step 3 high rise bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

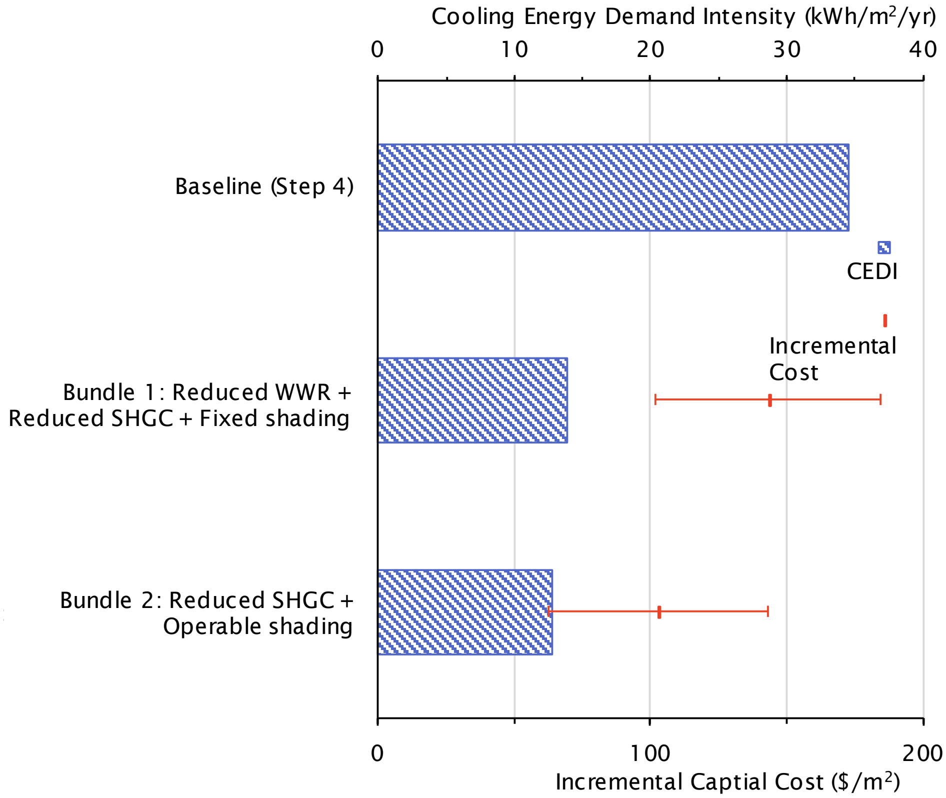

Figure 0.6 Incremental cost ($/m²) for the Step 4 high rise bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

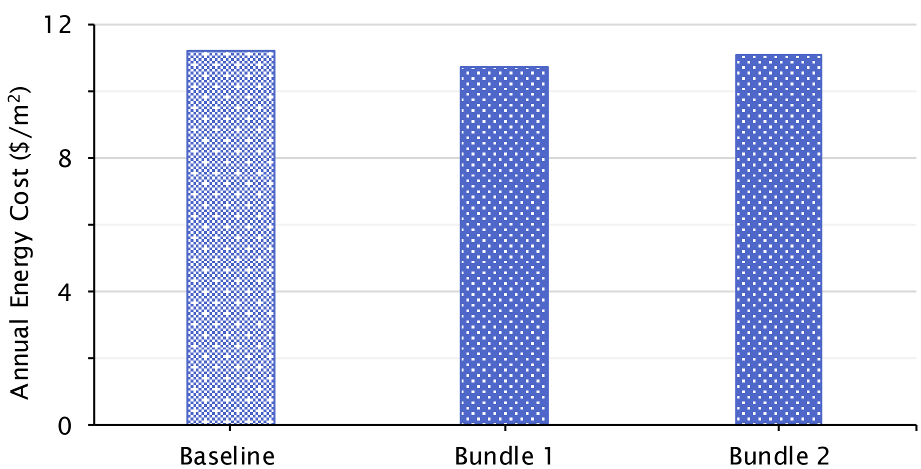

Figure 0.7 Annual energy cost ($/m²) for the Step 3 high rise baseline and bundles

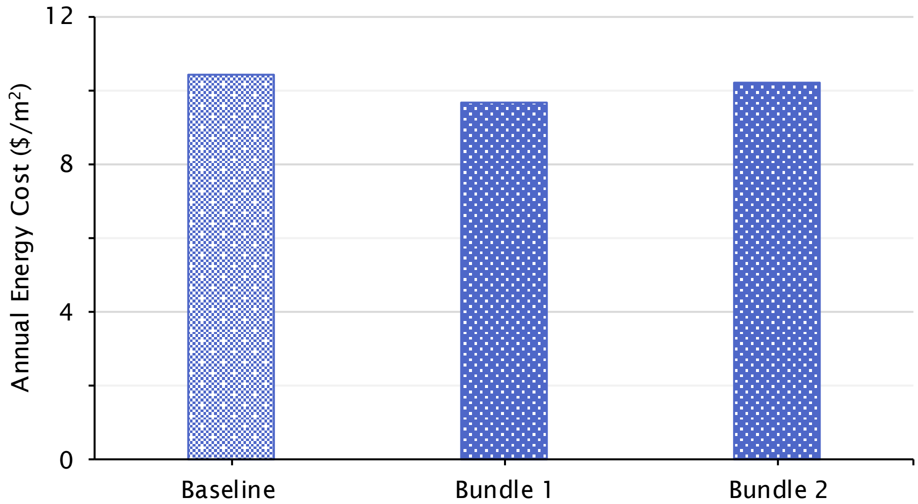

Figure 0.8 Annual energy cost ($/m²) for the Step 4 high rise baseline and bundles

TABLE 0.3 ENERGY COST SAVINGS COMPARED TO THE BASELINE (STEP 3)		
	Bundle 1	Bundle 2
Energy Cost Savings (%)	4%	1%

TABLE 0.4 ENERGY COST SAVINGS COMPARED TO THE BASELINE (STEP 4)		
	Bundle 1	Bundle 2
Energy Cost Savings (%)	8%	2%

0.3.3 Low Rise Existing Building

- Given the typically poor performance of windows in this building type, any passive measures that reduce direct solar heat gain will lead to a significant reduction of overheated hours. If resources are limited, such efforts could focus on the south and west facing elevations where the solar heat gains are most impactful.
- The most cost-effective (in terms of incremental capital cost) strategy to reduce the number of overheated hours below the 200-hour threshold is to upgrade to higher performance windows with a low SHGC and to install exterior operable shading (Bundle 2). Besides improving the thermal comfort and resiliency of the building, this upgrade also results in a decrease in space heating demand, and therefore a reduction of the overall energy use, annual energy cost and GHG emissions compared to the baseline.
- Even greater energy and energy cost savings as well as thermal comfort improvements can be reached by also improving the enclosure (Bundle 4), which is recommended for inclusion when an enclosure renewal is already planned.
- The cost of installing a high efficiency HRV with bypass and a cooling coil downstream of the HRV, or adding full mechanical cooling via a ductless air source heat pump, is roughly comparable. However, air source heat pumps provide heating and cooling by recirculating air but do not provide any ventilation. The co-benefit to installing HRVs in existing buildings is that it provides filtered outdoor air, which can be desirable during a poor air quality event, or in response to noise or safety concerns, when occupants want to keep windows closed.
- Combined in-suite HRV heat pumps are a promising emerging technology for this building type, especially for condominium buildings that have individual suite metering and ownership. The performance would be analogous to the modeled HRV + cooling coil, but would allow building owners to address heating, cooling and ventilation via a single piece of equipment. Passive upgrades may also be required to increase the likelihood that the equipment could meet the heating and cooling demand.
- Installing a high efficiency HRV with bypass and a cooling coil downstream of the HRV may result in a small increase in annual energy cost and total energy use of the building, due to the addition of cooling energy and additional fan power. If the goal is to achieve the 200-hour threshold *and* reduce energy demand, then the installation of this system is recommended to be bundled with design strategies such as enclosure upgrades to achieve energy, GHG emissions, and energy cost savings (as well as improved thermal comfort and resilience).
- If mechanical cooling is installed in an existing building with high SHGC glazing, it is recommended to add exterior shading and/or upgrade the windows to limit excessive cooling energy demand and peak cooling loads.

Summary graphics of the low rise existing archetype results are shown below.

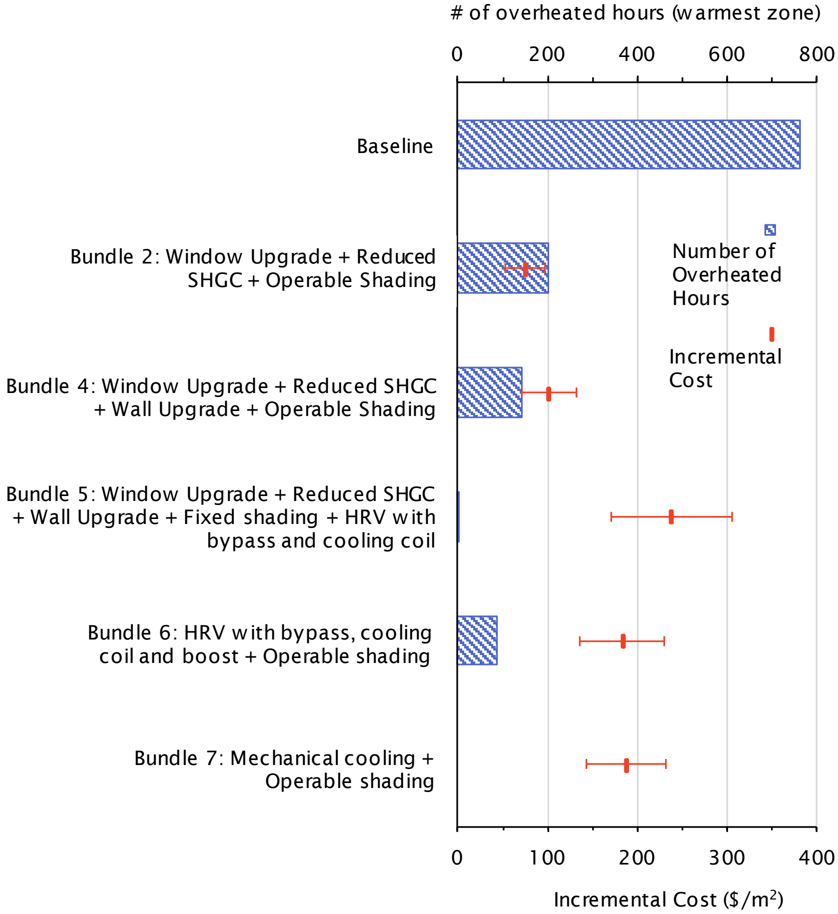

Figure 0.9 Incremental cost ($/m²) for the bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

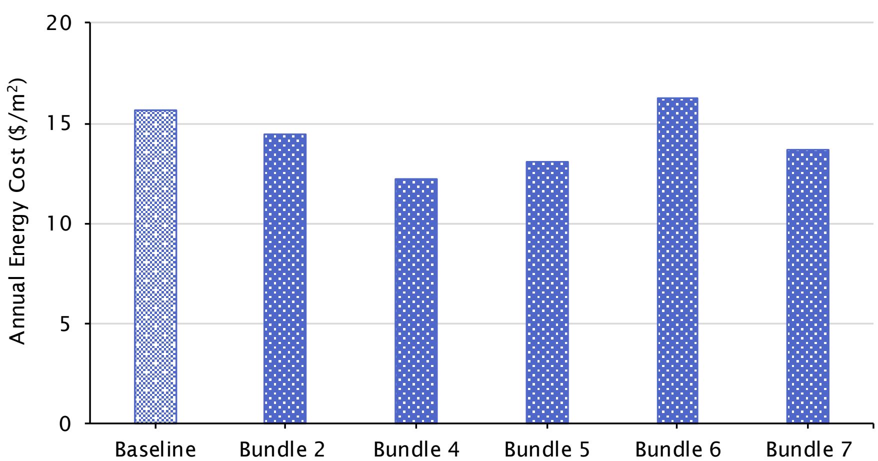

Figure 0.10 Annual energy cost ($/m²) for the baseline and bundles.

TABLE 0.5 ENERGY COST SAVINGS COMPARED TO BASELINE					
	Bundle 2	Bundle 4	Bundle 5	Bundle 6	Bundle 7
Energy Cost Savings (%)	8%	22%	16%	-4%	12%

0.3.4 High Rise Existing Building

→ The high rise existing archetype baseline performs the worst of all the archetypes from an overheating perspective, due to the combined effect of high solar gains through poor performing glazing and high window to wall ratio; high occupant density, and lack of mechanical ventilation and cooling.

→ Any passive measures that reduce solar heat gain will significantly improve comfort performance with this archetype and should be encouraged at every opportunity (e.g. at time of window replacement). It may not be appropriate to apply the 80% acceptability limit to this existing building type or to not do so without sufficient financial support to facilitate the changes required.

→ Only two bundles meet the 200-hour threshold based on the RCP-8.5 2050s climate. Of the two bundles, full mechanical cooling + operable shading is the most cost-effective strategy in terms of incremental capital cost and annual energy cost, although it does not address ventilation.

→ Besides improving the archetype's resilience to increasing outdoor air temperatures, installing air source heat pumps for heating and cooling also reduces the total energy use of the building (due to the higher equipment efficiency).

→ The other bundle that meets the 200-hour threshold based on the RCP-8.5 2050s climate consists of a window upgrade (with reduced SHGC), wall upgrade, fixed exterior shading and installation of HRVs that allows for bypass and boost as needed, and a cooling coil downstream of the HRV. Even though this bundle is more costly it should be considered if an enclosure renewal is already being considered and if providing mechanical ventilation is a priority.

→ Combined in-suite HRV heat pumps are a promising emerging technology for this building type, especially for condominium buildings that have individual suite metering and ownership. The performance would be analogous to the modeled HRV + cooling coil, but would allow building owners to address heating, cooling and ventilation via a single piece of equipment.

Summary graphics of the high rise existing archetype results are shown below.

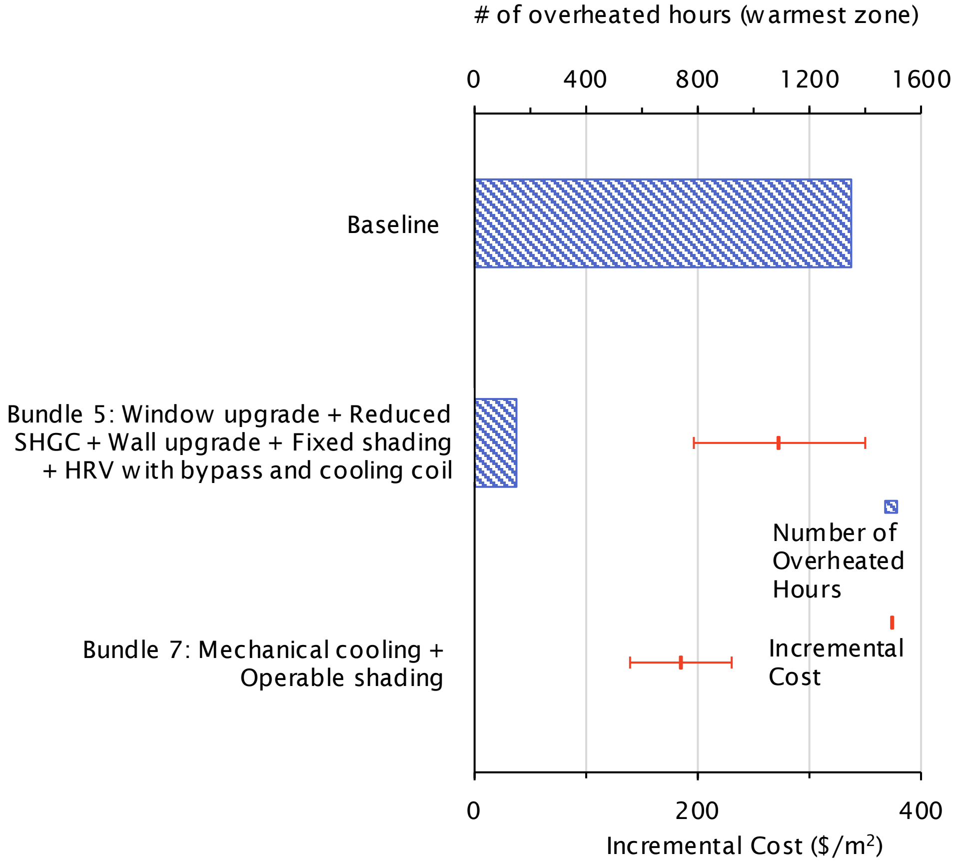

Figure 0.11 Incremental cost ($/m²) for the bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

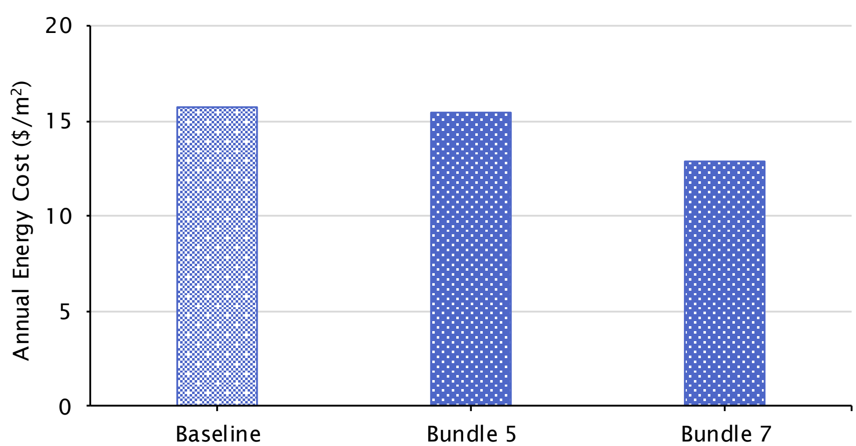

Figure 0.12 Annual energy cost ($/m²) for the baseline and bundles.

TABLE 0.6 ENERGY COST SAVINGS COMPARED TO BASELINE		
	Bundle 5	Bundle 7
Energy cost savings (%)	1%	18%

0.4 Key Findings – Sensitivity Analysis

Sensitivity analysis was performed to test modelling assumptions that are known to have considerable potential impact on results, and to test our best performing bundles against external climate related events. The ideal solutions not only provide adequate thermal comfort in a cost-effective, energy- and emissions-efficient manner, but they are also resilient to disruptive events such as wildfires and power outages.

0.4.1 Internal Heat Gains

A sensitivity analysis was carried out based on the new building low rise baseline and Bundle 1 (reduced WWR, exterior fixed shading and reduced SHGC), which meets the 80% acceptability limit based on the RCP-8.5 2050s climate file.

Figure 0.13 shows the number of overheated hours for the warmest suite for the low and high IHG scenario, along with the baseline assumption (NECB 2011).

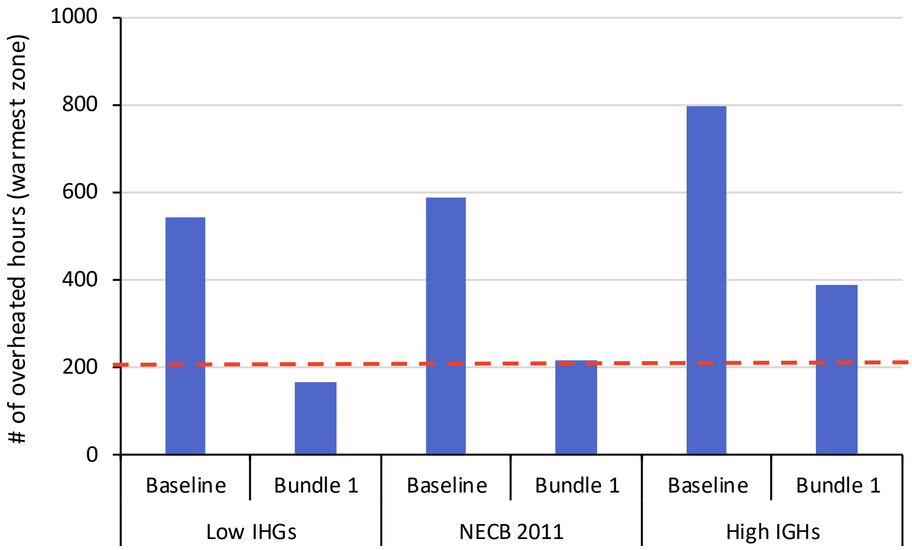

Figure 0.13 Sensitivity analysis of internal heat gains based on new building low rise archetype and Bundle 1, modelled with the RCP-8.5 2050s climate file.

The results suggest that if the IHGs were to be higher than predicted when designing Bundle 1, the number of overheated hours would exceed the 200 hour limit in the RCP-8.5 2050s scenario. In this scenario, the number of overheated hours roughly doubles over the NECB 2011 baseline. This suggests that both the baseline and Bundle 1 are quite sensitive to high IGHs (e.g. a densely occupied suite).

0.4.2 Natural Ventilation

In this study the modelled natural ventilation is based on the assumption that occupants open their windows as needed for optimized thermal comfort, though occupants may not open their windows due to reasons such as poor air quality, bugs, noise, or safety reasons. Part of the rationale for this sensitivity analysis is to test CAMM bundles for their resilience against air quality events such as wildfires.

Two bundles were analyzed for the low rise new building:

→ Bundle 1: reduced WWR, exterior fixed shading and reduced SHGC

→ Bundle 3: high efficiency HRV with cooling coil and boost as needed, and operable shading.

Recall that Bundle 1 has a minimum efficiency HRV (per the baseline) with no mechanical cooling.

Figure 0.14 shows the modelled operative temperature for the Step 3 (baseline) low rise new building baseline and the two bundles in the event of no natural ventilation (i.e. windows are kept closed), based on the RCP-8.5 2050s climate file. The interior temperatures are shown for a summer week, together with the outdoor dry-bulb (2050s) for the same period.

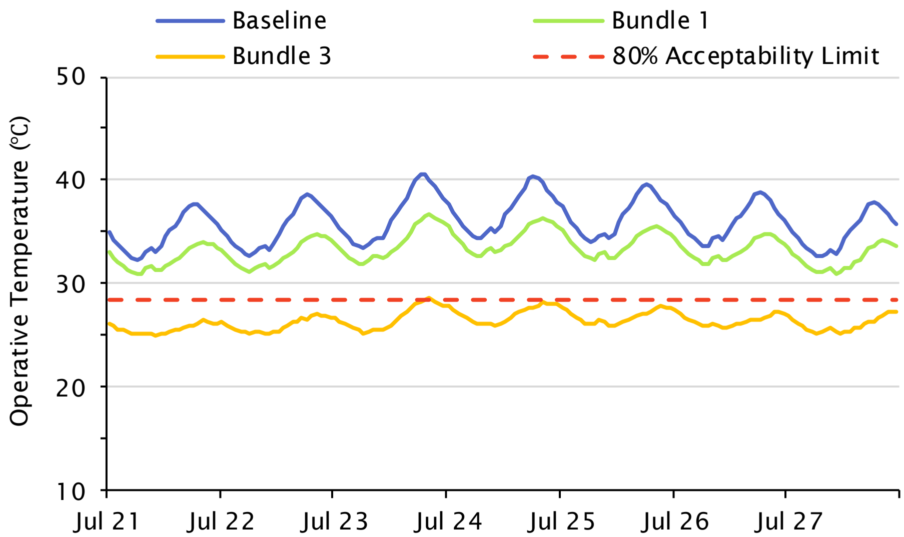

Figure 0.14 Modelled operative temperature for low rise new building Step 3 baseline, bundle 1 and bundle 3 in the event of no natural ventilation, based on the RCP-8.5 2050s climate file. The indoor temperatures are shown together with dry-bulb outdoor temperature for a summer week. The red dashed line illustrates the 80% acceptability limit.

As shown in the figure, both the baseline and Bundle 1 exceed the 80% acceptability limit for the whole week. However, Bundle 3 successfully keeps the operative temperature below the acceptability limit, and therefore shows higher resilience against wildfire smoke events and other events that may influence occupants to keep windows closed. This is primarily due to the addition of a cooling coil to the heat recovery ventilation system. Heat recovery ventilation systems also typically have filters that provide additional resilience against air quality related events.

0.4.3 Power Outage

A sensitivity analysis was carried out to further understand how a mechanically cooled archetype may perform in the event of a power outage. The sensitivity analysis was based on the Step 4 high rise new building baseline and Bundle 2 (operable shading and reduced SHGC) – in other words, one scenario with no additional cooling-focused passive measures and one with cooling focused passive measures.

Figure 0.15 shows the modelled operative temperature for the Step 4 baseline and Bundle 2 during normal operation, and for a power outage event during a summer week (i.e. no cooling, plug loads, ventilation, etc.).

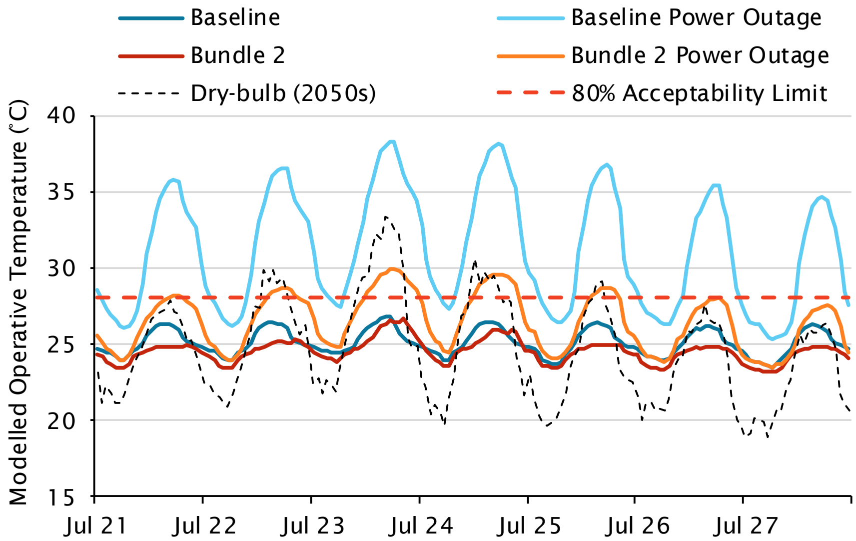

Figure 0.15 Modelled operative temperature for the Step 4 high rise new building baseline and Bundle 2, during normal operation and during a power outage event for a summer week.

As shown in the figure, the passive measures make a substantial difference to the thermal comfort in the event of a power outage, demonstrating the additional resiliency benefit of incorporating cooling focused passive measures into a building with full mechanical cooling.

0.3.4 RCP-8.5 2080s

A sensitivity analysis was carried out to further understand how new building archetypes that are designed to meet the thermal comfort criteria based on the RCP-2050s climate conditions would perform later in the century, or if the RCP-8.5 2080s climate conditions were to occur earlier than predicted. This sensitivity analysis can also be seen as a 2050s 'hot summer' stress test of the archetypes.

For the low rise new building, the baseline, Step 3 and Step 4 passive bundles were modelled with the RCP-8.5 2080s climate as follows:

- Bundle 1 – Step 3: Reduced window to wall ratio + Reduced SHGC + Fixed shading
- Bundle 2 – Step 3: Reduced SHGC + Operable shading
- Bundle 1 – Step 4: Reduced window to wall ratio + Fixed shading
- Bundle 2 – Step 4: Operable shading

Figure 0.16 shows the number of overheated hours for the warmest zone based on the RCP-8.5 2020s, 2050s, and 2080s climate file. As shown, the risk of overheating increases significantly for both the Step 3 and Step 4 baseline archetypes, illustrating the need for design strategies beyond simply meeting the current BC ESC metrics to address future thermal comfort.

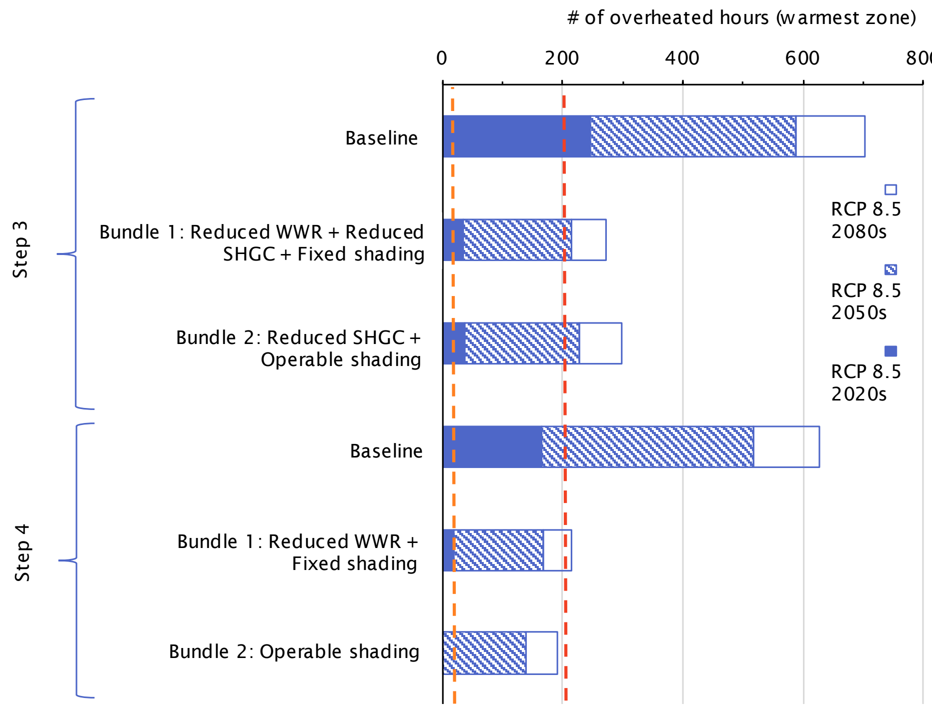

Figure 0.16 Number of overheated hours for the warmest zone, modelled with the RCP-8.5 2020s, 2050s, and 2080s climate files. The red dashed line illustrates the 200 hour threshold, and the orange dashed line illustrates the 20 hour threshold for vulnerable populations.

The passive bundles show a significant reduction in the risk of overheating for the RCP-8.5 2080s climate file, although the only bundle that meets the 200-hour limit is the Step 4 archetype with operable shading. These results demonstrate the benefit of a higher performing enclosure.

For the high rise new building both bundles were modelled for the Step 3 and 4 archetype. Recall that the high rise new building includes mechanical cooling in the baseline and that the Step 4 baseline includes a higher performing wall assembly than the Step 3 archetype.

→ Bundle 1 – Step 3 and 4: Reduced window to wall ratio + Reduced SHGC + Fixed shading

→ Bundle 2 – Step 3 and 4: Reduced SHGC + Operable shading

Figure 0.17 shows the CEDI at the building level for the Step 3 and Step 4 high rise new building and bundles, modelled with the RCP-8.5 2020s, 2050s and 2080s climate file. The red dashed line illustrates the PHI cooling energy demand limit of 15 kWh/m²a.

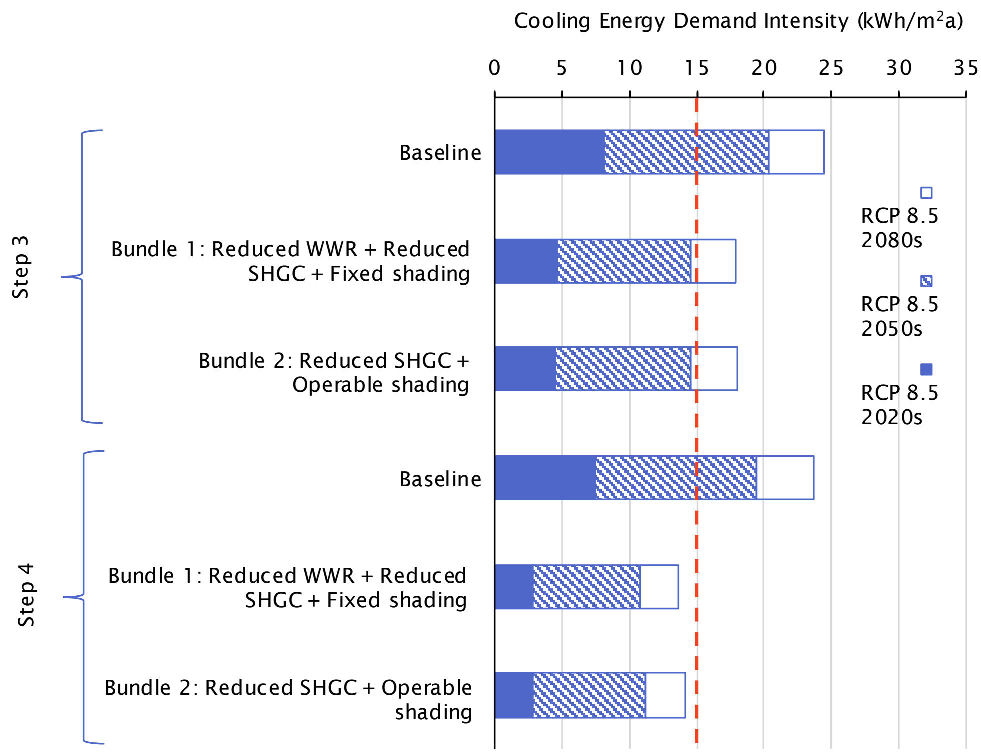

Figure 0.17 Cooling energy demand intensity (CEDI) for new high rise at building level, modelled with the RCP-8.5 2020s. 2050s, and 2080s climate files. The red dashed line illustrates the PHI limit of 15 kWh/m²a.

As shown, all bundles exceed the PHI limit based on the RCP-8.5 2080s climate file. As seen for the low rise new building, the Step 4 bundles perform better than the Step 3 ones, again demonstrating the benefit of a higher performing enclosure towards reducing cooling energy use.

1 Introduction

1.1 Context

The University of British Columbia (UBC), the Province of BC, and several jurisdictions in Metro Vancouver are leading the way toward high performance buildings with recent steps to implement the BC Energy Step Code and develop related green building strategies. These organizations are committed to improving the energy performance and reducing GHG emissions of residential buildings while meeting the housing needs of the growing population in Metro Vancouver and beyond.

As part of the transformation to high performance buildings, the project partners understand the importance of addressing future climate conditions and developing policies and standards that will ensure new buildings are adapted to the uncertain futures posed by climate change. A chief concern is rising outdoor temperatures, potentially leading to overheating risks. The project partners also recognize the significant contribution that existing buildings make to a community's energy and greenhouse gas emissions, as well as the significant number of people who are living in existing buildings that will still be operating under future climate conditions.

A combination of passive and active building cooling strategies is likely required to maintain thermal comfort under a changing climate, while energy requirements for space heating are expected to decline in the Metro Vancouver region. This shifting climate will require new design and adaptation measures to maintain thermal comfort, and will impact energy consumption, peak demand, and Greenhouse Gas (GHG) emission trends. Identifying measures that enable adaptation without increasing energy consumption, operating costs, or GHG emissions is a desired outcome.

1.2 Objectives

The primary objective of this study is to assess the implications of increasing outdoor air temperatures due to climate change on the thermal comfort of multifamily residential buildings in the Lower Mainland, and to identify cost-effective design measures that will maintain thermal comfort under future climate conditions.

A variety of climate adaptation and mitigation measures (CAMMs) suitable for both new and existing, high and low rise multifamily residential buildings are explored using future climate projections. Ideally, solutions are identified that improve thermal comfort without sacrificing parallel societal objectives to reduce energy consumption and greenhouse gas emissions. It is also desirable that identified solutions improve the resiliency of buildings to maintain comfort during increasingly common extreme weather events such as unusually high temperatures, wildfire-induced poor air quality, or power outages.

The results of this study will support development of design guidelines, policies and standards that ensure new building provide residents with thermally comfortable environments, as well as programs that improve the thermal comfort of existing residential buildings. This study will also guide best practises for incorporating projections of warmer future climate conditions into building energy modelling and design.

2 Methodology

The methodology is summarized for the following tasks:

→ Define Archetypes

→ Assess Future Climate Impacts

→ Identify and Assess Climate Adaptation and Mitigation Measures

→ Complete Costing and Financial Analysis

→ Develop Recommendations for Methods and Standards

The methodology is described in further detail below.

2.1 Archetypes

This study evaluated four primary archetypes, representative of the development typologies in UBC's residential neighbourhoods and across the Lower Mainland:

1. New Building: Low Rise – 6-storey
2. New Building: High Rise – 22-storey
3. Existing Building: Low Rise – 4-storey
4. Existing Building: High Rise – 13-storey

The new building models were based on models used in the previous UBC Residential Archetype study[4] carried out by RDH. The low rise and high rise baseline archetypes were set up to meet Step 3 and Step 2 of BC Energy Step Code (BC ESC), respectively.

The existing building models were developed by adapting the new building models to the size, assemblies, and systems typical of construction from the 1980s and 1990s. The characteristics for the existing archetypes are based on previous existing building studies carried out by RDH, including the Low-Rise MURB Energy Study[5], and the City of Vancouver 80% GHG reduction study[6], both of which included market analysis to develop archetype energy models characteristic of existing buildings in the Lower Mainland.

The four baseline archetypes were modelled using the climate file currently used for building code compliance (Canadian Weather for Energy Calculations, CWEC, released in 2016)[7]. Energy modelling was completed using the simulation program OpenStudio v.2.7.0, an interface for EnergyPlus (v.9.1.0). This is an open source program that is free of charge.

Key characteristics of the baseline archetypes are summarized in the following sections. A detailed summary of the energy model inputs for each archetype is provided in Appendix A.

[4] UBC Modelling Study: Residential Archetypes; report prepared for UBC Campus and Community Planning by RDH, December 2017.
[5] Energy Consumption in Low-Rise Multifamily Residential Buildings in British Columbia; report prepared for BC Housing by RDH, May 2017. Available online: https://www.bchousing.org/publications/Low-Rise-Energy-Study.pdf
[6] Exploring Options for 80% GHG Reductions in Downtown Buildings; report prepared for City of Vancouver by RDH, March 2017.
[7] City of Vancouver Energy Modelling Guidelines Version 2.0, July 11, 2018

2.1.1 New Building Low Rise

The low rise new building archetype is a 6-storey wood frame multi-unit residential building with a 2-level below-grade parkade. The baseline archetype has hydronic in-floor radiant heating and no mechanical cooling.

This archetype was adapted from the low rise model used in the UBC Residential Archetype study, in which suite ventilation air was supplied via corridor pressurization make-up air unit and operable windows. As this does not represent current practice, the system was updated to minimum efficiency in-suite heat recovery ventilator units with corridor make-up air for pressurization. This change resulted in the baseline model meeting Step 3 of the BC ESC.

The new building low rise baseline is heated via in-floor hydronic heating with district energy connection (no cooling). The system choice aligns with typical new construction at the UBC given their district energy system; however, this system type is less common in other areas of the Lower Mainland. An additional analysis was therefore completed to understand the impact and cost associated with the CAMM bundles for a low rise new building with electric baseboards as the baseline heating system. The results of the additional analysis are provided in Appendix D.

Table 2.1 summarizes the key characteristics for the low rise new building baseline. Additional model inputs are provided in Appendix A.

TABLE 2.1 LOW RISE NEW BUILDING BASELINE ARCHETYPE DESCRIPTION	
Floor Area	4,700 m² (approx. 51,000 ft²)
Number of stories	6
Enclosure	Wood frame with batt insulation (R_{eff}–15.6). Double glazed windows in non-metal frames (USI-1.8 [U-0.31], SHGC-0.36), 40% window to wall ratio.
HVAC	In-floor hydronic radiant heating with district energy connection provides heat to the suites. Tempered outdoor air pressurizes the corridors. Outdoor air is provided via minimum efficiency (60%) in-suite HRV units with no by-pass. No mechanical cooling.
DHW	District energy connection[8]

2.1.2 New Building High Rise

The high rise new building archetype is a 22-storey multi-unit residential building with sixteen 2-storey townhouses built over a 2-level below-grade parkade. The baseline archetype has hydronic fan coil units providing heating and cooling to the suites and corridors, with minimum efficiency in-suite HRVs providing ventilation.

[8] District energy for domestic hot water is a possible system choice for UBC and other regions that have district energy, although central gas-fired boilers or in-suite electric hot water heaters are likely more prevalent across the Metro region. The district DHW option was used across all archetypes for simplicity. Other system choices would possibly impact the total energy consumption and GHGI but because none of the CAMMS modify the domestic hot water system, these choices would not alter the relative analysis in a meaningful way.

Table 2.2 summarizes key characteristics for the high rise new building baseline. Additional model inputs are provided in Appendix A.

TABLE 2.2 HIGH RISE NEW BUILDING BASELINE ARCHETYPE DESCRIPTION	
Floor Area	26,500 m^2 (approx. 285,000 ft^2)
Number of stories	Tower: 22 Townhouse: 2
Enclosure	Concrete construction (R_{eff}-3). Double glazed windows in aluminum frames (USI-2.6 [U-0.46], SHGC-0.36). Tower: 55% window to wall ratio, townhouse: 30% window to wall ratio.
HVAC	Hydronic fan coil units provide heating (district energy connection) and cooling (chiller) to suites and corridors. Outdoor air is provided via minimum efficiency (60%) in-suite HRV units with no by-pass, with tempered corridor make-up air.
DHW	District energy connection[9]

2.1.3 Existing Building Low Rise

The low rise existing building archetype is a 4-storey multi-unit residential building with 2-level underground parkade, and with assemblies and systems typical of the 1980s to 1990s. The proposed archetype characteristics are based on a previous existing building study carried out by RDH[10].

Table 2.3 summarizes key characteristics for the low rise existing building baseline. Additional model inputs are provided in Appendix A.

TABLE 2.3 LOW RISE EXISTING BUILDING BASELINE ARCHETYPE DESCRIPTION	
Vintage	Typical 1980s-90s
Floor Area	3,100 m^2 (approx. 33,700 ft^2)
Number of stories	4
Enclosure	Wood frame with batt insulation (R_{eff}-11). Double glazed windows in non-thermally broken aluminum frames (USI-3.5 [U-0.62], SHGC-0.66). 30% window to wall ratio.
HVAC	Electric baseboards provide heat to the suites and corridors. Outdoor air is supplied via corridor make-up air and operable windows, with occupant-controlled bathroom and kitchen exhaust fans in suites. There is no mechanical cooling.
DHW	District energy connection[11]

[9] District energy for domestic hot water is a possible system choice for UBC and other regions that have district energy, although central gas-fired boilers or in-suite electric hot water heaters are likely more prevalent across the Metro region. The district DHW option was used across all archetypes for simplicity. Other system choices would possibly impact the total energy consumption and GHGI but because none of the CAMMS modify the domestic hot water system, these choices would not alter the relative analysis in a meaningful way.

[10] Phase II Strata Energy Study report prepared for City of Vancouver by RDH, September 2017

[11] District energy for domestic hot water is a possible system choice for UBC and other regions that have district energy, although central gas-fired boilers or in-suite electric hot water heaters are likely more prevalent across the Metro region. The district DHW option was used across all archetypes for simplicity. Other system choices would

2.1.4 Existing Building High Rise

The high rise existing building is a 13-storey multi-unit high rise residential building constructed in the 1980s to 1990s. The proposed archetype characteristics are based on a previous existing building study carried out by RDH[12].

Table 2.4 summarizes key characteristics for the high rise existing building baseline. Additional model inputs are provided in Appendix A.

TABLE 2.4 HIGH RISE EXISTING BUILDING BASELINE ARCHETYPE DESCRIPTION	
Vintage	Typical 1980s-90s
Floor Area	16,656 m² (approx. 179,200 ft²)
Number of stories	Tower: 13 Townhouse: 2
Enclosure	Steel stud walls with uninsulated slab edges (R_{eff}-3). Double glazed windows in non-thermally broken aluminum frames (USI-3.5 [U-0.62], SHGC-0.66). 60% window to wall ratio.
HVAC	Electric baseboards provide heat to the suites and corridors. Outdoor air is supplied via corridor make-up air and operable windows, with occupant-controlled bathroom and kitchen exhaust fans in suites. There is no mechanical cooling.
DHW	District energy connection[11]

2.2 Future Climate Impacts

To assess future climate impacts, the archetypes were modelled using future climate files specific to UBC, provided by the Pacific Climate Impact Consortium (PCIC). The future climate files are based on the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 8.5 scenario[13] for 2020s, 2050s, and 2080s. The RCP-8.5 pathway represents the 'business as usual' greenhouse gas concentration scenario (i.e. the projected future climate if we take no committed action to reducing carbon emissions). And if significant action *is* taken to address climate change, following RCP-8.5 as the baseline extends the timeframe for climate change resiliency of the building (e.g. the building would be adapted up to a 2100 timeframe).

The intent of this step is to understand how the baseline archetypes can be expected to perform in the future if we make no interventions during design or renewal to address thermal comfort. This then creates a comparison point against which to test potential climate adaptation and mitigation measures.

The thermal comfort, energy, and emission metrics are described in further detail below.

possibly impact the total energy consumption and GHGI but because none of the CAMMS modify the domestic hot water system, these choices would not alter the relative analysis in a meaningful way.

[12] Exploring Options for 80% GHG Reductions in Downtown Buildings; report prepared for City of Vancouver by RDH, March 2017.

[13] https://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf

2.2.1 Thermal Comfort Metrics

There is not currently an established threshold for 'acceptable' thermal comfort in a changing climate, although several standards and guidelines point toward this metric for at least our current climate, including the following:

- → The City of Vancouver Energy Modelling Guideline (v2.0), referenced by the BC ESC, requires that the interior dry-bulb temperature of occupied space does not exceed the 80% acceptability limit, as outlined in ASHRAE 55-2010 Section 5.3, for more than 200 hours per year for any thermal zone. The City of Vancouver Energy Modelling Guideline (v2.0) also defines a maximum threshold for "vulnerable groups" of 20 hours exceeding the 80% acceptability limit. These limits only apply to spaces that are naturally ventilated, without mechanical cooling.
- → Citing numerous national and international heat-related health studies, Toronto Public Health recommends that a maximum indoor temperature standard of 26° C for multi-family rental buildings be considered to reduce premature mortality and emergency medical service calls associated with extreme heat events. [14]
- → The Chartered Institution of Building Services Engineers (CIBSE) sets similar absolute operative temperature limits depending on the space type (for example, bedrooms cannot exceed 26°C for more than 1% of night-time hours)[15].

In this study, the number of overheated hours per year is reported. An overheated hour is defined as an hour when the interior operative temperature exceeds the upper 80% acceptability limit (ASHRAE 55-2010). The threshold of 200-hour above the 80% acceptability limit defined in the City of Vancouver Energy Modelling Guideline (v.2.0) is used as a reference point in this study since it is the currently used standard within BC, although it may not prove acceptable by occupants on a consistent basis, and even less so as outdoor temperatures increase over time.

The upper 80% acceptability temperature limit (meaning that around 80%, of the occupants find the space thermally acceptable) is calculated based on the monthly mean outdoor air temperature[16]. Figure 2.1 shows the monthly upper temperature limit for the different climate files used in this study. As shown, an upper acceptability limit is applicable to more months as the monthly mean outdoor air temperature increases. Based on the CWEC 2016 file, six out of twelve months are considered to be in need of an upper temperature limit to ensure thermal comfort. Based on the RCP-8.5 2020s and 2050s files, the number of months increases to seven, and based on the RCP-8.5 2080s file, this period is nine months. Since the upper acceptability limit is determined relative to the outdoor air temperature, the limit increases with rising monthly mean outdoor air temperatures.

[14] City of Toronto HL8.5: Update on Extreme Heat and Maximum Indoor Temperature Standard for Multi-Unit Residential Buildings. https://www.toronto.ca/legdocs/mmis/2015/hl/bgrd/backgroundfile-85835.pdf
[15] The Chartered Institution of Building Services Engineers (CIBCSE), TM52: The limits of thermal comfort: Avoiding Overheating in European Buildings, 2013
[16] The upper 80% acceptability temperature limit is applicable when the monthly mean outdoor temperature is greater than 10°C and less than 33.5°C.

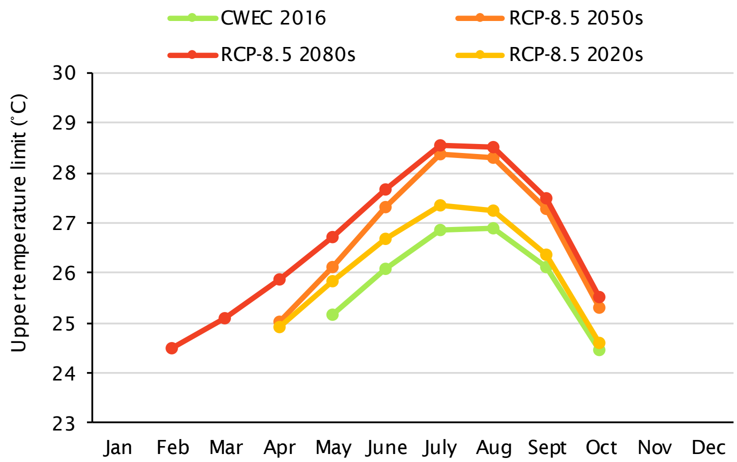

Figure 2.1 The upper 80% acceptability temperature limit for each month following ASHRAE 55-2010 Section 5.3, for the CWEC 2016, RCP-8.5 2020s, 2050s and 2080s climate files for UBC.

To understand the magnitude of overheating, the modelled peak operative temperature for each iteration and representative suites on each elevation are also reported.

2.2.2 Energy and Emission Metrics

In addition to evaluating the impact of future climate on thermal comfort, the impacts on overall energy performance and greenhouse gas emissions related to building operation were evaluated[17].

The BC ESC performance metrics for Part 3 buildings (TEDI and TEUI), and the Vancouver Building Bylaw emission metric (GHGI) were used to assess future climate impacts. Currently, there is no performance metric defined in the BC ESC for cooling energy. To allow for comparison of cooling energy demand between the different measures and climate scenarios, a metric for cooling energy demand was included in this analysis, referred to as 'cooling energy demand intensity', or CEDI, which is calculated in the same way as the TEDI, i.e. the annual cooling demand for space conditioning and conditioning of ventilation air (not accounting for system efficiency).

Since the thermal comfort metric outlined in BC ESC (number of hours exceeding the 80% acceptability limit) only applies to non-mechanically cooled archetypes, CEDI and peak cooling load of the space are reported at the zone level for the mechanically cooled archetypes (high rise new building), to understand the relative differences throughout the building.

Table 2.5 summarizes the energy and emission metrics included in this study.

[17] It should be noted that buildings analyzed using energy simulation tools such as EnergyPlus and IES-VE include multiple prescribed assumptions for occupancy, weather, and internal loads. As such they are not intended to predict actual energy consumption or be predictive of actual internal temperatures. Modelled temperatures should therefore be used as a metric to compare scenarios and options.

TABLE 2.5 DEFINITION OF ENERGY AND EMISSION METRICS		
Metric	**Unit**	**Description**
TEUI, Total Energy Use Intensity	kWh/m^2a	The annual sum of all energy used on site per unit area.
TEDI, Thermal Energy Demand Intensity	kWh/m^2a	The annual heating energy demand for space conditioning and conditioning of ventilation air per unit area. Note that TEDI does not account for system efficiency.
GHGI, Greenhouse Gas Intensity	$kgCO_2e/m^2a$	Annual greenhouse gas emissions associated with the use of all energy utilities on site per unit area.
CEDI, Cooling Energy Demand Intensity	kWh/m^2a	The annual cooling energy demand for space conditioning and conditioning of ventilation air per unit area. Note that CEDI does not account for system efficiency.
Peak Cooling Load	W/m^2	Maximum cooling required per unit area (not accounting for system efficiency) for space conditioning and conditioning of ventilation air. This metric is analogous to the "Cooling Load" criteria in the Passive House International standard. It is only reported for the archetype with mechanical cooling (i.e. high rise new)
Peak Heating Demand	W/m^2	Maximum energy required (accounting for system efficiency) to meet the peak heating load for space conditioning and conditioning of ventilation air. This is a typical metric used by utilities to determine peak demand charges, although here it is normalized to floor area to enable easier comparison between archetypes.
Peak Cooling Demand	W/m^2	Maximum energy required (accounting for system efficiency) to meet the peak cooling load for space conditioning and conditioning of ventilation air. This is a typical metric used by utilities to determine peak demand charges, although here it is normalized to floor area to enable comparison between archetypes.

The BC ESC performance metrics are discussed throughout this report, and the targets for Part 3 buildings (Climate Zone 4) are summarized in Table 2.6 for reference[18].

TABLE 2.6 BC ENERGY STEP CODE COMPLIANCE TARGETS FOR PART 3 BUILDINGS		
	TEDI (kWh/m^2a)	**TEUI (kWh/m^2a)**
Step 2	45	130
Step 3	30	120
Step 4	15	100

[18] http://free.bcpublications.ca/civix/document/id/public/bcbc2018/bcbc_2018dbs102r2

Table 2.7 summarizes the emission factors used to calculate the GHGI. The emission factor for electricity is based on the City of Vancouver Energy Modelling Guideline v.2.0[19]. Two emission factors for district energy were provided by UBC, one based on the current system and one based on the future district energy system that is planned to consist of 60% renewable energy by 2024.

TABLE 2.7 EMISSION FACTORS*	
Fuel Type	**Emission Factor (kg CO_2e/kWh)**
Electricity	0.011
District Energy (UBC – Current)	0.220
District Energy (UBC – Future)	0.088

2.2.3 Climate Files

This section provides background on the climate files used for the analysis.

Historical climate files

For Step Code compliance modelling it is required to use the CWEC (Canadian Weather for Energy Calculations) 2016 climate files. The CWEC files are provided in Typical Meteorological Year (TMY) format and are specifically design for use in energy simulations.

TMY files are created by combining 12 statistical median months chosen from a continuous 15-30-year period of historical data for meteorological variables such as temperature, wind speed, global solar radiation, relative humidity etc. The intent of TMY files is to represent the typical long-term weather pattern at a specific location. Table 2.8 summarizes the actual year from which historical data has been selected for each month to create the CWEC 2016 file for Vancouver (YVR Int. Airport). For this study, PCIC provided a CWEC file for UBC, adjusted based on the Vancouver CWEC 2016 file.

TABLE 2.8 REFERENCE YEAR FOR EACH MONTH FOR THE CWEC 2016 VANCOUVER FILE											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011	2000	2000	2013	2003	2005	2002	2011	2003	2009	2007	2011

This approach results in a file that represents the average climate at a specific location and does not include events such as cold snaps or heat waves. Currently, there is no requirement for code compliance to use weather files that represents warmer, or colder, conditions to stress test archetypes.

Future climate files

Future climate projections, based on how the climate is changing in response to increasing concentrations of greenhouse gasses in the atmosphere, are based on global/regional climate models. Climate models describe the physical processes and interactions between the atmosphere, ocean, cryosphere (ice and snow), and land surface based on general principles of fluid dynamics and thermodynamics.

[19] City of Vancouver Energy Modelling Guideline v.2. Available online: https://guidelines.vancouver.ca/E006.pdf

In 2014, the Intergovernmental Panel on Climate Change (IPCC) finalized the fifth Assessment Report (AR5) which includes four greenhouse gas concentration pathways, called Representative Concentration Pathways (RCPs)[20]. These concentration pathways describe possible climate futures depending on different levels of greenhouse gas radiative forcings. In AR5, political and socio-economic scenarios are then attributed to the respective RCP values.

In this study, the simulations assume the RCP-8.5 emission scenario. The RCP-8.5 scenario is commonly referred to as the 'business as usual' scenario, i.e. the projected future climate if we take no committed action to reduce carbon emissions. Even if significant action is taken to address climate change, following RCP-8.5 as the baseline extends the timeframe for climate change resiliency of the building.

The interest in creating future climate files for building performance simulation has increased in recent years and a number of methods have been developed to create hourly weather files that take climate change into account. The future climate files used in this study are based on a methodology referred to as *morphing*. The concept behind morphing is to generate weather files that account for climate change by adjusting historical observations with results from simulations made with global and/or regional climate models. A key benefit of this method is that it allows for spatial and temporal downscaling by using site-specific weather data, so that future projections can be generated while preserving the characteristics of the weather for the specific location[21].

It should be noted that the future climate files are built off the CWEC 2016 file, which are themselves built based on historical averages and designed to captures typical (median) weather conditions, and thus do not include extreme weather events. It is likely that extreme weather events will become more common in the future as a results of climate change. Designing buildings based on typical conditions could lead to future vulnerability as extreme events have greater leverage over the impact of building operation. As such, while the future climate files are a useful tool for comparing a range of future possibilities, they are not a definitive projection of future climate. To allow designers and engineers to stress test building performance and adapt building design for atypical conditions further research is recommended to focus on creating weather files that represent hotter than average conditions or include the effects of extreme events.

The future climate files used in this study were developed by PCIC, based on the Vancouver YVR Int. Airport CWEC 2016 file. Files were developed for three future time periods: centred on 2020s, 2050s and 2080s (i.e., 2011-2040, 2041-2070, 2071-2100). While the climate models generate predictions for multiple meteorological variables, the files in this study adjusted sensible temperature only, and left all other variables unchanged. This could be a limiting assumption, as the wet-bulb temperatures may also have an effect on mechanical cooling systems and the apparent comfort metrics associated with occupant overheating.

Comparison of historical and future climate files for UBC

Figure 2.2 shows the monthly average, minimum and maximum dry-bulb temperature for each climate file used in this study. As the figure shows, the 2080s temperatures are

[20] https://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf
[21] Ek, M., Murdock, T., Sobie, S., Cavka, B., Coughlin, B., Wells, R., Future weather files to support climate resilient building design in Vancouver, 1st International Conference on New Horizons in Green Civil Engineering (NHICE-01), 2018

higher during the winter and spring months compared to the 2050s file, though the summer maximum temperature is not significantly higher.

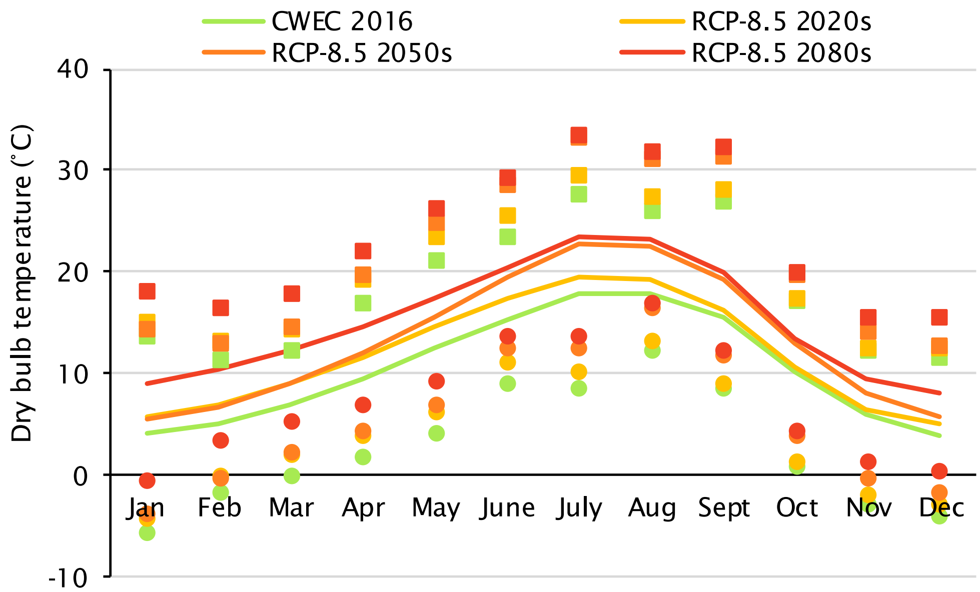

Figure 2.2 Monthly average, maximum, and minimum dry-bulb temperature (°C) for CWEC 2016 and RCP-8.5 2020s, 2050s, and 2080s climate files for UBC.

Figure 2.3 shows the cooling degree days (CDD) and heating degree days (HDD) for each file. Degree days is a measurement that quantifies the demand needed for heating and cooling. The metric represents the number of degrees that a day's average temperature is below, or above 18°C, which is assumed be the temperature below and above which the building needs to be heated or cooled, respectively.

As the figure shows, the CDD is predicted to increase from approx. 40 based on the CWEC 2016 file, to approx. 400 based on the RCP-8.5 2080s. The HDD is predicted to decrease from approx. 2,800 based on the CWEC 2016 file, to 1,500 based on the RCP-8.5 2080s.

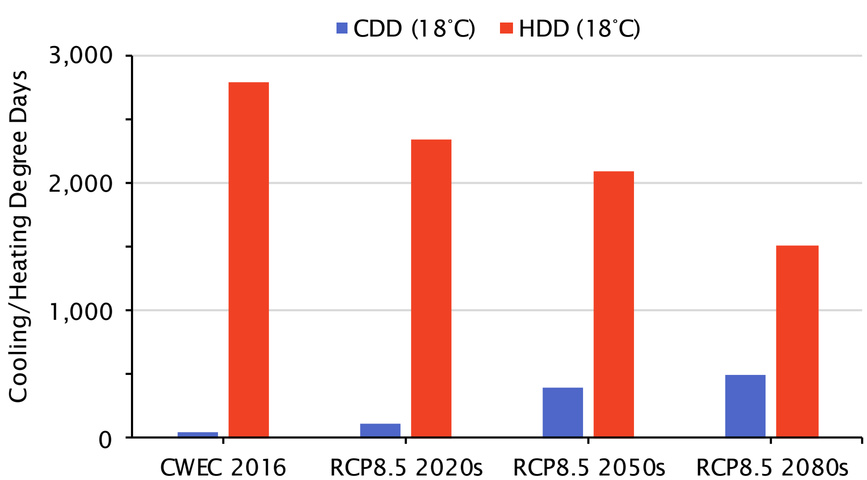

Figure 2.3 Cooling and heating degree days based on the CWEC 2016 file and RCP-8.5 2020s, 2050s and 2080s for UBC.

2.3 Climate Adaptation and Mitigation Measures

A list of climate adaptation and mitigation measures[22] (CAMMs) were developed to address thermal comfort vulnerabilities appropriate to each of the new and existing, high- and low-rise archetypes. The CAMMs were selected based on project experience, stakeholder consultation, and other climate adaptation and mitigation studies[23, 24], with the intent to focus our analysis on the strategies that are already known to be effective and were expected to perform well under the RCP-8.5 2050s climate scenario. The focus was on hard adaptation strategies, or measures that form part of the infrastructure; soft adaptation strategies, which relate to management, policies, and other protocols, were out of scope.

Both active (mechanical) and passive (solar heat gain reduction and enclosure) CAMMs were assessed. Table 2.9 summarizes the CAMMs. A detailed description of each CAMM is provided in Appendix B. Each CAMM was modelled for each archetype using the RCP-8.5 2050s climate file prepared by PCIC.

[22] Measures that improve a building's ability to *adapt* to climate change (in this study the focus is primarily on adapting to increasing outdoor air temperatures), and that also, ideally, *mitigate* (or reduce) greenhouse gas emissions related to the operation of the building.
[23] 1st and Clark Step Code Energy Model, prepared by Focal Engineering Inc., December 2018.
[24] Passive Cooling Measures for Multi-Unit Residential Buildings, prepared by Morrison Hershfield, April 2017.

TABLE 2.9 MODELLED CLIMATE ADAPTATION AND MITIGATION MEASURES					
	Description	Archetype(s)			
		New Building Low Rise	New Building High Rise	Existing Building Low Rise	Existing Building High Rise
Solar Heat Gain Reduction	Reduced Window to Wall Ratio → 30% WWR[25]	x	x		
	Exterior Shading – Operable → Design and control optimized to prevent unwanted solar gain (east-, south-, and west-facing windows)	x	x	x	x
	Exterior Shading – Overhangs/Fins → Design optimized to prevent unwanted solar gain (east-, south-, and west-facing windows)	x	x	x	x
	Reduced SHGC → SHGC-0.28[26]	x	x	x	x
	Dynamic Glazing → Variable SHGC depending on external conditions	x	x	x	x
Enclosure	Improved Wall Thermal Performance	x	x	x	x
	Improved Roof Thermal Performance	x	x	x	x
	Improved Window Thermal Performance	x	x		
	Improved Window Performance (Thermal + SHGC)			x	x
Mechanical	HRV with bypass and boosted flow rate as needed	x		x	x
	HRV with bypass, boosted flow rate as needed, and cooling coil in ventilation system	x		x	x
	Full mechanical cooling – Hydronic, integrated heating and cooling	x	x		
	Full mechanical cooling – Ductless (e.g. air source heat pump)			x	x

[25] Recommended window to wall ratio based on Passive Design Toolkit, published by City of Vancouver, July 2009.
[26] Lowest recommended SHGC based on BC Housing Overheating and Air Quality Design Guide, June 2019.

2.3.1 CAMM Bundles

To view the combined impact of multiple measures that are likely to be implemented concurrently, bundles of CAMMs were developed, costed, and modelled for each archetype. The bundles were designed based on the results of the individual climate measures and costing analysis, and informed by the practical likelihood and/or desirability that specific measures might be implemented together.

The passive bundles focus on optimizing the effects of passive cooling strategies by strategically combining cost-effective measures (see Section 2.4 for costing methodology). The combined passive and mechanical cooling options were designed for optimal cost-effectiveness. The bundles were designed to meet the thermal comfort criteria based on the RCP-8.5 2020s climate file, with a mind to the simplicity and practicality of also being "*2050s ready*". The concept of "*2050 ready*" means that the design of the building includes adaptive capacity for overheating risks (i.e. potentially vulnerable systems are designed to be readily upgraded to improve occupant comfort by the 2050s without adding significant capital costs or disruptive work). Designing for adaptive capacity includes consideration of infrastructure replacement cycles and the associated upstream and downstream implications. An example would be to allow space for added or larger capacity cooling equipment with properly designed ducts and power availability, but delaying installation until a future equipment replacement or upgrade cycle is needed, or overheating concerns become apparent.

For the new building archetypes, bundles were also devised to comply with the top steps of the BC ESC, to further understand how higher step archetypes may perform under future climate conditions, and to identify any specific design strategies that either help or hinder the future comfort performance of these higher step buildings.

2.4 Costing and Financial Analysis

To understand the cost associated with implementing the different design strategies, the incremental capital cost (ICC) of each CAMM and bundle was estimated, as well as the annual energy cost for the baseline archetypes and bundles.

For the new building archetypes, the CAMM incremental cost included only the additional cost to adapt the building design relative to the baseline archetype. For the existing building archetypes, the incremental cost was relative to an assumed baseline building renewal project. This applies specifically for enclosure renewal related measures, which are intended to capture building upgrade opportunities when renewal projects are already planned. For example, the cost of improving wall thermal performance assumed an exterior cladding renewal was already proceeding. The CAMM cost therefore only included the cost of the additional material and labour.

Various sources were used to estimate the CAMM incremental costs. These sources included previous RDH project experience, product cost estimates from vendors, and Gordian RS Means (Accessed Online Aug 2019, using 2019 Q2 data for Vancouver). When a wide range of incremental costs for a CAMM was found (for example with exterior operable shades, for which there are numerous types available), high and low costs were reported and a mean between the two was calculated. If a range of incremental costs were not found, the mean ICC was estimated to have an uncertainty of +/- 20%. Incremental cost upper bound uncertainty is the difference between the mean-cost and the high-cost estimate, while the lower bound uncertainty is the difference between the mean-cost and the low-cost estimate.

The annual energy cost was calculated for the baseline and bundles, based on the archetypes' energy use under the RCP-8.5 2050s climate scenario. The utility rate ($/kWh) for district energy was provided by UBC, and the utility rate ($/kWh) for electricity was calculated based on the current available rates for residential buildings within BC[27]. The utility rates are summarized in Table 2.10. The energy cost was determined based on current utility rates, even though the energy use is based on 2050s climate; therefore, the calculated annual energy cost is only meant to allow for relative comparison among different design strategies.

TABLE 2.10 UTILITY RATES	
	Utility Rate ($/kWh)
Electricity	$0.0945 per kWh for the first 1,350 kWh (in an average two-month billing period) $0.1417 per kWh over the 1,350 threshold
District Energy	$0.042 per kWh

[27] BC Hydro, Residential Electricity Rates, https://app.bchydro.com/accounts-billing/rates-energy-use/electricity-rates/residential-rates.html

2.5 Sensitivity Analysis

A sensitivity analysis was conducted based on selected bundles and the RCP-8.5 climate file for 2050s. The sensitivity analysis aimed to answer the following questions:

→ How would an optimized building perform if the internal heat gains were higher or lower than predicted in the model?

→ How would an optimized building perform in the event of no natural ventilation (i.e. windows are kept closed)?

→ How would an optimized building perform in the event of an extended power outage?

→ How would an optimized building perform under the RCP-8.5 2080s climate scenario?

2.5.1 Internal heat gains

The impact of internal heat gains (IHGs) was evaluated by modelling a low and a high internal heat gain scenario. The assumptions were based on the BC Hydro Energy Modelling Guideline which outlined different miscellaneous electric load scenarios for dwelling units depending on the population of the building. The low plug load (2.68 W/m²) was based on single occupancy with no in-suite laundry and no dishwasher. The high plug load (7.17 W/m²) was based on a typical family with one or more kids, with in-suite laundry and dishwasher. The BC Hydro Energy Modelling Guideline also provides a schedule that assumes that the loads are on for an equivalent of 15.8 hours per day.

The baseline assumption in this study was based on NECB 2011, which assumes a plug load of 5 W/m² and the provided schedule assumes that the loads are on for an equivalent of 10.6 hours per day.

For the purpose of this sensitivity analysis, a low IHG case was modelled by combining the low BC Hydro plug load (2.68 W/m²) and the NECB schedule which assumes that the loads are on for fewer hours compared to the BC Hydro schedule. The lower IHG case results in an annual load of 10 kWh/m²a. For the high IHG case the high BC Hydro plug load (7.17 W/m²) was modelled with the BC Hydro schedule, which results in an annual load of 41 kWh/m²a. Table 2.11 summarizes the modelled scenarios.

TABLE 2.11 ASSUMPTIONS FOR SENSNTIVITY ANALYSIS OF INTERNAL HEAT GAINS

	Load	Schedule	Annual Load
Low	BC Hydro Low 2.68 W/m²	NECB 2011 10.6 hrs/day	10 kWh/m²a
Baseline	NECB 2011 5 W/m²	NECB 2011 10.6 hrs/day	19 kWh/m²a
High	BC Hydro High 7.17 W/m²	BC Hydro 15.8 hrs/day	41 kWh/m²a

2.5.2 Natural Ventilation

Natural ventilation has a significant impact on thermal comfort and is highly dependent on occupant behaviour, location and orientation of the building, and its surroundings.

In this study the modelled natural ventilation rate is based on the assumption that occupants open their windows as needed for optimized thermal comfort, though occupants may not open their windows due to reasons such as poor air quality, bugs, noise, or safety reasons. Part of the rationale for this sensitivity analysis is to test CAMM bundles for their resilience against air quality events such as wildfires. To understand how well specific bundles perform when windows are closed, they were modelled with no natural ventilation during the hottest summer week using the RCP-8.5 2050s climate file.

2.5.3 Power Outage

As the climate gets warmer and occupants increasingly expect mechanical cooling in buildings, dependency on electricity for thermal comfort during the cooling season increases. To assess how a mechanically cooled building would perform in the event of a power outage, key CAMM bundles were modelled by assuming that fans, mechanical cooling, plug loads, lighting and other electric equipment are turned off during the hottest summer week using the RCP-8.5 2050s climate file.

2.5.4 RCP-2080s Climate

Buildings that are now in the design stage or currently in construction will likely experience a significant change in climate throughout its lifetime. To understand how archetypes that are designed to meet the thermal comfort requirement based on the RCP-8.5 2050s climate file will perform later in the century, or if the predicted RCP-8.5 2080s climate conditions were to occur earlier, select bundles were modelled with the RCP-8.5 2080s climate file. Since the RCP-8.5 climate files are created based on a TMY file format, this sensitivity analysis can also be seen as a 2050s ‘hot summer’ stress test of the archetypes.

3 Results

This section summarizes the results for the following:

- → Thermal comfort, energy and GHG analysis for each baseline archetype
- → Thermal comfort, energy, GHG and cost analysis for CAMMs and bundles for each archetype

3.1 New Building Low Rise

This section summarizes the results for the new building low rise archetype. Recall that the low rise new building baseline archetype is designed to meet Step 3 of the BC Energy Step Code. Key findings are summarized at the end of the section (Section 3.1.4).

3.1.1 Baseline Results

Thermal Comfort Analysis

The low rise new building baseline is a non-mechanically cooled archetype. Therefore, it must be demonstrated that the number of overheated hours, as defined in ASHRAE 55-2010 Section 5.3, do not exceed 200 hours per year for any thermal zone (the 80% acceptability limit). The number of overheated hours is reported out together with modelled peak operative temperature. The thermal comfort metrics are reported at zone level to understand the risk of overheating and relative differences across the building. Figure 3.1 shows the number of hours per year that exceed the 80% acceptability limit. The layout of the floor plate is shown, with colour coding used to illustrate the variation in number of overheated hours.

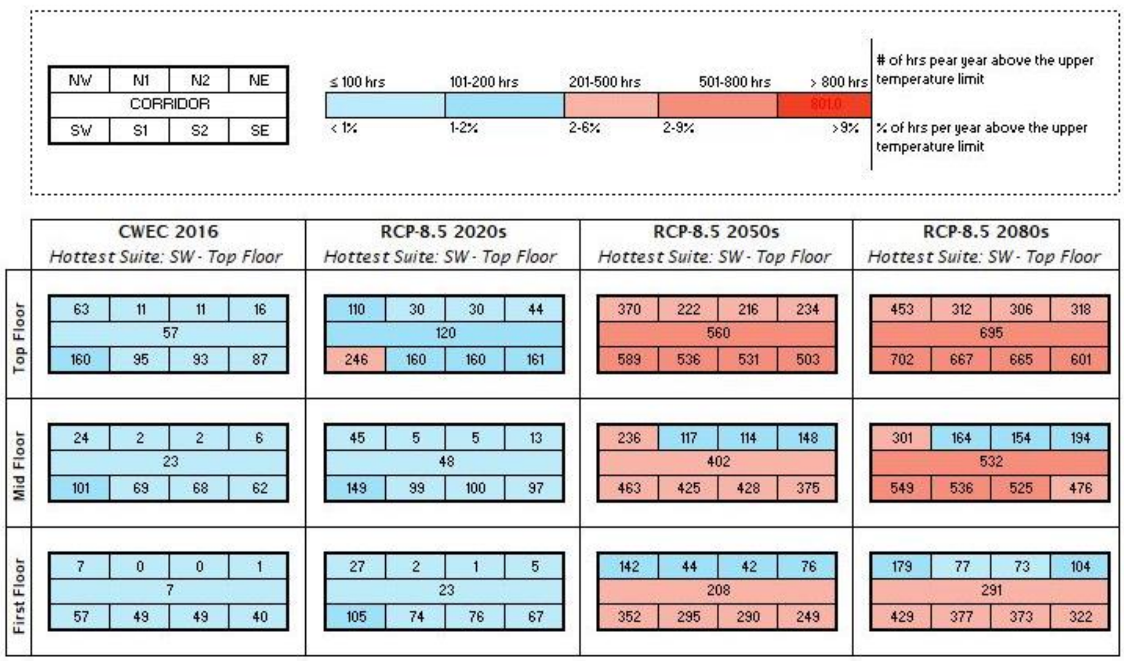

Figure 3.1 Number of hours that exceed the 80% acceptability limit. The zones that meet the 200 hr limit are shown as blue. The zones that exceed the 200 hr limit are colour coded as different shades of red. A darker red indicates a higher number of overheated hours.

The baseline thermal comfort results show that, based on the CWEC 2016 climate file, no suite exceeds the 80% acceptability limit for more than 200 hours. However, all south-facing suites exceed the 20-hour threshold for vulnerable populations. Based on the 2020s file, all suites show a higher number of overheated hours compared to the CWEC 2016 scenario and one suite exceeds the 200-hour limit. For the 2050s and 2080s files, the number of suites that exceed the 80% acceptability limit for more than 200 hours is 32, or 67% of the suites.

The south-west facing corner suite on the top floor shows the highest number of overheated hours for all four climate files, followed by the south facing and south-east facing suites. This is due to the higher exposure to solar radiation which results in higher solar heat gains compared to less sun exposed orientations. The top floor is hottest, likely due to the combination of increased sun exposure of the roof and stack effect. The lowest north facing suites generally remain within or close to the comfort limit even in the future climate scenarios.

Figure 3.2 shows modelled peak operative temperature, also in a building zone format, with colour coding used to illustrate the variation in peak temperature. The date and time of the hottest hour is also indicated.

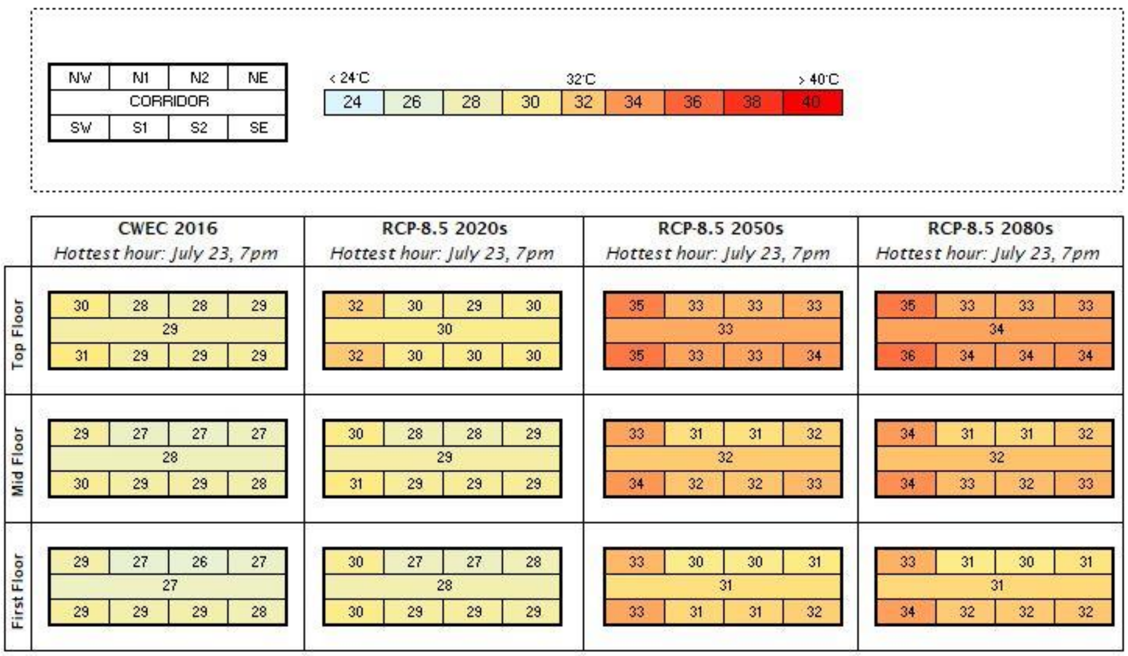

Figure 3.2 Modelled peak operative temperature (°C) for each zone and climate file. The zones are colour coded to illustrate the variation in peak temperature.

The number of overheated hours is higher for the south-west, south-east and directly south facing suites, though the modelled peak operative temperature is higher for the south-west facing and north-west facing corner suites. The higher modelled temperatures seen for the west-facing suites are likely a result of higher solar gains.

The thermal comfort results shown in Figure 3.1 and Figure 3.2 are summarized in Table 3.1. The results indicate that the baseline design meets the thermal comfort criteria as defined in the BC ESC. However, as the climate gets warmer, the number of overheated hours and peak operative temperatures increase and the baseline design no longer meets the thermal comfort criteria. The 2020s scenario only marginally exceeds the comfort criteria as defined in the BC ESC. Note that the baseline design exceeds the thermal comfort threshold for vulnerable population for all climate scenarios.

TABLE 3.1 SUMMARY OF BASELINE THERMAL COMFORT RESULTS FOR THE LOW RISE NEW BUILDING ARCHETYPE

	CWEC 2016	RCP-8.5 2020s	RCP-8.5 2050s	RCP-8.5 2080s
# of suites > 80% acceptability limit	0	1	32	32
% of suites > 80% acceptability limit	0	2%	67%	67%
Highest # of overheated hours (Zone level)	160	246	589	702
Suite with highest # of overheated hours	South-west facing corner suite on top floor			
Peak operative temperature (°C)	31	32	35	36
Suite with highest peak operative temperature	South-west facing corner suite on top floor			

Figure 3.3 shows the modelled hourly operative temperature for the warmest suite during the warmest week for the four climate scenarios. The red dashed line illustrates the 80% acceptability limit based on the CWEC 2016 file.

As the figure shows, the operative temperature based on the 2020s climate file is slightly warmer than CWEC 2016, and significantly warmer based on the 2050s and 2080s climate.

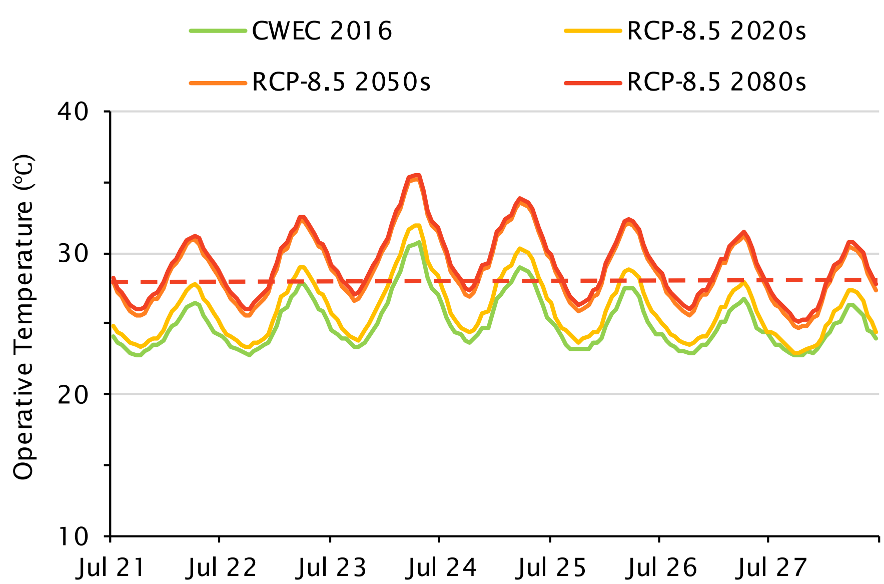

Figure 3.3 Modelled interior operative temperature (°C) for the warmest suite for the low rise new building baseline, shown for one summer week, based on the CWEC 2016, RCP-8.5 2020s, 2050s and 2080s climate files. The red dashed line illustrates the 80% acceptability limit based on the CWEC 2016 climate file.

Energy and Emission Analysis

Figure 3.4 summarizes annual total energy use intensity (TEUI) and thermal energy demand intensity (TEDI) for the low rise new building baseline. Recall that the low rise new building baseline archetype meets Step 3 of the BC ESC and does not have mechanical cooling. The grey dashed line illustrates the Step 3 TEUI target (120 kWh/m²a) and the red dashed line illustrates the Step 3 TEDI target (30 kWh/m²a).

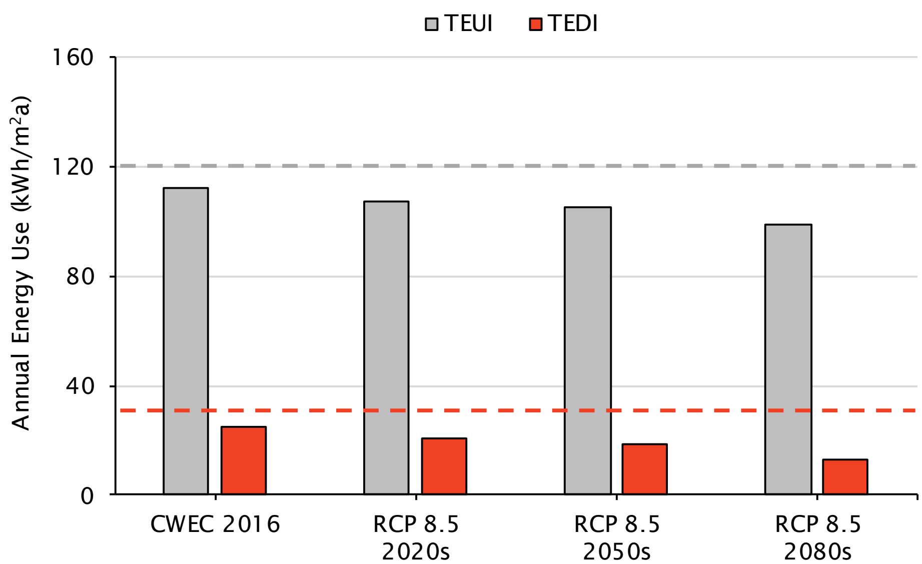

Figure 3.4 Annual total energy use intensity (TEUI) and thermal energy demand intensity (TEDI) results for the low rise new building baseline. The grey dashed line shows the Step 3 TEUI target (120 kWh/m²a), and the red dashed line shows the Step 3 TEDI target (30 kWh/m²a).

Table 3.2 summarizes the energy and emission results for the low rise new building baseline. As shown, the three energy related metrics (TEDI, TEUI and peak heating demand) and the emission metric (GHGI) decrease as the climate gets warmer, due to the decreased space heating demand. Compared to the CWEC 2016 results, TEDI decreases 30% based on the RCP-8.5 2050s climate file, and 56% based on the RCP-8.5 2080s climate file. However, the models indicate that more than half (67%) of the suites exceed the thermal comfort 80% acceptability limit based on the 2050s and 2080s climate files. So, while the TEDI and TEUI targets are being met, thermal comfort criteria are not being met for most suites by the 2050s.

TABLE 3.2 SUMMARY OF BASELINE ENERGY AND EMISSION RESULTS FOR THE LOW RISE NEW BUILDING ARCHETYPE				
	CWEC 2016	RCP-8.5 2020s	RCP-8.5 2050s	RCP-8.5 2080s
TEUI (kWh/m^2a)	111	105	103	96
TEDI (kWh/m^2a)	23	18	16	10
Peak heating demand[1] (W/m^2)	20	17	17	16
GHGI[2] – Current ($kgCO_2e/m^2a$)	13	12	11	10
GHGI[2] – Future ($kgCO_2e/m^2a$)	6	5	5	4

[1]Peak heating demand on grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the current emission factor (GHGI – Current) for the UBC district energy system as well as the emission factor for the future district energy system(GHGI – Future) that is planned to consist of 60% renewable energy by 2024.

3.1.2 Climate Adaptation + Mitigation Measures

This section summarizes the thermal comfort and costing results for the individual CAMMs for the low rise new building. A detailed description of each climate adaptation measure is provided in Appendix B.

Thermal Comfort Analysis

Figure 3.5 shows the number of overheated hours in the warmest zone for the baseline archetype and each CAMM, based on the RCP-8.5 2050s climate file. The red dashed line illustrates the 200-hour limit, and the black dashed line presents the baseline results.

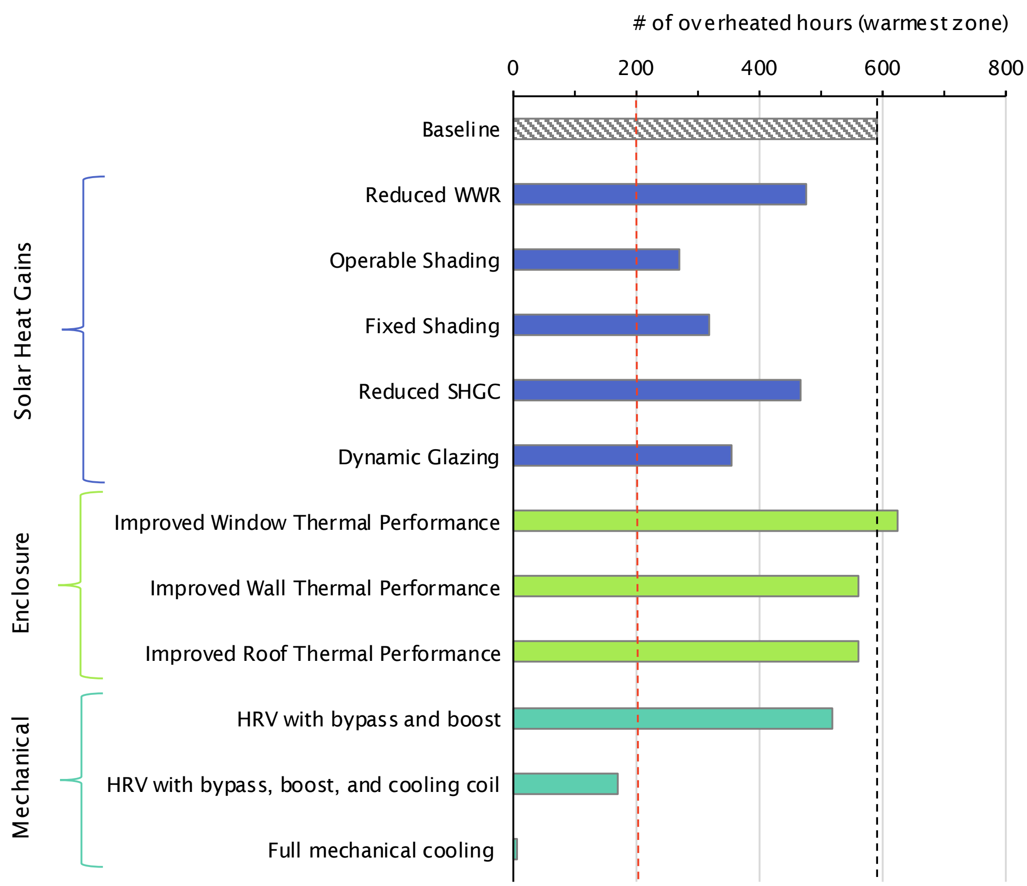

Figure 3.5. Number of overheated hours for the warmest zone for the baseline and each individual CAMM, modelled with the RCP-8.5 2050s climate file. The red dashed line illustrates the 200 hour limit, and the black dashed line indicates the baseline results.

As seen in Figure 3.5, the most effective passive measure on its own is operable shading, followed by fixed shading and dynamic glazing. Though the exterior shading measures are close to the 200 hour limit, none of the passive measures on their own reduce the number of overheated hours for the warmest suite below 200 hours for the 2050s scenario.

The results indicate that upgrading the ventilation system to include a high efficiency HRV that can operate in boost and bypass mode as needed, plus a cooling coil downstream of the HRV, meets the thermal comfort criteria based on the RCP-8.5 2050s climate file. This suggests that full mechanical cooling is not required for this archetype in 2050s climate (provided we accept the 200-hour 80% acceptability limit).

As an individual measure, dramatically improving the window thermal performance (to USI-0.8) without combining with passive cooling measures leads to a slight increase in overheating. This suggests that installing a window that has very low thermal transmittance without also addressing solar heat gain may increase the risk of overheating.

Costing Analysis

The incremental cost of each CAMM compared to the baseline is presented in Figure 3.6 together with the thermal comfort results shown in the previous section. The red error bars illustrate the high and low CAMM cost. Appendix C provides additional costing details.

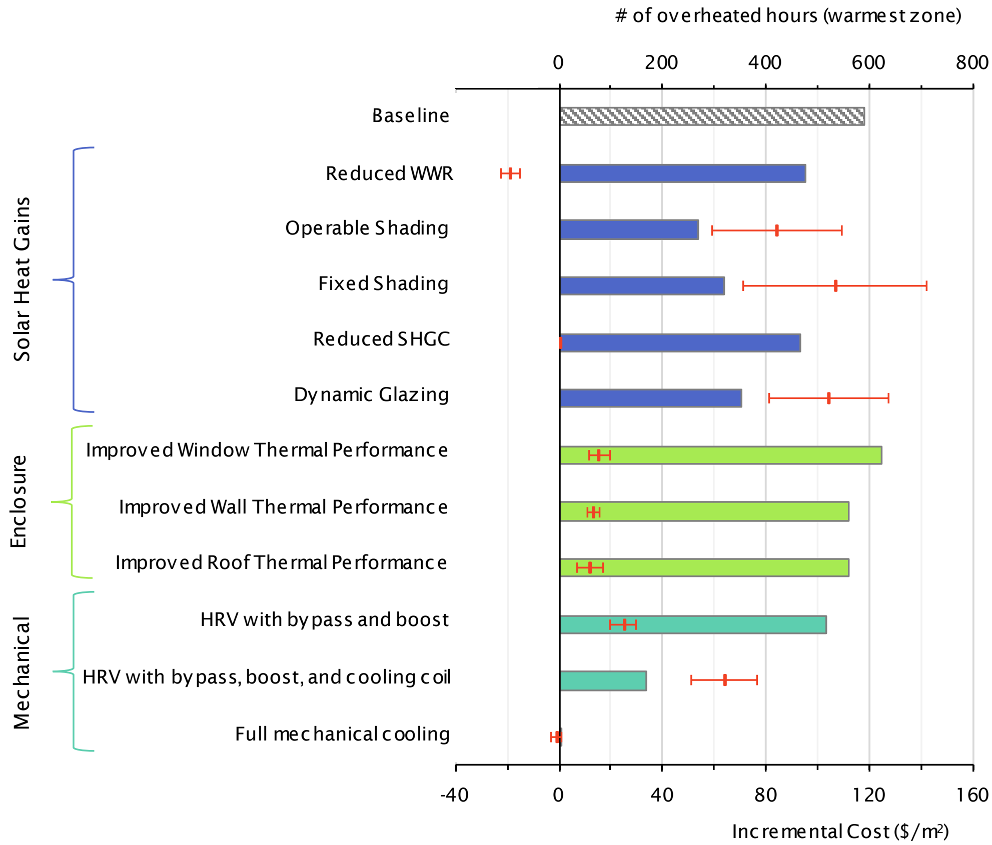

Figure 3.6 The red lines show the incremental cost ($/m²) on building level, the error bars show the high and low cost. The number of overheated hours is shown for the warmest suite based on RCP-8.5 2050s climate file.

The reduced WWR measure shows a negative incremental cost as there is a capital cost reduction associated with installing less window area. The reduced SHGC measure shows no incremental cost because the cost to upgrade glazing with lower SHGC for new construction is very small. These results indicate that designing for reduced WWR and SHGC are both promising strategies given that they reduce the risk of overheating with either a negligible or positive impact on incremental costs.

On the active side, the high efficiency HRV measure with cooling coil is cost effective compared to the passive measures but less cost-effective than changing the mechanical heating and cooling system to provide full mechanical cooling.

The full mechanical cooling measure includes installation of air source heat pumps that provide heating and cooling via in-suite hydronic FCUs. The baseline includes in-floor hydronic heating (no cooling), and as such the incremental capital cost of switching the mechanical system to an integrated heating and cooling system is shown to be negligible. The baseline choice reflects UBC's preference given their district energy system, but is less common in other areas of the Lower Mainland. If, for example, electric baseboard heaters were used in the baseline case, the incremental cost to upgrade to heat pumps would be significantly higher.

3.1.3 CAMM Bundles

Based on the analysis of the impact on overheated hours of the individual CAMMs and the costing analysis, bundles of CAMMs were assembled, following the approach described in Section 2.3.1.

For the new building low rise, the archetype was also adjusted to comply with BC ESC Step 4, to understand how the higher step archetype's performance may differ from the Step 3 baseline in a future climate. Bundles were then applied to each of the Step 3 and Step 4 archetypes.

Recall that the new building low rise baseline is heated via in-floor hydronic heating with district energy connection. As mentioned in Section 2.1.1, an additional analysis was completed to understand the impact and cost associated with the CAMM bundles for a low rise new archetype with a more common electric baseboard baseline heating system. The results of the additional analysis are provided in Appendix D.

Step 3

The modelled bundles for the Step 3 archetype are summarized in Table 3.3. Two passive bundles (Bundle 1 and Bundle 2), and two combined passive and active bundles (Bundle 3 and Bundle 4) were modelled. Bundle 3 includes partial cooling through the ventilation unit, whereas Bundle 4 consists of full mechanical cooling through an air source heat pump supplying in-suite fan-coil units. The measures included in the bundles are described in further detail in Appendix B.

TABLE 3.3 MODELLED BUNDLES FOR STEP 3 LOW RISE NEW BUILDING ARCHETYPE		
		Description
Passive	Step 3 – Bundle 1	→ Reduced WWR to 30% (from 40%) → Reduced SHGC to 0.28 (from 0.36) → Fixed shading
	Step 3 – Bundle 2	→ Reduced SHGC to 0.28 (from 0.36) → Operable shading
Combined	Step 3 – Bundle 3	→ High efficiency HRV with bypass, cooling coil and boost as needed → Reduced SHGC to 0.28 (from 0.36) → Operable shading
	Step 3 – Bundle 4	→ Full mechanical cooling → Reduced SHGC to 0.28 (from 0.36) → Operable shading

Operable shading showed a higher reduction in overheating hours than fixed shading, however, the model assumes that occupants control the shading devices as needed for optimal solar heat gain reduction. Fixed shading can be favourable for projects where passive design (limited occupancy control) is a priority. Furthermore, operable shading may need maintenance throughout the lifetime of the shading device, and/or be replaced throughout the lifetime of the building. Because of the co-benefits of fixed shading, the measure is included in the bundle analysis.

Thermal Comfort Analysis

Figure 3.7 shows the number of overheated hours for the *warmest zone* in the Step 3 low rise new building baseline and bundle archetypes. The modelled risk of overheating is shown based on the RCP-8.5 2020s and 2050s climate files. The red dashed line illustrates the 200 hour limit, and the orange dashed line illustrates the 20 hour limit for vulnerable populations. Table 3.4 summarizes the results shown in Figure 3.7. The red font colour indicates that the thermal comfort criteria (80% acceptability limit) is exceeded.

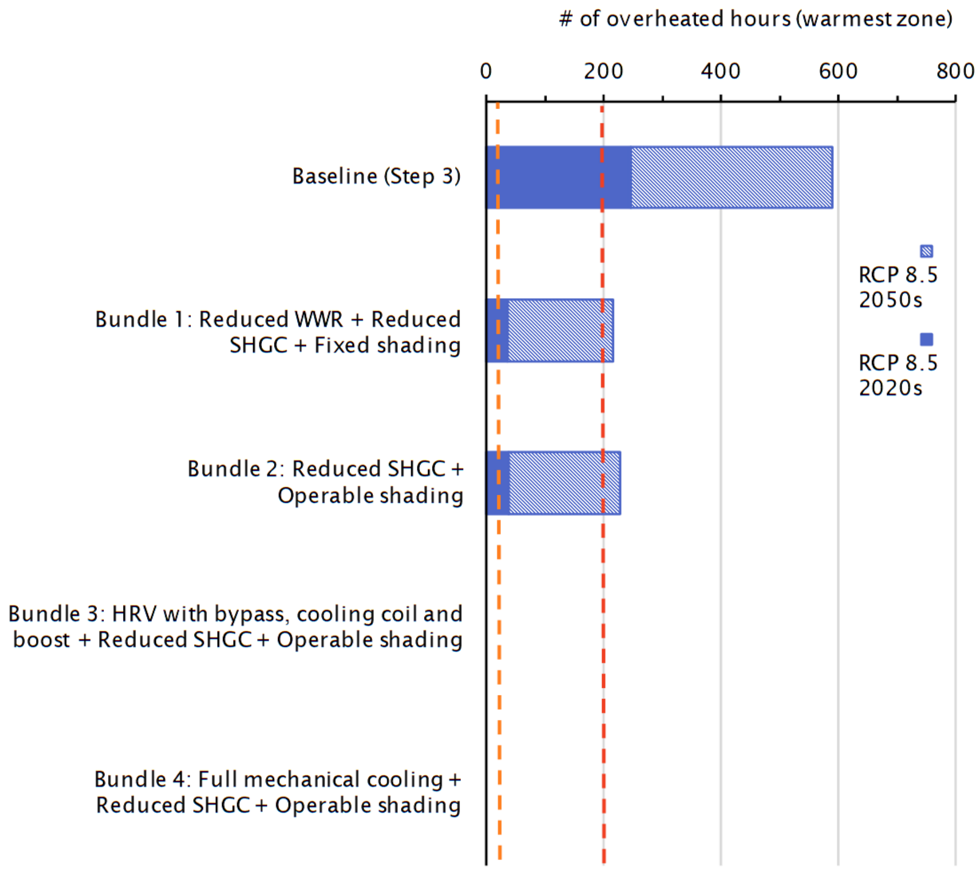

Figure 3.7 Number of overheated hours for the warmest zone in the Step 3 low rise new building baseline and bundle archetypes, based on the RCP-8.5 2020s and 2050s climate files. The red dashed line illustrates the 200 hour limit, and the orange dashed line illustrates the 20 hour limit for vulnerable population.

TABLE 3.4 NUMBER OF OVERHEATED HOURS FOR THE WARMEST ZONE FOR THE STEP 3 LOW RISE NEW BUILDING BASELINE AND MODELLED BUNDLES

	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
RCP-8.5 2020s	246	35	37	0	0
RCP-8.5 2050s	589	215	227	0	0

The results show that the warmest zone for both the passive bundles (Bundle 1 and Bundle 2) are below the 200-hour target based on the RCP-8.5 2020s climate file, though both passive bundles slightly exceed the 200 hour threshold based on the RCP-8.5 2050s climate file. Both combined bundles (Bundle 3 and Bundle 4) reduce the number of overheated hours below the 20-hour threshold for vulnerable populations, based on the RCP-8.5 2020s and 2050s climate file. These results illustrate that the Step 3 baseline archetype performs reasonably well from a comfort perspective in the RCP-8.5 2020s climate, but is vulnerable under the 2050s scenario, whereas all of the bundles perform relatively well in both future scenarios.

Table 3.5 summarizes the whole building thermal comfort results for the Step 3 baseline and bundles, modelled with the RCP-8.5 2050s climate file. Both the passive and combined bundles reduce the risk of overheating and peak operative temperature significantly at the whole building level. The number of suites that exceed the 80% acceptability limit decrease from 32 (67%) to 3 (6%) for the passive bundles and no suites exceed the 80% acceptability limit for the combined bundles.

TABLE 3.5 SUMMARY OF BUNDLE THERMAL COMFORT RESULTS FOR THE STEP 3 LOW RISE NEW BUILDING BASED ON RCP-8.5 2050S CLIMATE FILE

	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
# of zones > 80% acceptability limit	32	3	3	0	0
% of zones > 80% acceptability limit	67%	6%	6%	0%	0%
Highest # of overheated hours (zone level)	589	215	227	0	0
Peak operative temperature (°C)	36	33	33	28	27
Suite with highest peak operative temperature	South-west facing corner suite on top floor				

Figure 3.8 shows the modelled operative temperature for the Step 3 low rise new building baseline and bundles for the hottest summer week based on the RCP-8.5 2050s climate file. The red dashed line illustrates the 80% acceptability limit for July.

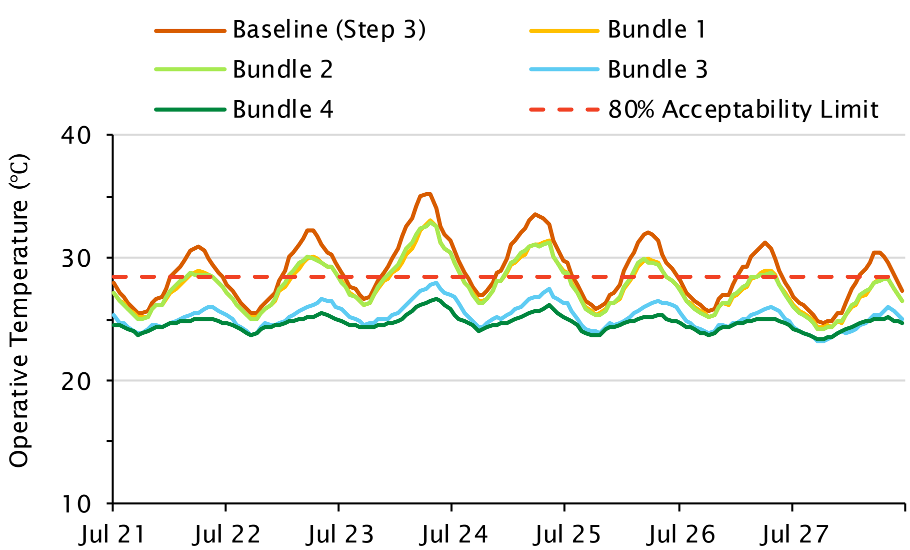

Figure 3.8 Modelled operative temperature (°C) for the warmest suite for the Step 3 low rise new building baseline and bundles based on the RCP-8.5 2050s climate file, shown for the hottest summer week.

The results indicate that partial cooling in combination with operable exterior shading (Bundle 3) eliminates all overheated hours and achieves comparable interior temperature as full mechanical cooling (bundle 4) during the hottest summer week.

Energy and Emission Analysis

Table 3.6 summarizes the energy and GHG results for the passive bundles for the Step 3 low rise new building archetype based on the RCP-8.5 2050s climate file. Note that the passive bundles for the Step 3 archetype marginally exceed the 200 hour threshold based on the 2050s scenario, however, the energy and emission results for these bundles are still included since they are close to the limit and may still be viable solutions.

TABLE 3.6 ENERGY AND GHG RESULTS FOR THE STEP 3 LOW RISE NEW BUILDING PASSIVE BUNDLES BASED ON THE RCP-8.5 2050S CLIMATE FILE

	Baseline (Step 3)	Bundle 1	Bundle 2
TEUI (kWh/m²a)	105	104	106
TEDI (kWh/m²a)	19	18	19
Peak heating demand[1] (W/m²)	18	15	19
GHGI[2] (kgCO_2e/m²a)	5	5	5

[1]Peak heating demand on grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

There is a relatively small difference in TEUI, TEDI, and peak heating demand between the baseline and the modelled passive bundles. The passive bundles are designed to reduce the solar heat gains to the space to reduce the risk for overheating, which can result in a slight increase in space heating demand, as is evident for Bundle 2 (operable shading + reduced SHGC).

Bundle 1 consists of reduced window to wall ratio, fixed exterior shading, and reduced SHGC. Although Bundle 1 also consists of design measures that reduce solar heat gains, the improved overall thermal performance of the envelope, due to the reduced WWR, results in an overall positive effect on TEDI and peak heating demand compared to the baseline.

Table 3.7 summarize the energy and GHG results for the combined bundles based on the RCP-8.5 2050s climate file. To quantify the impact of passive measures when combined with the active measures, the results for the individual active measures are included, i.e. the bundles without passive measures.

TABLE 3.7 ENERGY AND GHG RESULTS FOR THE STEP 3 LOW RISE NEW BUILDING COMBINED BUNDLES BASED ON THE RCP-8.5 2050S CLIMATE FILE					
	Baseline (Step 3)	HRV with bypass, cooling coil, and boost as needed		Full mechanical cooling	
		Without passive measures	**With** passive measures (Bundle 3)	**Without** passive measures	**With** passive measures (Bundle 4)
TEUI (kWh/m²a)	105	105	105	109	104
TEDI (kWh/m²a)	19	13	13	19	19
CEDI[1] (kWh/m²a)	n/a	9	8	16	12
TEDI + CEDI (kWh/m²a)	19	22	21	35	31
Peak heating demand[2] (W/m²)	18	13	13	6	6
Peak cooling demand[2] (W/m²)	n/a	10	7	9	6
Peak operative temperature (°C)	36	31	28	27	27
GHGI[3] ($kgCO_2e/m^2a$)	5	4	4	3	3

[1] Recall that there is currently no performance metric defined in the BC ESC for cooling energy. To allow for comparison of cooling energy demand between the different measures and climate scenarios, a metric for cooling energy demand is included in this analysis, referred to as 'cooling energy demand intensity', or CEDI, which is calculated in the same way as the TEDI, i.e. the annual cooling demand for space conditioning and conditioning of ventilation air (not accounting for system efficiency).
[2] Peak heating/cooling demand on grid (accounts for system efficiency), see Table 2.5 for full description.
[3] The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024

The lower TEDI shown for Bundle 3 compared to the baseline is due to the increase in HRV efficiency. Despite the reduction in heating demand, TEUI is unchanged compared to the baseline due to the increase in fan power and addition of cooling energy consumption.

Bundle 4 consists of full mechanical cooling via an air source heat pump supplying in-suite fan-coil units; the higher system efficiency of which results in a lower peak heating demand and peak cooling demand compared to Bundle 3.

The results show that the addition of passive cooling measures to the actively cooled archetypes significantly reduces CEDI and peak cooling demand. The reduced cooling energy demand is shown for both Bundle 3 (partial cooling) and Bundle 4 (full cooling) compared to the individual active measures, i.e. the bundles without passive measures. Both Bundle 3 and Bundle 4 result in slightly lower or similar total building energy consumption (TEUI) and GHGI as the Step 3 baseline, while also significantly reducing the risk of overheating based on 2050s climate.

Besides the positive impact of passive cooling measures on cooling energy demand, adding design measures to mitigate solar heat gains can also result in reduced operation costs and may allow for reduced cooling equipment size.

Costing Analysis

This section summarizes the costing analysis of the Step 3 low rise new building bundles, including the incremental capital cost ($/m²) and annual energy cost ($/m²). Additional costing details are provided in Appendix C. Note that the passive bundles for the Step 3 archetype marginally exceed the 200 hour threshold based on the 2050s scenario; however, the bundles are still included in the costing analysis since they are close to the limit and may be viable solutions.

Figure 3.9 shows the incremental cost at the building level for the Step 3 bundles. To understand the cost-effectiveness of each bundle the incremental cost is shown together with the number of overheated hours based on the RCP-8.5 2050s climate file. The error bars illustrate the high and low bundle cost.

Figure 3.10 shows the annual energy cost for the Step 3 baseline and bundles. Table 3.8 summarizes the energy cost savings compared to the baseline.

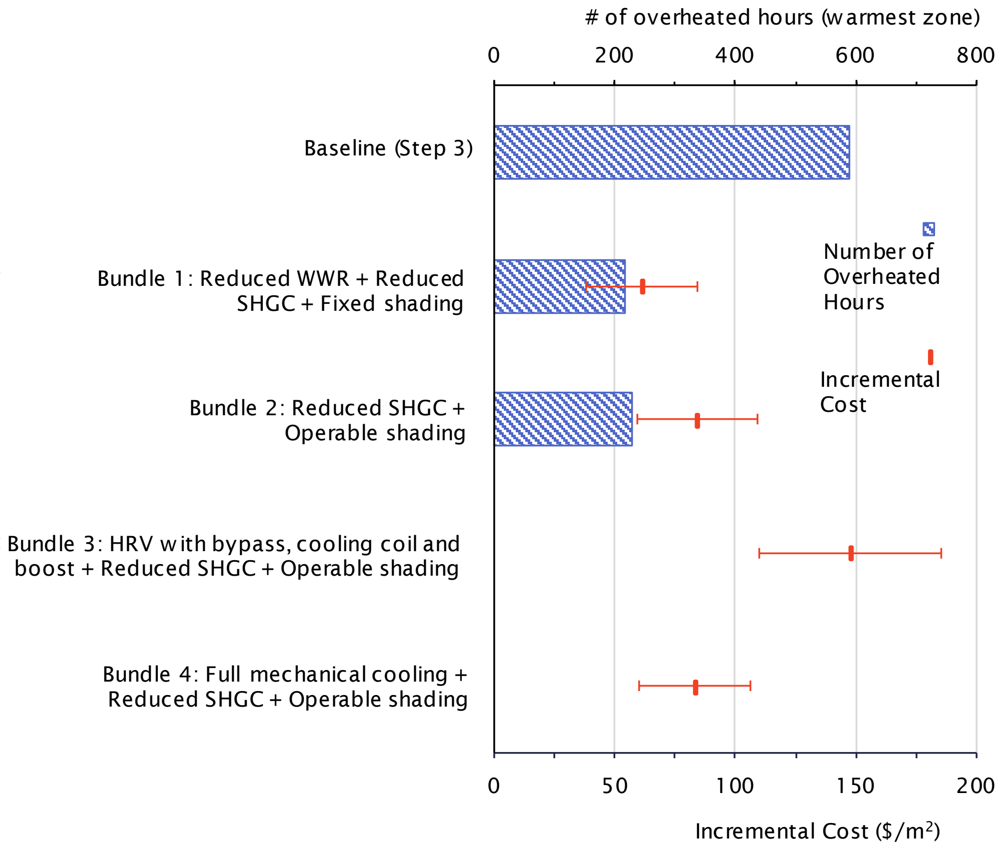

Figure 3.9 Incremental cost ($/m²) for the Step 3 bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

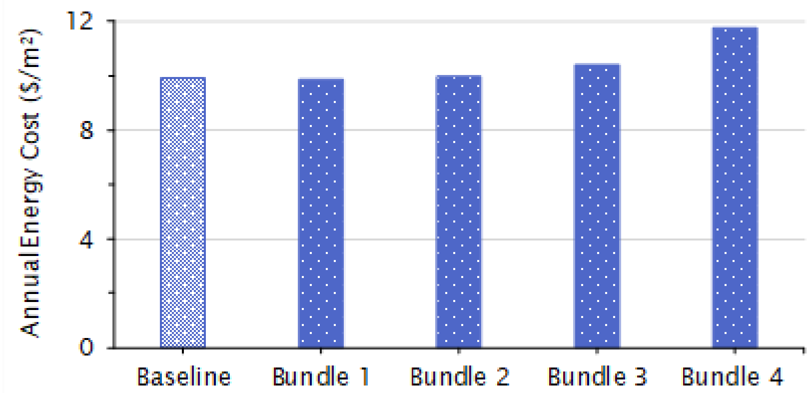

Figure 3.10 Annual energy cost ($/m²) for the Step 3 baseline and bundles.

TABLE 3.8 ENERGY COST SAVINGS COMPARED TO THE BASELINE (STEP 3)				
	Bundle 1	Bundle 2	Bundle 3	Bundle 4
Energy Cost Savings (%)	0%	0%	-5%	-19%

The average incremental cost of Bundle 4 (full mechanical cooling) is comparable to the passive bundle. However, as discussed in Section 3.1.2, a different baseline heating system (e.g. electric baseboards) would considerably increase the incremental cost of adding full mechanical cooling. Appendix D provides the incremental cost of this bundle compared to an electric baseboard baseline.

Neither of the combined bundles (Bundle 3 and 4) result in an increase in total energy use compared to the baseline. And both reduce GHG emissions. However, both result in an increase in annual energy *cost*. The bundles result in lower heating energy use (district energy) due to heat recovery or higher heating equipment efficiency, but also increased cooing energy use (electricity). Since the current utility rate for electricity is higher than district energy (in this scenario), there is an increase in total annual energy cost. Refer to Appendix D for the energy cost savings of the combined bundles compared to an electric baseboard baseline.

Step 4

To meet the BC ESC Step 4 targets, the overall thermal performance of the enclosure was improved by upgrading the windows, wall and roof, and the minimum efficiency HRVs were upgraded to high efficiency HRVs with bypass. Table 3.9 summarizes the adjustments that were made to the Step 3 low rise new building baseline to meet Step 4.

TABLE 3.9 ADJUSTMENTS MADE TO MEET STEP 4 OF THE BC ESC FOR THE LOW RISE NEW BUILDING ARCHETYPES	
	Description
Step 4	→ Improved window performance to USI-0.8 (U-0.14), SHGC-0.28 → Improved wall thermal performance to R_{eff}-27 → Improved roof thermal performance to R_{eff}-40 → Upgraded HRVs to 85% efficient with bypass

The modelled bundles for the Step 4 archetype are summarized in Table 3.10. The difference between the Step 3 and Step 4 bundles is that the reduced SHGC measures is included in the Step 4 baseline, and therefore not included as an additional design measure in the bundles.

Two passive bundles (Bundle 1 and Bundle 2), and two combined passive and active bundles (Bundle 3 and Bundle 4) were modelled. The measures are described in further detail in Appendix B.

TABLE 3.10 MODELLED BUNDLES FOR STEP 4 LOW RISE NEW BUILDING ARCHETYPE		
		Description
Passive	Step 4 – Bundle 1	→ Reduced WWR to 30% (from 40%) → Fixed shading
	Step 4 – Bundle 2	→ Operable shading
Combined	Step 4 – Bundle 3	→ Cooling coil downstream of HRV, and boost as needed → Operable shading
	Step 4 – Bundle 4	→ Full mechanical cooling → Operable shading

Thermal Comfort Analysis

Figure 3.11 shows the number of overheated hours for the *warmest zone* in the Step 4 low rise new building baseline and bundle archetypes. The modelled risk of overheating is shown based on the RCP-8.5 2020s and 2050s climate files. The red dashed line illustrates the 200 hour limit, and the orange dashed line illustrates the 20 hour limit for vulnerable population. Table 3.11 summarizes the results shown in Figure 3.11.

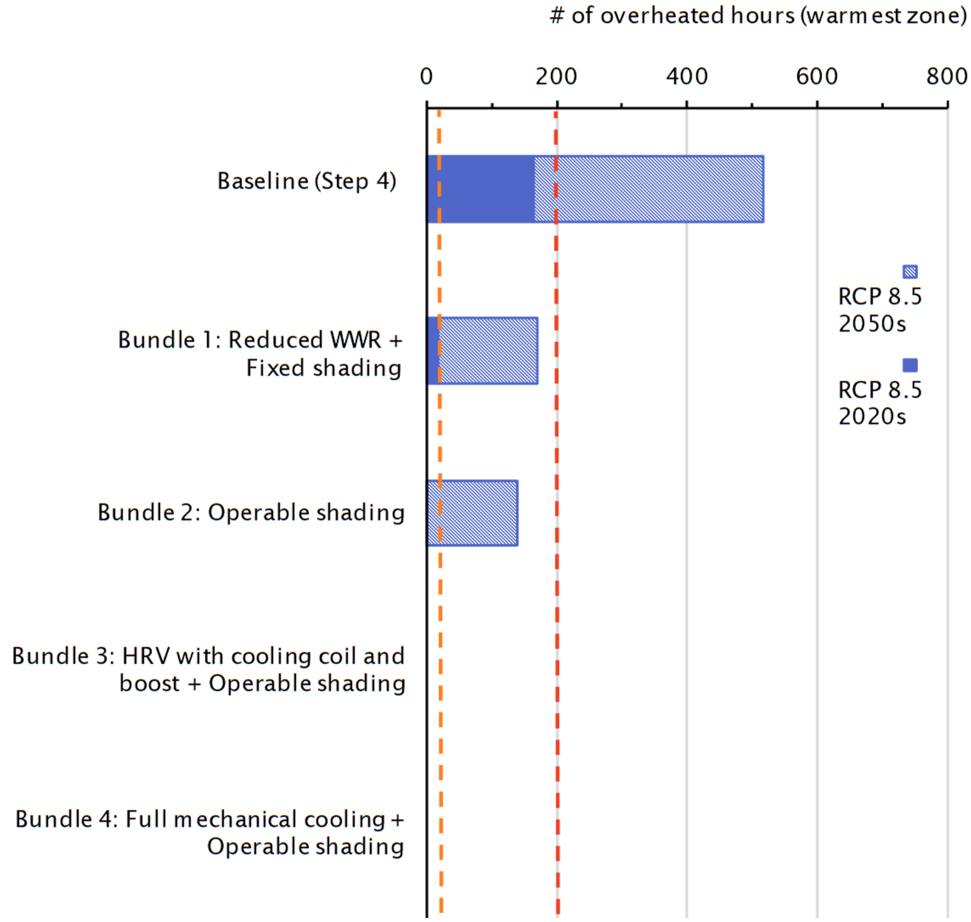

Figure 3.11 Number of overheated hours for the Step 4 low rise new building baseline and modelled bundles based on the RCP-8.5 2020s and 2050s climate files. The red dashed line illustrates the 200 hour limit, and the orange dashed line illustrates the 20 hour limit for vulnerable population.

TABLE 3.11 NUMBER OF OVERHEATED HOURS FOR THE WARMEST ZONE FOR THE STEP 4 BASELINE AND MODELLED BUNDLES

	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
RCP-8.5 2020s	164	18	1	0	0
RCP-8.5 2050s	517	169	139	0	0

Table 3.12 summarizes the thermal comfort results for the Step 4 baseline and bundles, modelled with the RCP-8.5 2050s climate file. The results show that all bundles reduce the number of overheated hours below the 200-hour target for all suites, based on both the RCP-8.5 2020s and 2050s climate file. All bundles are below the 20-hour target for vulnerable populations based on the RCP-8.5 2020s climate file, though the passive-only bundles exceed the 20 hour based on the RCP-8.5 2050s climate file. The results show that the Step 4 baseline and its bundles perform better, from a thermal comfort perspective, than the Step 3 baseline and bundles.

TABLE 3.12 SUMMARY OF BUNDLE THERMAL COMFORT RESULTS FOR THE STEP 4 LOW RISE NEW BUILDING BASED ON RCP-8.5 2050S CLIMATE FILE					
	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
# of zones > 80% acceptability limit	25	0	0	0	0
% of zones > 80% acceptability limit	52%	0%	0%	0%	0%
Highest # of overheated hours (zone level)	517	169	139	0	0
Peak operative temperature (°C)	34	32	32	28	27
Suite with highest peak operative temperature	South-west facing corner suite on top floor				

Figure 3.12 shows the modelled operative temperature for the Step 4 low rise new building baseline and bundles for the hottest summer week based on the RCP-8.5 2050s climate file. The red dashed line illustrates the 80% acceptability limit for July.

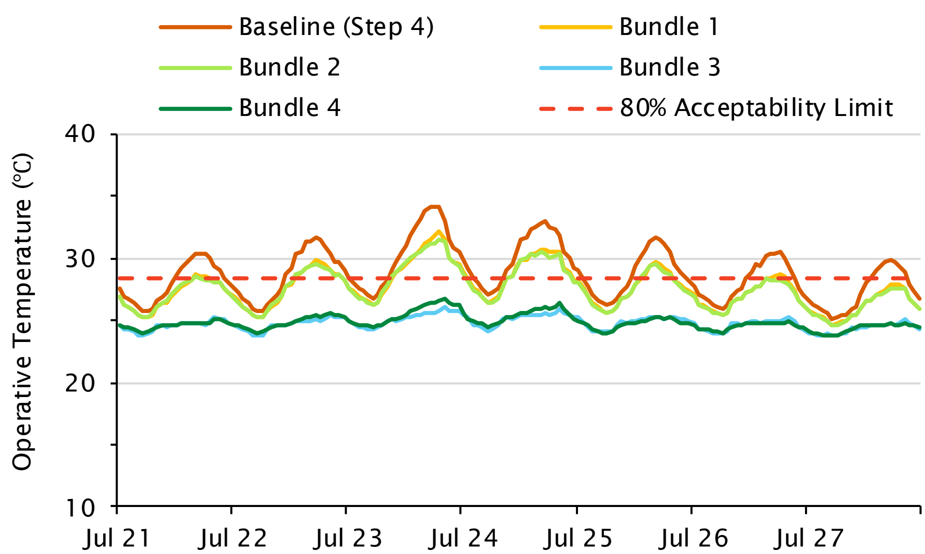

Figure 3.12 Modelled operative temperature (°C) for the warmest suite for the Step 4 low rise new building bundles, shown for the hottest summer week.

As seen for the Step 3 archetype, the results indicate that cooling only the ventilation air, in combination with operable exterior shading (Bundle 3), eliminates all overheated hours and achieves comparable interior temperatures as full mechanical cooling (Bundle 4) during the hottest summer week.

Energy and Emission Analysis

Table 3.13 summarizes the energy and GHG results for the passive bundles for the Step 4 low rise new building archetype based on the RCP-8.5 2050s climate file.

TABLE 3.13 PASSIVE BUNDLE RESULTS FOR LOW RISE NEW BUILDING STEP 4 BASED ON RCP-8.5 2050S CLIMATE FILE			
	Baseline	Bundle 1	Bundle 2
TEUI (kWh/m^2a)	96	96	97
TEDI (kWh/m^2a)	11	11	11
Peak heating demand[1] (W/m^2)	13	13	13
GHGI[2] ($kgCO_2e/m^2a$)	4	4	4

[1]Peak heating demand on grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

Similar to the Step 3 archetype, there is relatively small difference in TEUI, TEDI, and peak heating demand between the baseline and the modelled passive bundles. The slight increase in TEUI shown for Bundle 2 is a result of an increase in heating demand, as a result of the reduced solar heat gains to the space.

Table 3.14 summarizes the results for the active bundles for the Step 4 low rise new building. For comparison, the results for the individual active measures are included, i.e. the bundles without passive measures. Red font color indicates that the Step 4 target has been exceeded.

TABLE 3.14 COMBINED BUNDLE RESULTS FOR LOW RISE NEW BUILDING STEP 4 BASED ON RCP-8.5 2050S CLIMATE FILE					
	Baseline (Step 4)	HRV with bypass, cooling coil, and boost as needed		Full mechanical cooling	
		Without passive measures	**With** passive measures (Bundle 3)	**Without** passive measures	**With** passive measures (Bundle 4)
TEUI (kWh/m^2a)	96	100	99	105	99
TEDI (kWh/m^2a)	11	11	11	11	11
CEDI (kWh/m^2a)	n/a	9	8	15	10
TEDI + CEDI (kWh/m^2a)	n/a	20	19	26	21
Peak heating demand[1] (W/m^2)	13	13	13	5	5
Peak cooling demand[1] (W/m^2)	n/a	10	7	8	4
Peak operative temperature (°C)	34	30	28	27	27
GHGI[2] ($kgCO_2e/m^2a$)	4	4	4	3	3

[1]Peak heating/cooling demand on grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

The results show the beneficial reduction to the CEDI and peak cooling demand from incorporating passive measures in a fully and partially mechanically cooled scenario.

Note that the Step 4 BC ESC target for TEUI is exceeded for the full mechanical cooling case without passive cooling measures. The addition of passive cooling measures (Bundle 4) reduces the cooling energy use and lowers the TEUI below the Step 4 target, although all active bundles are close to exceeding the Step 4 TEUI limit and further adjustments may be required (for example further reducing the cooling energy demand by additional solar reduction measures, or further improvements to enclosure thermal performance) to address thermal comfort *and* meet the TEUI target.

Costing Analysis

This section summarizes the costing analysis of the Step 4 low rise new building bundles, including the incremental capital cost ($/m²) and annual energy cost ($/m²). Additional costing data are provided in Appendix C.

Figure 3.13 shows the incremental cost on building level for the Step 4 bundles together with the number of overheated hours based on the RCP-8.5 2050s climate file. The error bars illustrate the high and low bundle cost.

Figure 3.14 shows the annual energy cost impact for the Step 3 baseline and bundles. Table 3.15 summarizes the energy cost savings compared to the baseline.

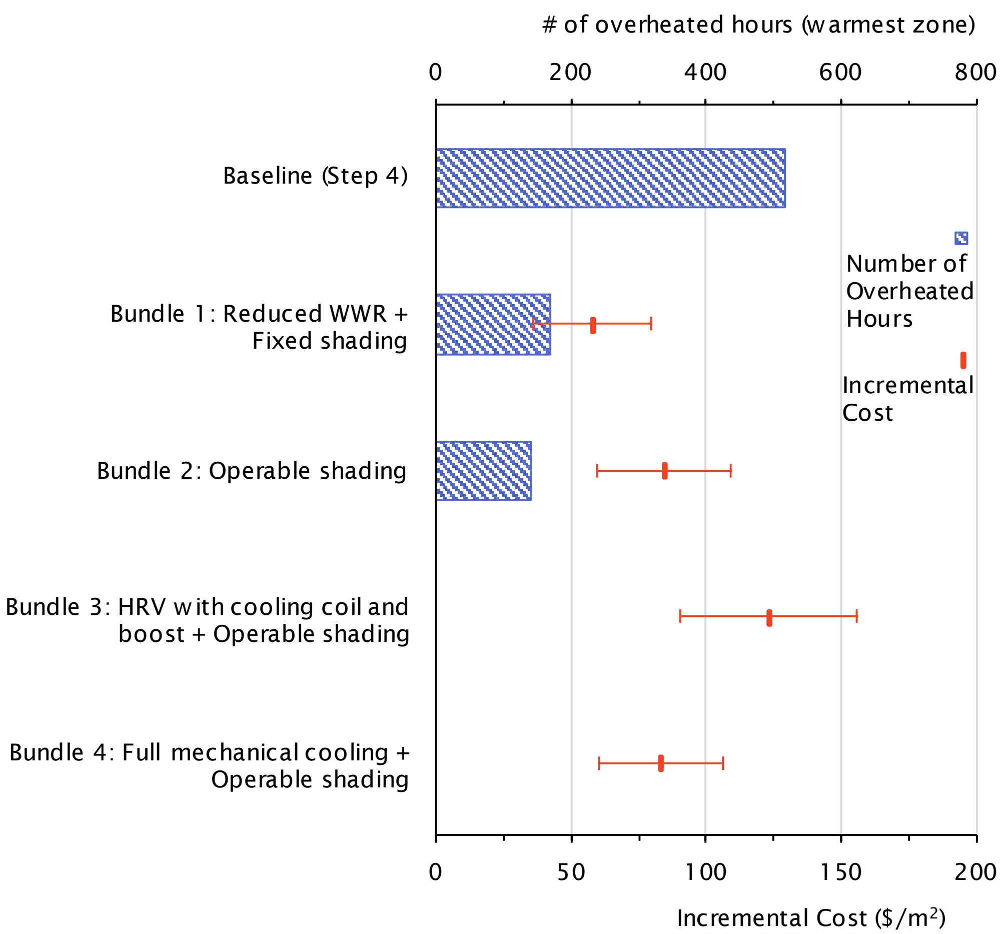

Figure 3.13 Incremental cost ($/m²) for the Step 4 bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

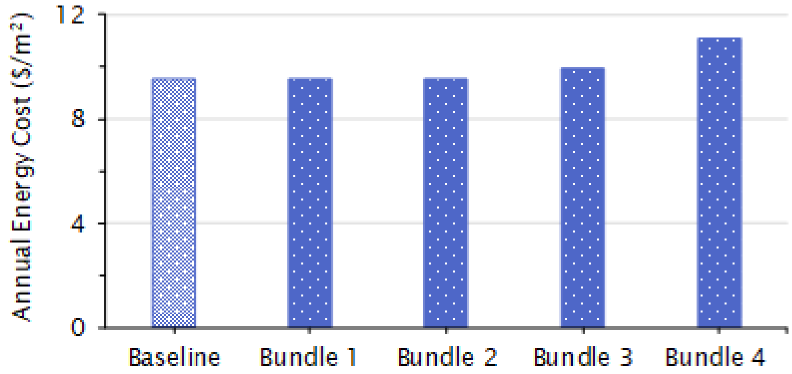

Figure 3.14 Annual energy cost ($/m²) for the Step 4 baseline and bundles.

TABLE 3.15 ENERGY COST SAVINGS COMPARED TO THE BASELINE (STEP 4)				
	Bundle 1	Bundle 2	Bundle 3	Bundle 4
Energy Cost Savings (%)	0%	0%	-4%	-16%

The results show that there is an increase in the annual energy cost for both combined bundles (Bundle 3 and 4). This is because the bundles result in a small increase in total energy use due to the addition of cooling, as well as a switch from district energy to electricity, which has a higher utility rate. However, since there is a switch from district energy to electricity, and the emission factor in this case is lower for electricity than district energy, Bundle 4 results in a reduction in GHG emissions, and the GHG emissions for Bundle 3 are unchanged compared to the baseline.

Appendix D provides the energy cost savings and incremental cost of the bundle compared to an electric baseboard baseline.

3.1.4 Key Findings – Low Rise New Building

→ Both Step 3 and Step 4 baseline archetypes are vulnerable to overheating under the 2050s scenario. This suggests that some deliberate design strategies beyond simply meeting the current BC ESC metrics are required to address future thermal comfort.

→ The modelling results show that the Step 4 baseline and bundles perform better, from a thermal comfort and energy perspective, than the Step 3 baseline and bundles. To meet the Step 4 TEDI target, the thermal performance of the enclosure had to be improved. As there are less heat losses through the enclosure, the building becomes more vulnerable to overheating if solar heat gains are not controlled, and/or if unwanted warm air is brought in through the ventilation system. Therefore, high performance windows with reduced SHGC and high efficiency HRVs with bypass were also implemented in the Step 4 case to meet the BC ESC thermal comfort criteria.

→ Reduced Window to Wall Ratio and glazing with a reduced Solar Heat Gain Coefficient are two essentially zero incremental cost design measures with a beneficial impact on reducing the risk of overheating. However, both strategies may reduce winter solar gains and increase thermal energy demand, and as such, each strategy must be evaluated within the context of a specific project and its other performance metrics.

→ For the Step 4 archetype, all modelled passive and combined bundles meet the thermal comfort criteria based on the RCP-8.5 2050s climate, though only the bundles including partial or full mechanical cooling meet the thermal comfort criteria for the Step 3 archetype.

→ For both the Step 3 and Step 4 archetypes, adding partial or full mechanical cooling is shown to increase the annual energy cost (due to an increase in electricity consumption). However, both solutions show that all overheated hours can be eliminated when modelled under the RCP-8.5 2050s climate scenario, without increasing the GHG emissions. The increase in utility cost is due to the baseline assumption of district heating, which is considerably less costly than grid electricity. If the baseline heating system had been, for example, electric baseboards, annual energy cost savings would have been realized in the bundles.

→ The results for both Step 3 and Step 4 archetypes indicate that upgrading the ventilation system to include a high efficiency HRV that can operate in boost and bypass mode as needed, plus a cooling coil downstream of the HRV, meets the thermal comfort criteria based on the 2050s climate file. This suggests that full mechanical cooling is not required for this archetype in the RCP-8.5 2050s climate, provided we accept the 200-hr 80% acceptability limit.

→ The addition of passive measures to the mechanically cooled bundles is shown to reduce the cooling energy consumption and peak cooling demand. The addition of passive cooling measures can also result in lower energy costs due to lower cooling energy use, and may allow for reduced cooling equipment size as a result of decreased peak cooling loads.

→ The peak cooling demand and CEDI are both lower for the fully mechanically cooled Step 4 archetype compared to Step 3, demonstrating the benefit of a high performance enclosure toward reducing mechanical cooling equipment size, cooling energy demand and associated operating costs.

- → A high performing enclosure also increases the likelihood that an emerging technology like combined heat recovery ventilator heat pumps can satisfy heating, cooling and ventilation system needs in a single piece of equipment.
- → It should be noted that the low incremental cost for full mechanical cooling results from the baseline system assumption, which for UBC is hydronic radiant heating with code minimum HRVs. A different type of baseline system would result in a considerably higher incremental cost to change to full mechanical cooling. An additional analysis was completed to understand the cost associated with this measure for a low rise new building with a more common baseline heating system. The archetype in the additional analysis is heated via electric baseboards, while all other characteristics are unchanged. The results of the additional analysis are provided in Appendix D.

3.2 New Building High Rise

This section summarizes the results for the new building high rise archetype. Recall that the high rise new building baseline archetype is designed to meet Step 2 of the BC Energy Step Code. Key findings are summarized at the end of the section (Section 3.2.4)

3.2.1 Baseline Results

Thermal comfort Analysis

The high rise building baseline archetype is mechanically cooled. Therefore, the thermal comfort metrics for the non-mechanically cooled archetypes do not apply (the equipment is auto-sized to limit number of overheating hours). Instead, the cooling energy demand intensity (CEDI) and peak cooling load are reported at zone level to provide an understanding of the relative differences across the building. Note that the peak cooling load does not account for system efficiency.

Figure 3.15 shows annual CEDI (kWh/m²a) at the zone level. The layout of the floor plate is shown, with the colour coding used to illustrate the variation in CEDI. The figure also shows CEDI at the building level for the different climate scenarios.

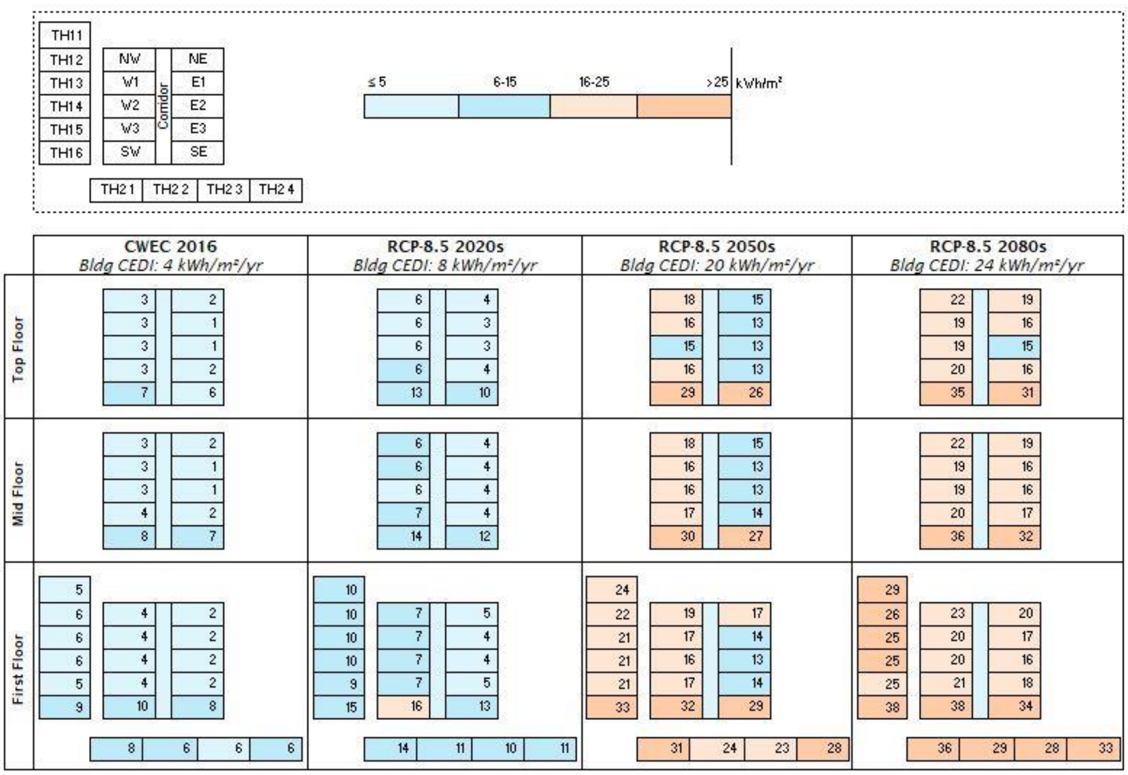

Figure 3.15 Cooling energy demand intensity (kWh/m²a) at zone level for each climate file. The zones that have a CEDI lower than the Passive House Institute requirement (15 kWh/m²a) are shown as blue. The zones that exceed 15 kWh/m²a are colour coded in different shades of orange. A darker orange indicates a higher CEDI.

Figure 3.16 shows the peak cooling load of the space (W/m²) at the zone level. The layout of the floor plate is shown, with colour coding used to illustrate the variation in peak cooling load. The figure also shows the peak cooling load for the whole building for the different climate scenarios.

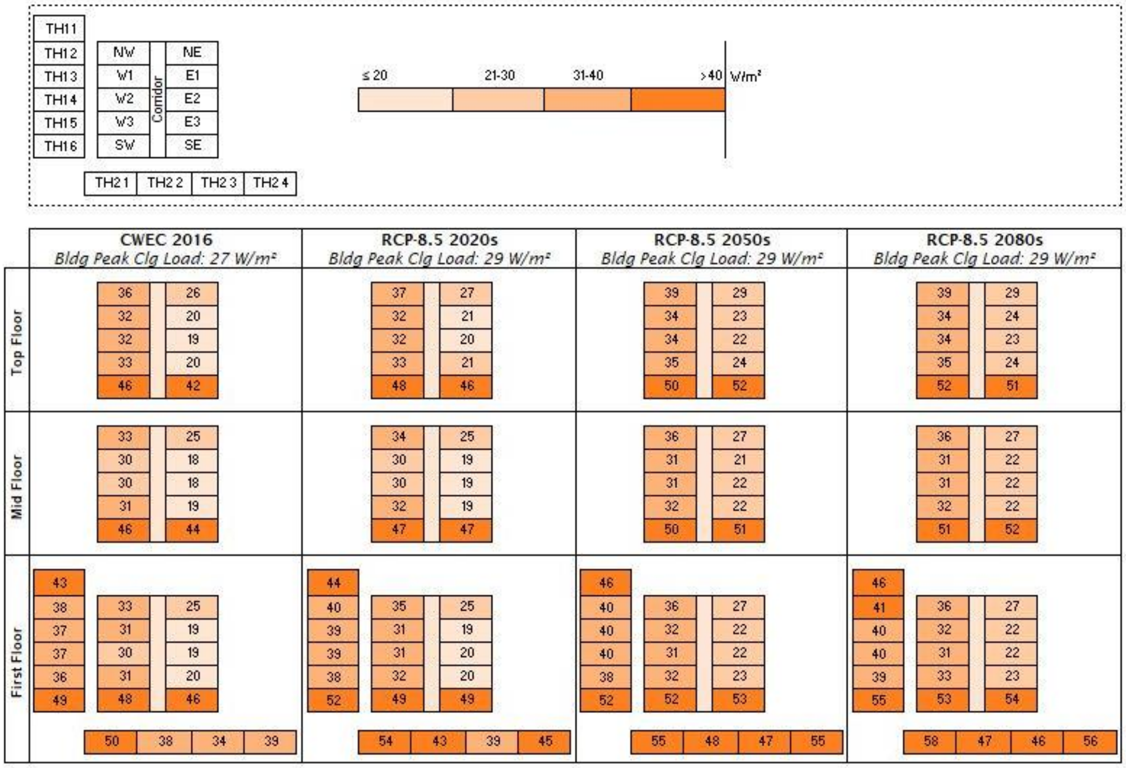

Figure 3.16 Peak cooling load (W/m²) at zone level for each climate scenario. A darker shade of orange indicates a higher peak cooling load. Note that the peak cooling load does not account for system efficiency.

The baseline results show that the south-west and south-east facing corner suites are the zones with the highest peak cooling load and cooling demand for all four climate files. This is due to the higher exposure to solar radiation which results in higher heat gains to the space compared to less sun exposed orientations.

The results shown in Figure 3.15 and Figure 3.16 are summarized in Table 3.16.

TABLE 3.16 SUMMARY OF BASELINE THERMAL COMFORT RESULTS FOR THE HIGH RISE NEW BUILDING

	CWEC 2016	RCP-8.5 2020s	RCP-8.5 2050s	RCP-8.5 2080s
Highest CEDI (kWh/m²a)	10	16	32	38
Suite with highest CEDI	South-west facing corner suite (tower) on first floor			
Building peak cooling load[1] (W/m²)	27	29	29	29
Highest peak cooling load[1] (W/m²)	50	54	55	58
Suite with highest peak cooling load	South-west facing corner unit (townhouse)			

[1]Peak cooling load of the space (does not accounts for system efficiency), see Table 2.5 for full description. The building peak cooling load is the peak load for the whole building, whereas the highest peak cooling load is the highest peak cooling load seen on suite level.

Energy and Emission Analysis

Figure 3.17 summarizes the annual TEUI, TEDI, and CEDI for the high rise new building baseline. Recall that the high rise new building baseline archetype is designed to meet Step 2 of the BC ESC. The grey dashed line illustrates the Step 2 TEUI target (130 kWh/m²a) and the red dashed line illustrates the TEDI target (45 kWh/m²a). There is currently no target for cooling energy demand within the BC ESC.

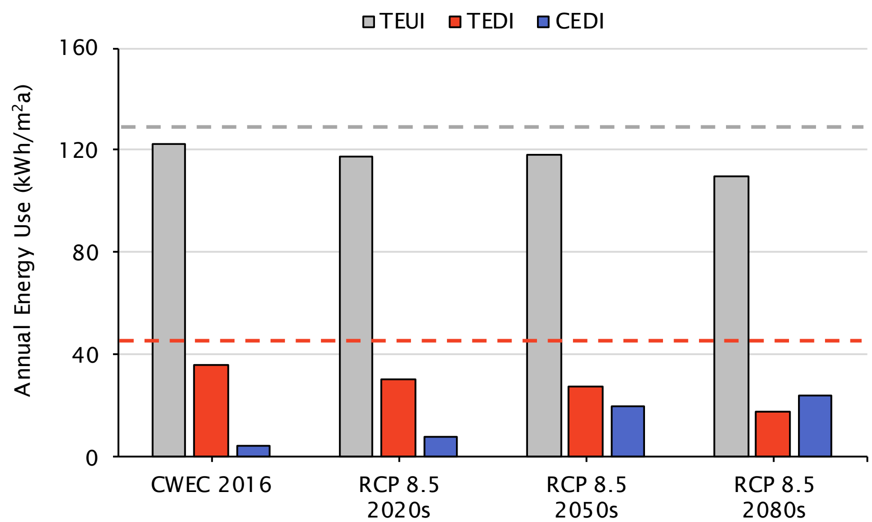

Figure 3.17 Annual total energy use intensity (TEUI), thermal energy demand intensity (TEDI) results and cooling energy demand intensity (CEDI) for the high rise new building baseline. The grey dashed line shows the Step 2 TEUI target (130 kWh/m²a), and the red dashed line shows the Step 2 TEDI target (45 kWh/m²a).

Table 3.17 summarizes the energy and emission metrics for the high rise new building baseline. As shown, TEDI decreases as the climate gets warmer, and CEDI increases. Based on the RCP-2080s climate file, the high rise new building baseline switches from heating- to cooling- dominated. The switch from heating to cooling dominated results in an overall decrease in TEUI, due to the higher efficiency equipment used for cooling compared to heating.

TABLE 3.17 HIGH RISE NEW BUILDING BASELINE (STEP 2) RESULTS				
	CWEC 2016	RCP-8.5 2020s	RCP-8.5 2050s	RCP-8.5 2080s
TEUI (kWh/m²a)	123	118	119	110
TEDI (kWh/m²a)	36	30	27	18
CEDI (kWh/m²a)	4	8	20	24
TEDI + CEDI (kWh/m²a)	40	38	47	42
Peak heating demand[1] (W/m²)	29	29	29	28
Peak cooling demand[1] (W/m²)	6	6	6	6
GHGI[2] – Current (kgCO_2e/m²a)	14	13	12	10
GHGI[2] – Future (kgCO_2e/m²a)	6	5	5	4

[1]Peak heating/cooling demand on grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the current emission factor (GHGI – Current) for the UBC district energy system as well as the emission factor for the future district energy system (GHGI – Future) that is planned to consist of 60% renewable energy by 2024.

3.2.2 Climate Adaptation + Mitigation Measures

This section summarizes the results for the individual CAMM analysis for the high rise new building baseline. A detailed description of each CAMM is provided in Appendix B.

Thermal Comfort Analysis

Figure 3.18 shows the annual CEDI at the building level for the baseline archetype and each CAMM, based on the RCP8.5-2050s climate file. While there is currently no CEDI target established in the BC ESC, an indicator line for the Passive House Institute (PHI) cooling energy demand intensity criteria (15 kWh/m²a) is included as a theoretical reference point. The black dashed line represents the baseline results.

As seen in Figure 3.18, operable exterior shading shows the highest reduction in CEDI, followed by dynamic glazing and fixed shading. These measures alone meet the PHI cooling energy target of 15 kWh/m²a, for the Step 2 baseline.

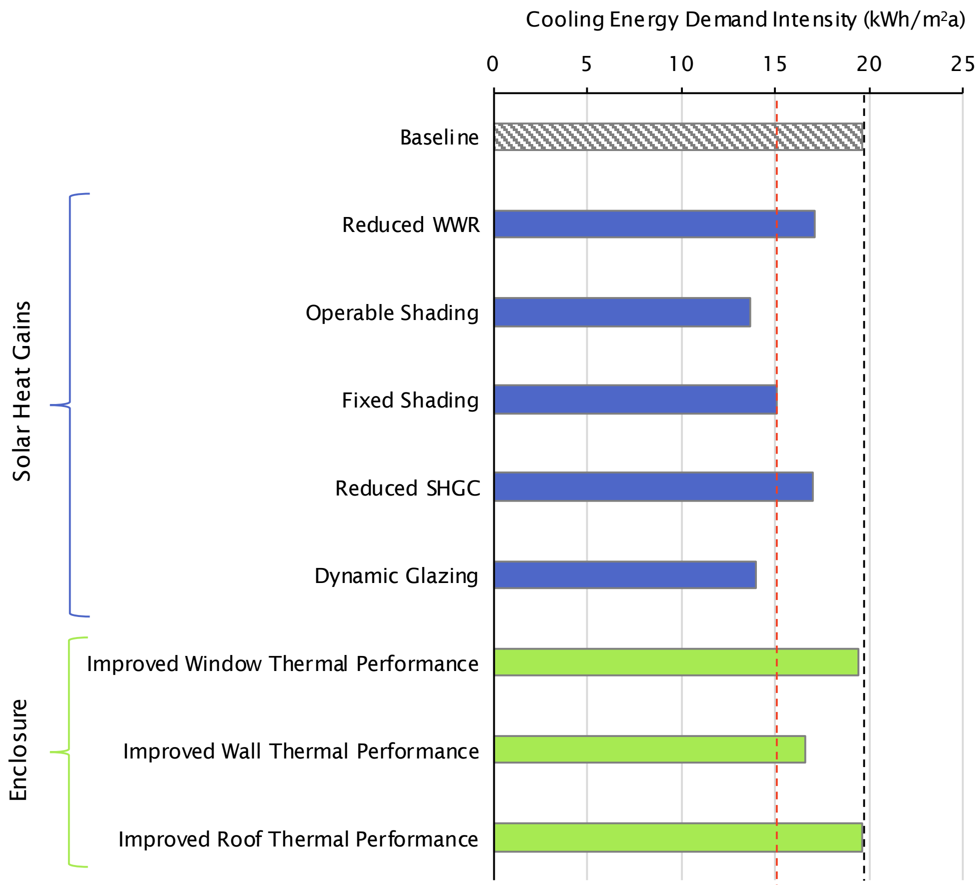

Figure 3.18 Building annual cooling energy demand intensity for the high rise new building baseline archetype and individual climate adaptation measures, modelled with the RCP-8.5 2050s climate file. The red dashed line indicates for the PHI cooling energy demand criteria (15 kWh/m²a), and the black dashed line presents the baseline results.

Costing Analysis

Figure 3.19 shows the cost analysis results for the individual CAMMs. The incremental cost compared to the baseline is presented together with the results from the CEDI analysis (shown in the previous section). The red lines show the average incremental cost ($\$/m^2$) and range at the building level. Appendix C provides additional costing data.

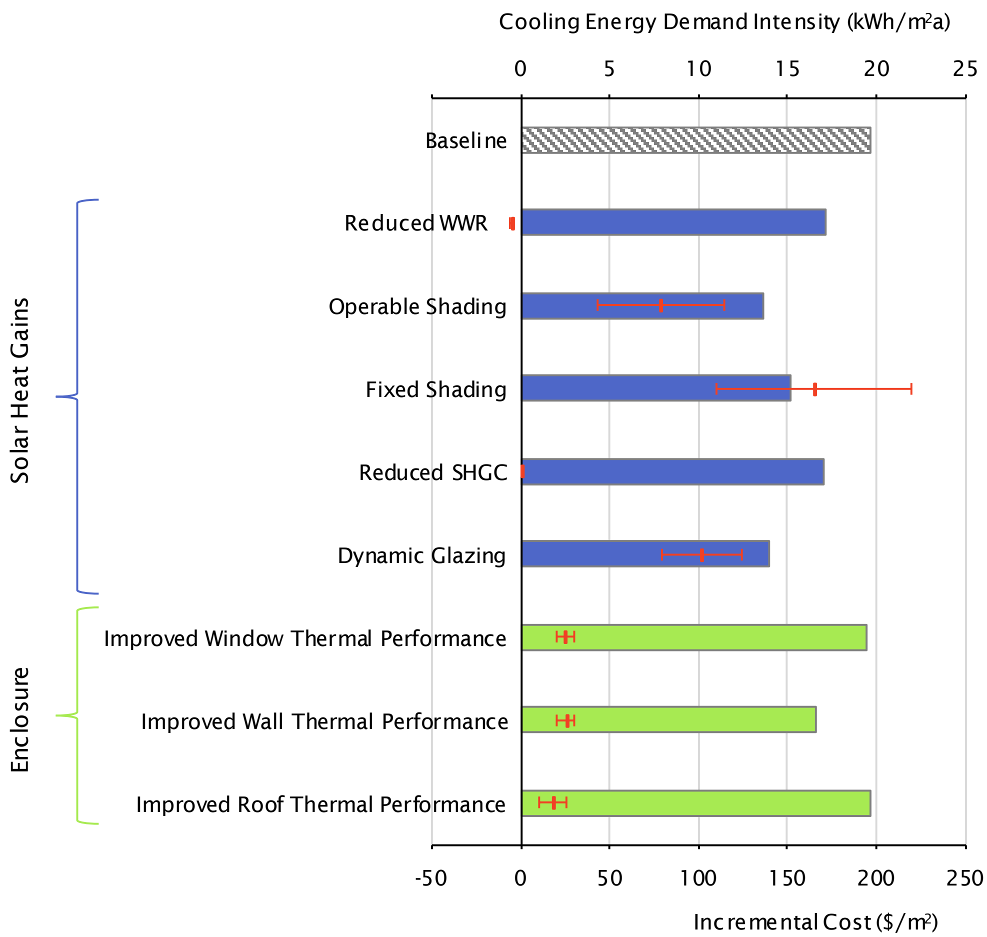

Figure 3.19 The red lines show the incremental cost ($\$/m^2$) on building level, the error bars show the high and low cost. The number of overheated hours is shown for the warmest suite based on RCP-8.5 2050s climate file

Similar to the low rise new building, the reduced WWR measure results in a negative incremental cost, meaning that the CAMM reduces the capital cost of the project. The reduced SHGC measure shows no incremental cost. Designing for reduced WWR and SHGC are both strategies that reduce the cooling energy demand with either a negligible or positive impact on incremental cost. However, both strategies may reduce winter solar gains and increase thermal energy demand, and as such, each strategy must be evaluated within the context of a specific project and its other performance metrics.

3.2.3 CAMM Bundles

Based on the results from the analysis of the individual climate measures, bundles of CAMMs were selected following the approach described in Section 2.3.1.

For the new building archetypes, the bundles were designed to comply with BC ESC Step 3 and Step 4, to further understand how higher step archetypes may perform in a future climate. Table 3.18 summarizes the adjustments that were made to the high rise new building baseline (Step 2) to meet the Step 3 and Step 4 targets.

TABLE 3.18 ADJUSTMENTS FOR HIGH RISE NEW BUILDING STEP 3 AND STEP 4 ARCHETYPES	
	Description
Step 3	→ Improved window thermal performance (USI-1.8)
Step 4	→ Improved window thermal performance (USI-1.14) → Improved wall thermal performance to (R_{eff}-15.6)

Figure 3.20 shows TEDI and CEDI for the high rise new building baseline (Step 2), Step 3 and Step 4. TEUI is summarized in Table 3.19. Though there is a significant difference in TEDI between the archetypes, there is a minor difference in CEDI. Note that the switch from TEDI- to CEDI-dominated occurs under the 2050s scenario for the Step 4 archetype, but not until the 2080s scenario for the Step 2 and Step 3 archetypes.

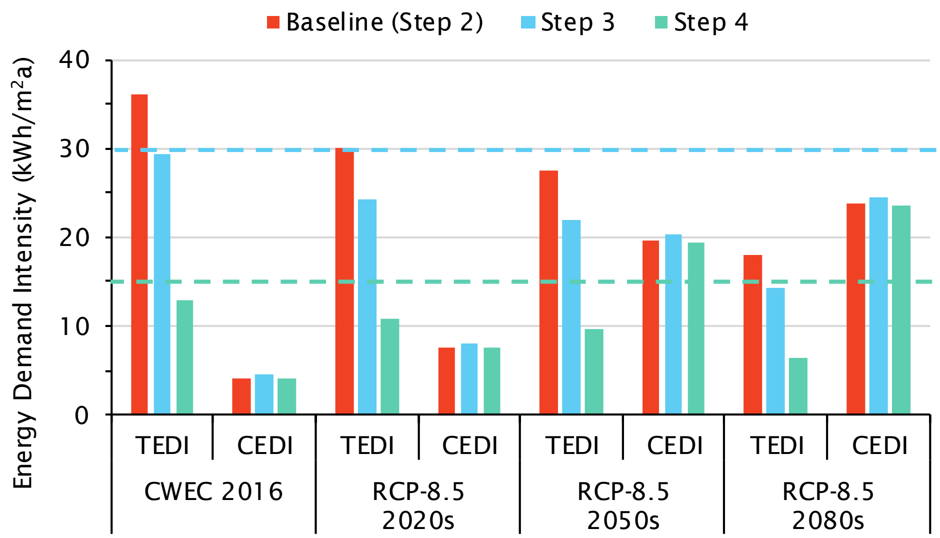

Figure 3.20 TEDI and CEDI for the baseline (Step 2) archetype and bundle baselines (Step 3 and Step 4), the blue and green dashed line show the TEDI target for Step 3 (30 kWh/m²a) and Step 4 (15 kWh/m²a), respectively.

TABLE 3.19 TOTAL ENERGY USE INTENSITY (TEUI) IN KWH/M2/A				
	CWEC 2016	RCP-8.5 2020s	RCP-8.5 2050s	RCP-8.5 2080s
Baseline (Step 2)	123	118	118	110
Step 3	116	112	113	106
Step 4	97	96	98	96

The modelled bundles for the Step 3 and Step 4 high rise new building archetypes are summarized in Table 3.20. Since the high rise new building includes mechanical cooling in the baseline, the bundles focus on passive measures to reduce the cooling energy demand and improve resiliency. The measures are described in further detail in Appendix B.

Even though fixed shading shows a higher average incremental cost and lower reduction in CEDI compared to the operable shading, fixed shading has other benefits (as discussed in Section 3.1.3) and is therefore included in the bundle analysis.

TABLE 3.20 MODELLED BUNDLES FOR HIGH RISE NEW BUILDING ARCHETYPE	
	Description
Bundle 1 – Passive	→ Reduced window to wall ratio to 30% → Fixed shading → Reduced SHGC to 0.28 (from 0.36)
Bundle 2 – Passive	→ Operable shading → Reduced SHGC to 0.28 (from 0.36)

Step 3

Thermal Comfort Analysis

Figure 3.21 shows CEDI for the warmest suite for the Step 3 high rise new building baseline and bundle archetypes. The effect of the bundles on the annual cooling energy demand on building level is discussed in the next section. Table 3.21 summarizes results shown in Figure 3.21.

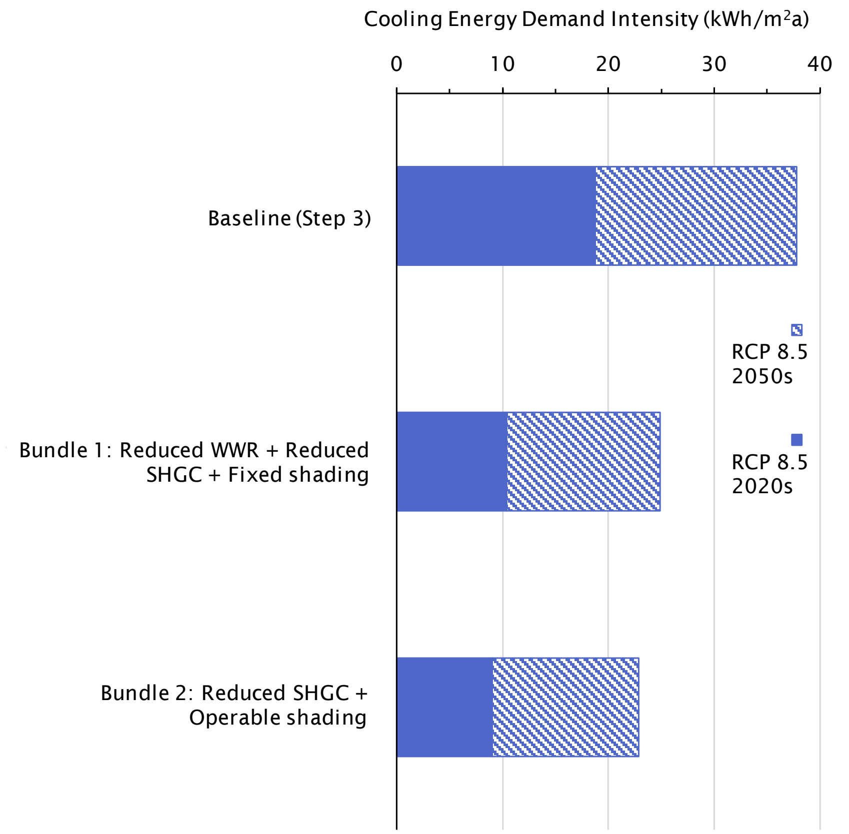

Figure 3.21 Cooling energy demand intensity (kWh/m²a) for the warmest suite for the Step 3 baseline and modelled bundles, for RCP-8.5 2020s and 2050s climate files.

TABLE 3.21 CEDI FOR THE WARMEST SUITE FOR THE STEP 3 BASELINE AND BUNDLES			
	Baseline	Bundle 1	Bundle 2
RCP-8.5 2020s	19	10	9
RCP-8.5 2050s	38	25	23

Table 3.22 summarizes peak cooling load at the suite level, based on the RCP-8.5 2050s climate file. The results show that the passive measures significantly reduce the CEDI and peak cooling load for the fully mechanically cooled high rise new building archetype.

TABLE 3.22 PEAK COOLING LOAD AT SUITE LEVEL FOR THE STEP 3 BASELINE AND BUNDLES BASED ON RCP-8.5 2050S CLIMATE FILE			
	Baseline	Bundle 1	Bundle 2
Highest peak cooling load (W/m²)	54	49	44

Energy and Emission Analysis

Figure 3.22 shows the TEDI and CEDI at the building level for the Step 3 baseline and bundle archetypes, based on the RCP-8.5 2020s, 2050s and 2080s climate files. The red dashed line illustrates the Step 3 TEDI target, and the orange dashed line indicates the PHI cooling energy demand limit for reference.

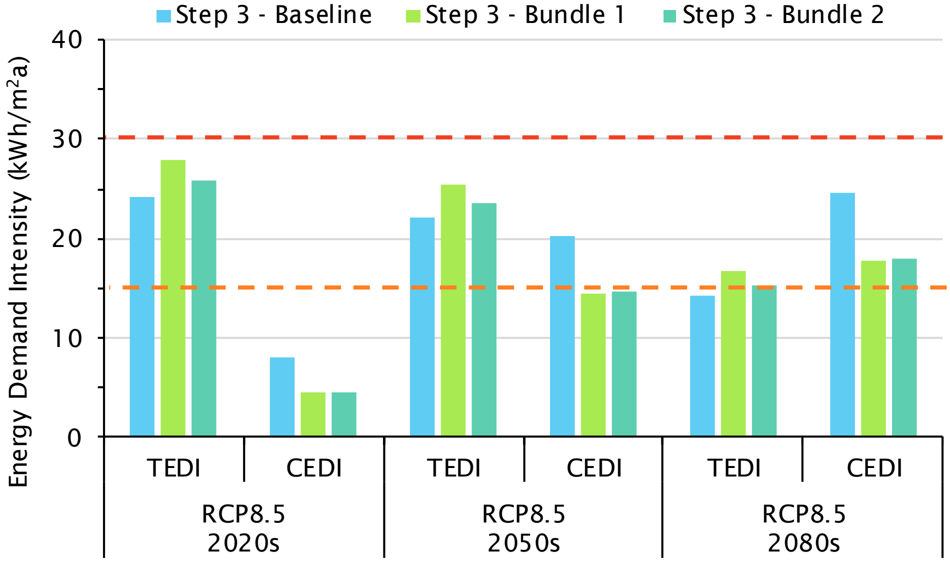

Figure 3.22 TEDI and CEDI results for the Step 3 high rise new building baseline and bundle archetypes based on RCP-8.5 2020s, 2050s, and 2080s climate files. The red dashed line illustrates the Step 3 TEDI target (30 kWh/m²a), and the orange dashed line illustrates a theoretical reference CEDI target (15 kWh/m²a)

Table 3.23 summarizes the energy and GHG results at the whole building level for the Step 3 baseline and bundles, based on the RCP-8.5 2050s climate file. The results show that incorporating passive cooling measures are a desirable strategy for reducing the CEDI and mitigating peak cooling demand.

TABLE 3.23 ENERGY AND GHG RESULTS FOR STEP 3 BASELINE AND BUNDLES BASED ON RCP-8.5 2050 CLIMATE FILE

	Baseline	Bundle 1	Bundle 2
TEUI (kWh/m²a)	113	112	113
TEDI (kWh/m²a)	22	25	24
CEDI (kWh/m²a)	20	15	15
TEDI + CEDI (kWh/m²a)	42	40	39
Peak heating demand[1] (W/m²)	26	26	26
Peak cooling demand[1] (W/m²)	6	5	4
GHGI[2] (kgCO$_2$e/m²a)	5	5	5

[1]Peak heating/cooling demand on grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

Costing Analysis

This section summarizes the costing analysis of the Step 3 high rise new building bundles, including the incremental capital cost ($/m²) and annual energy cost ($/m²). Additional costing details are provided in Appendix C.

Figure 3.23 shows the incremental cost on building level for the Step 3 bundles. The incremental cost is shown together with the number of overheated hours based on the RCP-8.5 2050s climate file. The error bars illustrate the high and low bundle cost.

Figure 3.24 shows the annual energy cost for the Step 3 baseline and bundles. Table 3.24 summarizes the energy cost savings compared to the baseline.

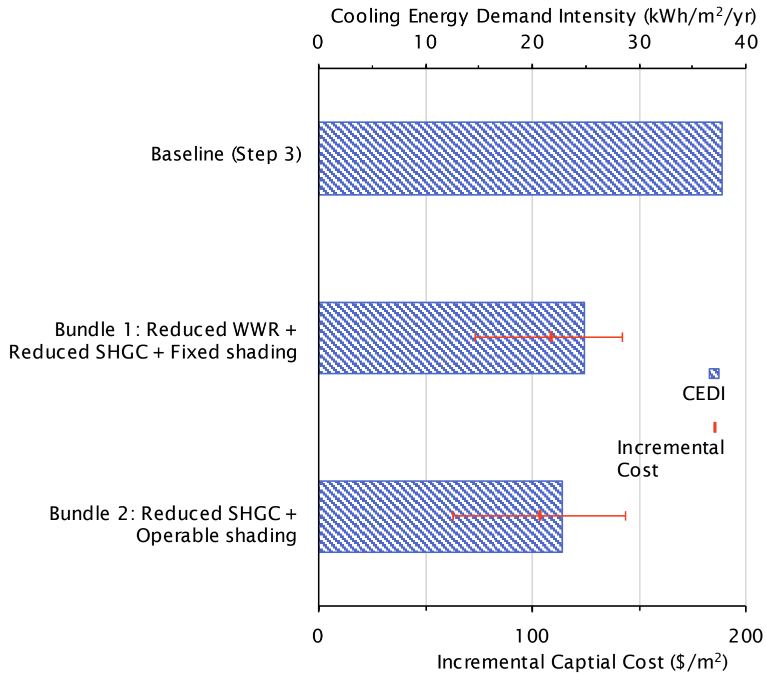

Figure 3.23 Incremental cost ($/m²) for the Step 3 bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

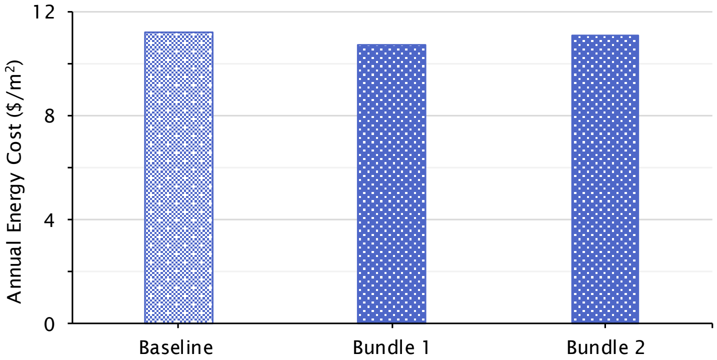

Figure 3.24 Annual energy cost ($/m²) for the Step 3 baseline and bundles

TABLE 3.24 ENERGY COST SAVINGS COMPARED TO THE BASELINE (STEP 3)		
	Bundle 1	Bundle 2
Energy Cost Savings (%)	4%	1%

The incremental cost of Bundle 1 and Bundle 2 are comparable. Even though a reduced window to wall ratio is shown to have a negative incremental cost and the reduced SHGC measure shows no incremental cost (see Figure 3.19), Bundle 1 is shown to have a slightly higher average incremental cost compared to Bundle 2. This is due to the higher expected incremental cost for fixed exterior shading compared to operable exterior shading. If a reduction in window to wall ratio and SHGC instead would be bundled with operable shading, the incremental cost would likely be lower than Bundle 2, and the reduction in CEDI would be slightly higher (based on the results shown in Section 3.2.2).

Both bundles result in a small decrease in annual energy cost, due to the reduction in cooling energy use.

Step 4

Thermal Comfort Analysis

Figure 3.25 shows the CEDI at the warmest suite for the Step 4 high rise new building baseline and bundle archetypes. Table 3.25 summarizes results shown in Figure 3.25.

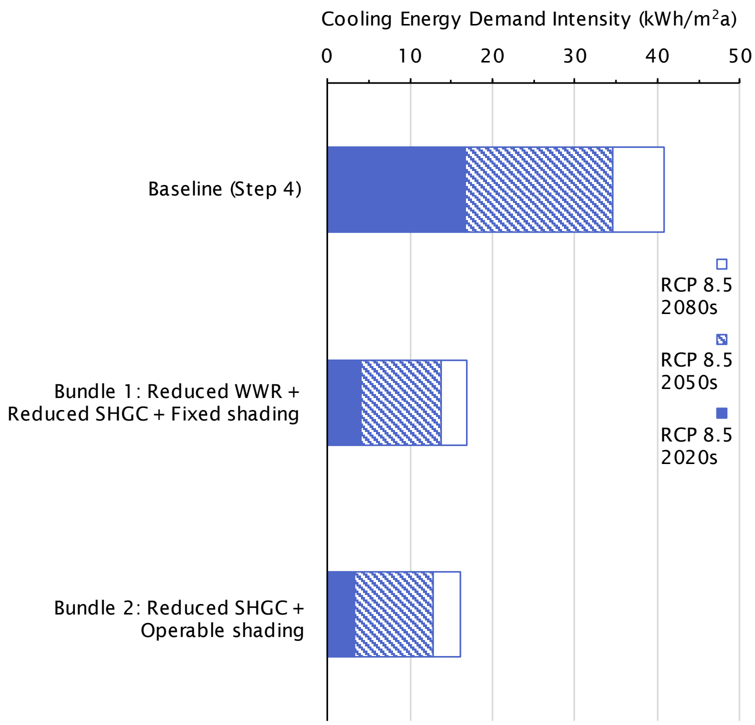

Figure 3.25 Cooling energy demand intensity (kWh/m²a) for the warmest suite for the Step 4 baseline and modelled bundles, modelled with RCP-8.5 2020s and 2050s climate files

TABLE 3.25 CEDI FOR THE WARMEST SUITE FOR THE STEP 4 BASELINE AND BUNDLES			
	Baseline	Bundle 1	Bundle 2
RCP-8.5 2020s	17	4	3
RCP-8.5 2050s	33	14	13

Table 3.26 summarizes the peak cooling load on suite level based on the RCP-8.5 2050s climate file, though the peak cooling load at the zone level is the same for the Step 3 and Step 4 archetypes – both show significant peak load reductions for Bundle 1 and 2. The Step 4 baseline archetype has a lower CEDI compared to the Step 3 baseline archetype, and the Step 4 passive bundles lead to a more dramatic decrease than the Step 3 archetype.

TABLE 3.26 PEAK COOLING LOAD AT SUITE LEVEL FOR THE STEP 4 BASELINE AND BUNDLES BASED ON RCP-8.5 2050S CLIMATE			
	Baseline	Bundle 1	Bundle 2
Highest peak cooling load[1] (W/m²)	48	28	22

[1]Peak cooling load of space (does not accounts for system efficiency), see Table 2.5 for full description.

Energy and Emission Analysis

Figure 3.26 shows the TEDI and CEDI for the Step 4 high rise new building baseline and bundle archetypes, based on the RCP-8.5 2020s, 2050s and 2080s climate files. The red dashed line illustrates the Step 4 TEDI target, and the PHI cooling energy demand limit for reference.

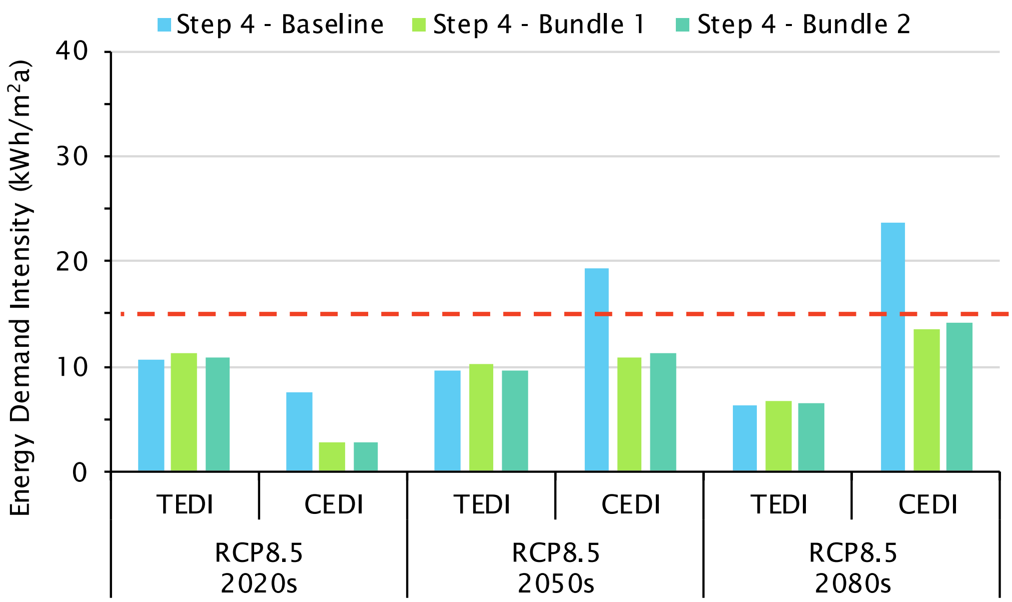

Figure 3.26 TEDI and CEDI results for the Step 4 high rise new building baseline and bundle archetypes based on CWEC 2016, RCP-8.5 2020s, 2050s, and 2080s climate files. The red dashed line illustrates the Step 4 TEDI target (15 kWh/m²a), and reference CEDI target (15 kWh/m2a)

Table 3.27 summarizes the energy and GHG results for the Step 4 baseline and bundles, based on the RCP-8.5 2050s climate file.

TABLE 3.27 ENERGY AND GHG RESULTS FOR STEP 4 BASELINE AND BUNDLES BASED ON RCP-8.5 2050S CLIMATE FILE			
	Step 4		
	Baseline	Bundle 1	Bundle 2
TEUI (kWh/m²a)	98	93	93
TEDI (kWh/m²a)	10	10	10
CEDI (kWh/m²a)	19	11	11
TEDI + CEDI (kWh/m²a)	29	21	21
Peak heating demand[1] (W/m²)	16	14	16
Peak cooling demand[1] (W/m²)	5	3	3
GHGI[2] ($kgCO_2e/m^2a$)	4	4	4

[1]Peak heating/cooling demand on the grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

The results show that the Step 4 bundles reduce the CEDI and peak cooling demand even further than the Step 3 bundles, which illustrates the benefit of a high performance enclosure. Compared to the Step 3 archetype, the results show that CEDI and TEDI are below the 15 kWh/m^{2}a target for both Step 4 bundles, and for all climate files.

Costing Analysis

This section summarizes the costing analysis of the Step 4 high rise new building bundles, including the incremental capital cost ($/m²) and annual energy cost ($/m²). Additional costing data are provided in Appendix C.

Figure 3.27 shows the incremental cost on building level for the Step 4 bundles. The incremental cost is shown together with the number of overheated hours based on the RCP-8.5 2050s climate file. The error bars illustrate the high and low bundle cost.

Figure 3.28 shows the annual energy cost for the Step 3 baseline and bundles. Table 3.28 summarizes the energy cost savings compared to the baseline.

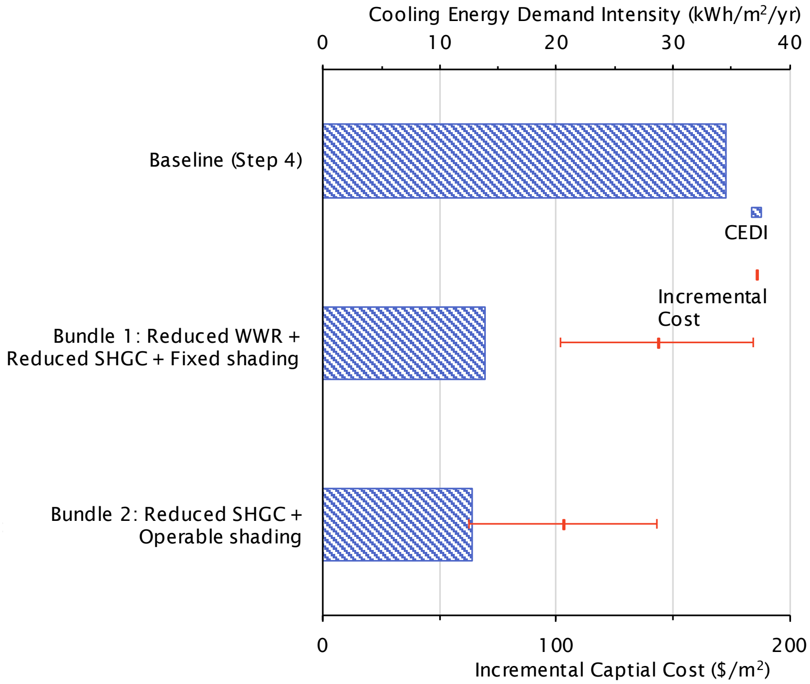

Figure 3.27 Incremental cost ($/m²) for the Step 4 bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

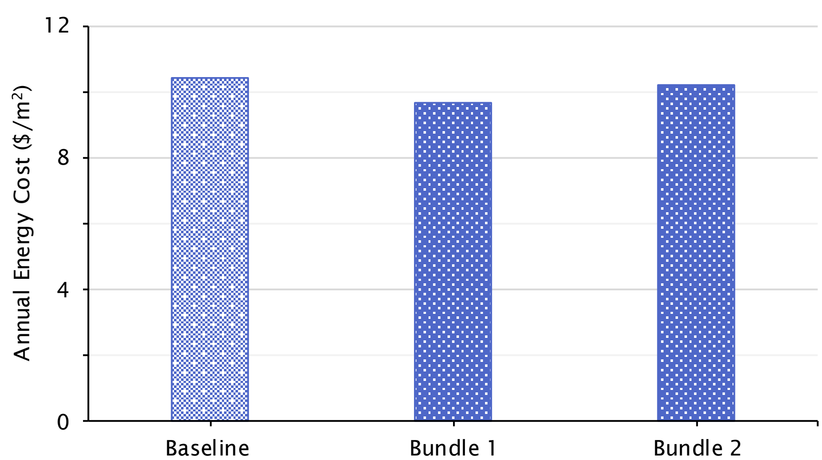

Figure 3.28 Annual energy cost ($/m²) for the Step 4 baseline and bundles

TABLE 3.28 ENERGY COST SAVINGS COMPARED TO THE BASELINE (STEP 4)		
	Bundle 1	Bundle 2
Energy Cost Savings (%)	8%	2%

The results show a greater difference between the Bundle 1 and Bundle 2 incremental cost for the Step 4 archetype compared to the Step 3 archetype. The reason is the higher cost for the Step 4 Bundle 1; the reduction in window to wall ratio increases the wall area, which for the Step 4 archetype is a higher performing, and higher cost, wall assembly compared to the Step 3 archetype.

The Step 4 baseline shows a slightly lower annual energy cost than the Step 3 baseline, due to the lower total energy use. The Step 4 bundles also show greater energy cost savings than the Step 3 bundles. This is because the Step 4 bundles result in higher reductions in CEDI. The Step 4 baseline includes a higher performing building enclosure. The results therefore illustrate the benefit of a higher performing building enclosure to achieve energy and cost savings.

Although the passive cooling measures show a significant reduction in CEDI, for both the Step 3 and Step 4 archetypes, the energy cost savings are relatively small. This is due to the high equipment efficiency of the cooling system, resulting in a small absolute reduction in cooling energy consumption and total energy consumption of the building.

3.2.4 Key Findings – High Rise New Building

→ Reduced Window to Wall Ratio and glazing with a reduced Solar Heat Gain Coefficient are two essentially zero incremental cost design measures with a considerable impact on annual cooling energy demand and peak cooling load. However, both strategies may reduce winter solar gains and increase thermal energy demand, and as such, each strategy must be evaluated within the context of a specific project and its other performance metrics.

→ Since there is currently no target established in the BC ESC for annual cooling energy demand (on building level), the Passive House Institute (PHI) criteria of 15 kWh/m²a has been used a reference point. The results show that neither the Step 3 nor the Step 4 baselines meet this target, while all modelled bundles meet the target.

→ Besides reducing the annual cooling energy consumption, the addition of passive cooling measures is also shown to reduce the peak cooling load and may allow for smaller cooling equipment size.

→ The addition of passive cooling measures also reduces the peak cooling demand on the electricity grid and hence the annual energy cost.

→ The Step 3 and Step 4 bundles consist of the same passive cooling measures, though the Step 4 bundles achieve higher reductions in annual cooling energy demand and peak cooling demand than the Step 3 bundles. The Step 4 baseline includes a higher performing building enclosure. The results therefore illustrate the benefit of a higher performing building enclosure for mitigating peak cooling demand and managing comfort while also meeting energy and emission reduction targets.

→ The peak cooling demand for the building in the Step 4 baseline case is 133 kW, which in itself is a 27 kW reduction over the Step 3 baseline case. With the Step 4 Bundle 2 (Reduced WWR, reduced SHGC and fixed shading), the peak cooling demand is reduced to 80 kW, which represents a 40% reduction over the Step 4 baseline and a 50% reduction over the Step 3 baseline.

→ The Step 4 bundles also result in a 5% decrease in total energy use (TEUI) compared to the Step 4 baseline, due to the reduction in cooling energy consumption. The Step 3 bundles do not result in a reduction in TEUI.

→ The Step 4 bundle archetypes are shown to be favourable compared to the Step 3 bundle archetypes in terms of energy performance, demand on electricity grid, GHG emissions, energy cost, and equipment size.

3.3 Existing Building Low Rise

This section presents the results for the existing building low rise archetype. The baseline archetype was developed to reflect a low rise existing building typical of the 1980s-90s. A detailed description of the archetype can be found in Section 2.1.3. Key findings are summarized at the end of the section (Section 3.3.4).

3.3.1 Baseline Results

Thermal Comfort Analysis

The low rise existing building baseline is a non-mechanically cooled archetype. To understand the level of thermal comfort and increased risk of overheating under future climate conditions, the number of overheated hours, as defined in ASHRAE 55-2010 Section 5.3, is reported together with modelled operative peak temperature. Although there is currently no thermal comfort criteria for existing buildings, the BC ESC compliance limit of 200 hours is used as the limit for number of overheated hours as a reference point, consistent with the low rise new building.

Figure 3.29 shows the number of hours per year that exceed the 80% acceptability limit outlined in ASHRAE 55-2010 Section 5.3. The layout of the floor plate is shown, with the colour coding used to illustrate the variation in number of overheated hours.

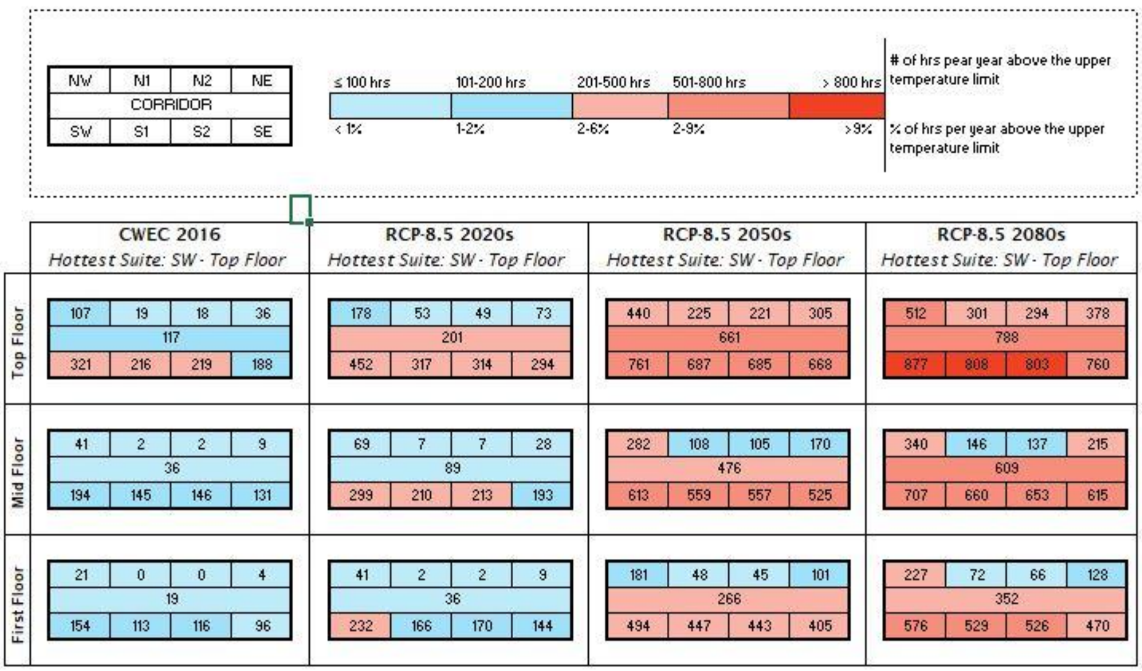

Figure 3.29 Number of hours that exceed the 80% acceptability limit reported at zone level for each floor of the low rise existing building baseline. The zones that do not exceed the limit of 200 overheated hours are shown as blue. The zones that exceed the 200 hour limit are colour coded as different shades of red. A darker red indicates a higher number of overheated hours.

The baseline thermal comfort results show that based on the CWEC 2016 climate file only the top south facing suites exceed the 80% acceptability limit for more than 200 hours, but only marginally so. Based on the 2020s file, 11 suites (34%) exceed the 200 hour limit and for the 2050s and 2080s files, the number of suites that exceed the 80% acceptability limit for more than 200 hours is 22 (69%) and 25 (78%).

Similar to the new building low rise baseline, the lowest north facing suites generally remain within or close to the comfort limits even in the future climate scenarios, and the south-west facing corner suite on the top floor is the warmest zone for all climate files. In general, the low rise existing building is warmer than the low rise new building baseline. This is mainly because the existing archetype's glazing is assumed to have a higher SHGC than the new low rise archetype, and there is no mechanical ventilation system.

Figure 3.30 shows modelled peak operative temperature for the low rise existing building, also in a building zone format with colour coding used to illustrate the variation in peak operative temperature. The figure also shows when the hottest hour occurs. Similar to the new building low rise baseline, the modelled operative peak temperature is higher for the south-west facing and north-west facing corner suites.

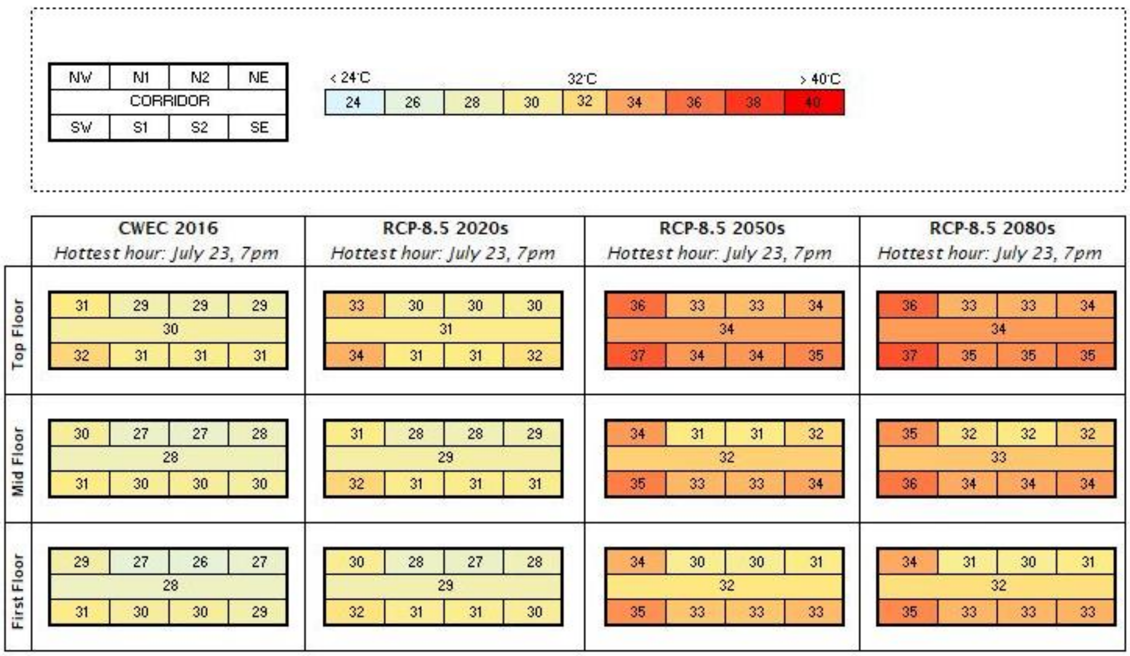

Figure 3.30 Modelled peak operative temperature (°C) for each zone and climate file. The zones are colour coded to illustrate the variation in peak temperature. A darker shade of red indicates a higher modelled peak temperature.

The thermal comfort results shown in Figure 3.29 and Figure 3.30 are summarized in Table 3.29. The results indicate that the baseline design meets the thermal comfort criteria as defined for new construction in the BC ESC for most but not all suites using the 2016 CWEC climate files. As the climate gets warmer, the number of overheated hours and peak operative temperatures increase significantly.

TABLE 3.29 SUMMARY OF BASELINE THERMAL COMFORT RESULTS FOR THE LOW RISE EXISTING BUILDING ARCHETYPE				
	CWEC 2016	RCP-8.5 2020s	RCP-8.5 2050s	RCP-8.5 2080s
# of suites > 80% acceptability limit	3	11	22	25
% of suites > 80% acceptability limit	9%	34%	69%	78%
Highest # of overheated hours (zone level)	321	452	761	877
Suite with highest # of overheated hours	South-west facing corner suite on top floor			
Peak operative temperature (°C)	32	34	37	37
Suite with highest peak operative temperature	South-west facing corner suite on top floor			

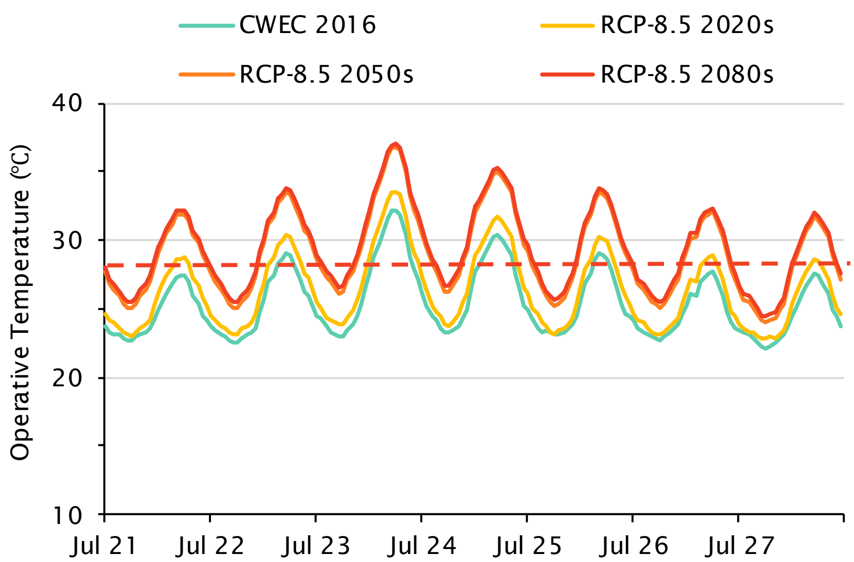

Figure 3.31 shows the modelled hourly operative temperature for the warmest suite during the warmest week for the low rise existing building baseline. The operative temperature is shown based on the CWEC 2016 climate file and RCP-8.5 2020s, 2050s and 2080s. The red dashed line illustrates the 80% acceptability limit based on the CWEC 2016 file.

As the figure shows, the operative temperature based on the 2020s climate file is slightly warmer than CWEC 2016, though the modelled temperature is significantly warmer based on the 2050s and 2080s climate.

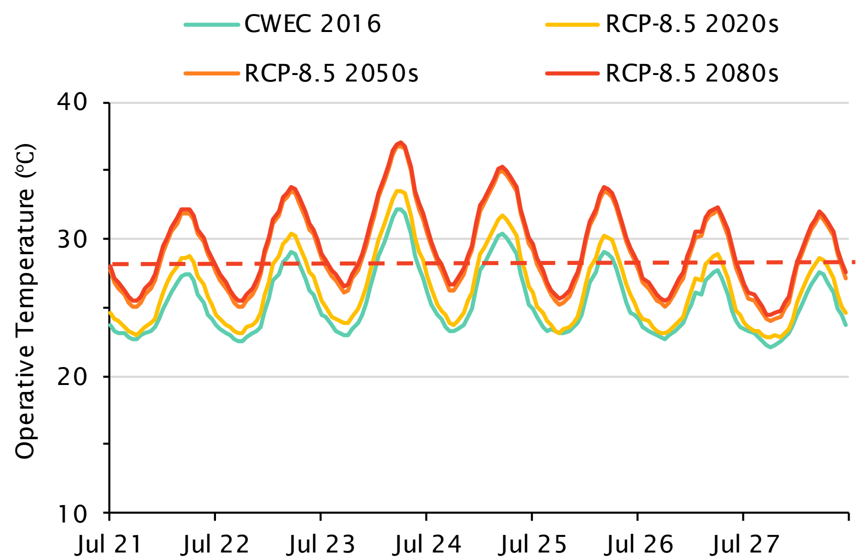

Figure 3.31 Modelled operative temperature (°C) for the warmest suite for the low rise existing building baseline. The interior temperature is shown for the warmest summer week, based on the CWEC 2016, RCP-8.5 2020s, 2050s and 2080s climate files. The red dashed line illustrates the 80% acceptability limit based on the CWEC 2016 climate file.

Energy and Emission Analysis

Figure 3.32 summarizes annual TEUI and TEDI for the low rise existing building baseline.

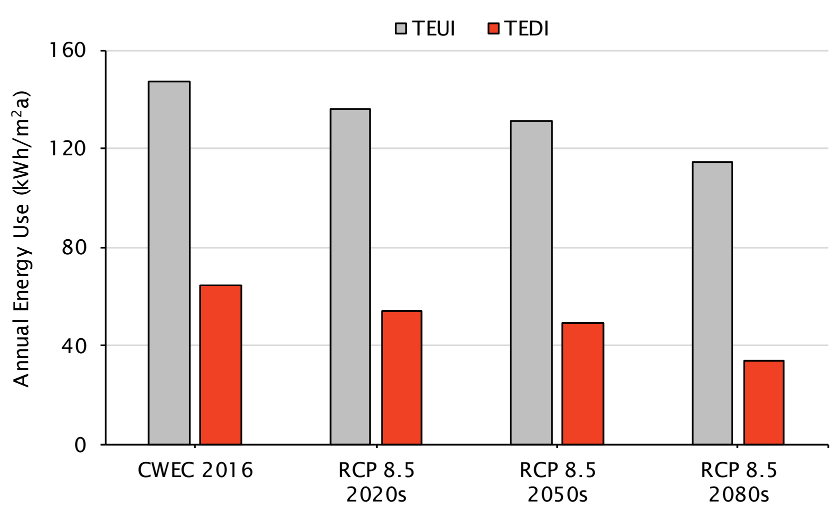

Figure 3.32 Annual total energy use intensity (TEUI) and thermal energy demand intensity (TEDI) results for the low rise existing building baseline.

The Step Code energy and City of Vancouver emission metrics are reported for the low rise existing building baseline to allow for comparison between the new and existing archetypes (although these metrics do not currently apply to existing buildings). Table 3.30 summarizes the baseline results from the energy and emission analysis for the low rise existing building baseline. Similar to the new building low rise, the three energy related metrics (TEUI, TEDI, and peak heating demand) decrease as the climate gets warmer, due to the decreased space heating demand and the lack of mechanical cooling in the baseline archetype.

The GHGI is shown to be relatively low for this archetype compared to the new building low rise. This is because the existing low rise archetype is heated by electric baseboards, and the new building is assumed to be connected to the UBC district energy system, which current has a higher emission factor than electricity.

TABLE 3.30 LOW RISE EXISTING BUILDING BASELINE RESULTS				
	CWEC 2016	RCP-8.5 2020s	RCP-8.5 2050s	RCP-8.5 2080s
TEUI (kWh/m^{2}a)	148	136	131	115
TEDI (kWh/m^{2}a)	64	54	49	34
Peak heating demand[1] (W/m^2)	37	35	35	29
GHGI[2] – Current (kgCO_2e/m^{2}a)	7	7	7	7
GHGI[2] – Future (kgCO_2e/m^{2}a)	4	4	4	3

[1]Peak heating demand on the grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the current emission factor (GHGI – Current) for the UBC district energy system as well as the emission factor for the future district energy system (GHGI – Future) that is planned to consist of 60% renewable energy by 2024.

3.3.2 Climate Adaptation + Mitigation Measures

This section summarizes the thermal comfort results for the individual CAMMs for the low rise existing building baseline. A detailed description of each CAMM is provided in Appendix B.

Thermal Comfort Analysis

Figure 3.33 shows the number of overheated hours in the warmest zone for the baseline archetype and each CAMM, based on the RCP-8.5 2050s climate file. The red dashed line illustrates the 200 hour limit, and the black dashed line presents the baseline results.

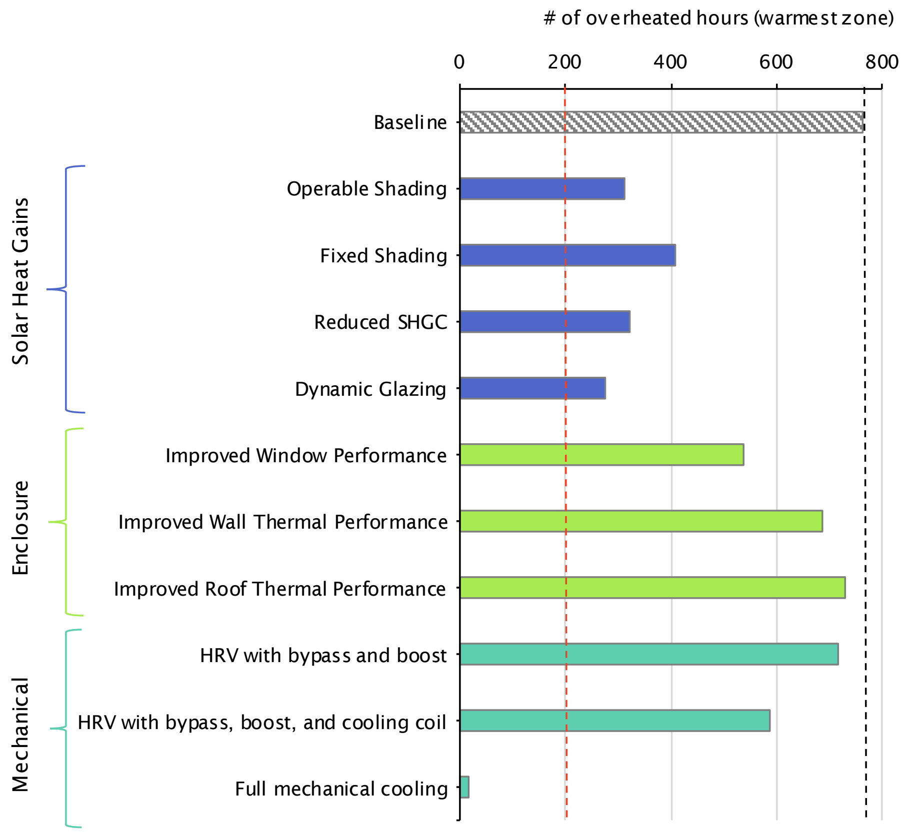

Figure 3.33 Number of overheated hours for the warmest zone and each individual climate adaptation measure, modelled with the RCP-8.5 2050s climate file. The red dashed line illustrates the 200 hour limit, and the black dashed line presents the baseline results.

The baseline archetype was set up to reflect a low rise building typical of 1980s-1990s. The baseline includes a high SHGC (no low-e coating), and therefore all measures that reduce the solar heat gains have a significant impact on the number of overheated hours. As seen in Figure 3.33, all modelled passive measures that mitigate solar heat gains have a significant positive effect on the risk of overheating.

Though the solar heat gain mitigation measures reduce the risk of overheating significantly, none of the passive measures reduce the number of overheated hours below the 200 threshold on its own. The passive measure that is shown to perform the best on its own is dynamic glazing followed by operable shading.

Compared to the low rise new building, the results for the HRV measures (with and without cooling coil) show a smaller reduction in number of overheated hours. This is because the solar heat gain to the suites is significantly larger for the existing building, and the airflow to the space is not sufficient to cool it. It should be noted that this measure would result in a higher reduction in overheated hours in combination with solar heat gain mitigation measures, such as window replacement (with a low SHGC).

Costing Analysis

The incremental cost of each CAMM compared to the baseline is presented in Figure 3.34 together with the thermal comfort results shown in the previous section. The red lines show the average and range of incremental cost ($/m²) at the building level. Note that the incremental cost for the enclosure measures are relative to an assumed baseline building renewal project. Appendix C provides additional costing details.

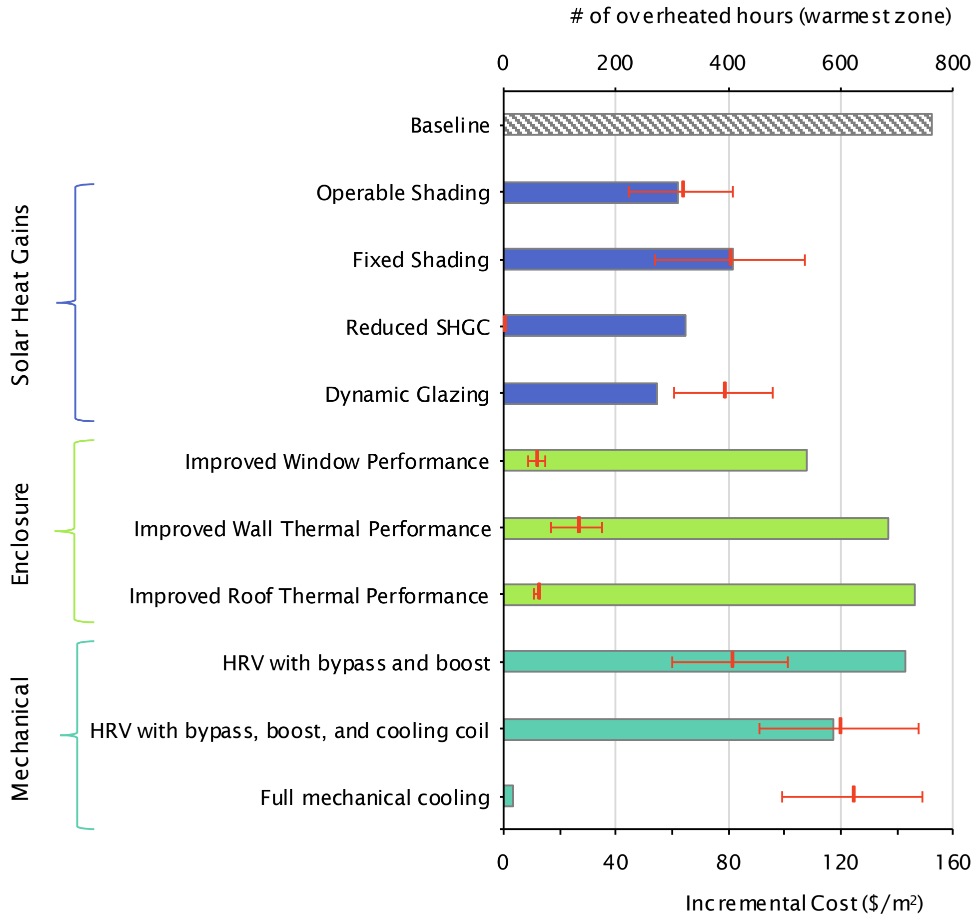

Figure 3.34 The red lines show the incremental cost ($/m²) on building level, the error bars show the high and low cost. The number of overheated hours is shown for the warmest suite based on RCP-8.5 2050s climate file.

The results show that upgrading the windows (with reduced SHGC) and adding operable shading are promising strategies for cost-effectively reducing the risk of overheating.

On the active side it is shown that partial cooling (HRV with cooling coil) and full mechanical cooling (through a ductless air source heat pump) are comparable in cost, though full mechanical cooling performs significantly better on its own (without passive measures) in terms of reducing the risk of overheating.

3.3.3 CAMM Bundles

CAMM bundles were selected based on the analysis of the individual climate measures, following the approach described in Section 2.3.1. The modelled bundles for the low rise existing building archetype are summarized in Table 3.31. Four passive bundles (Bundle 1-4), and 3 combined bundles (Bundle 5-7) were modelled.

Bundle 1 and 2 consist of solar heat gain reduction measures with a focus on improving thermal comfort. These are measures that would ideally be considered and implemented when a building's windows are already targeted for replacement or renewal. Bundle 3-5 represent comprehensive enclosure renewal scenarios, in which an enclosure renewal is already planned and measures that improve thermal comfort are considered. Bundle 5 also adds dedicated ventilation to the suites, with partial cooling though the ventilation system. Even though fixed shading showed a higher average incremental cost and lower reduction in overheating compared to the operable shading, fixed shading has other benefits (as discussed in Section 3.1.3) and is therefore included in the bundle analysis.

Bundle 6 and 7 represent scenarios where an enclosure upgrade may not be feasible or is not planned in the near future, so the focus is on non-enclosure measures.

TABLE 3.31 MODELLED BUNDLES FOR LOW RISE EXISTING BUILDING ARCHETYPE

		Description
Passive	Bundle 1 – Thermal Comfort Upgrade	→ Improved window thermal performance (USI-1.14) → Reduced SHGC to 0.28
	Bundle 2 – Thermal Comfort Upgrade	Bundle 1 + → Operable shading
	Bundle 3 – Enclosure Renewal Bundle	→ Improved window thermal performance (USI-1.14) → Reduced SHGC to 0.28 → Improved wall thermal performance
	Bundle 4 – Enclosure Renewal Bundle	Bundle 3 + → Operable shading
Combined	Bundle 5 – Renewal/Resilience Bundle	Bundle 3 + → Fixed shading → HRV with bypass, cooling coil and boost
	Bundle 6 – Resilience bundle	→ HRV with bypass, cooling coil and boost → Operable shading
	Bundle 7 - Active Thermal Comfort Upgrade	→ Full mechanical cooling → Operable shading

Thermal Comfort Analysis

Figure 3.35 shows the number of overheated hours for the warmest zone for the low rise existing building baseline and bundle archetypes. The modelled risk of overheating is shown based on the RCP-8.5 2020s and 2050s climate files. The red dashed line illustrates the 200 hour limit, and the orange dashed line illustrates the 20 hour limit for vulnerable populations.

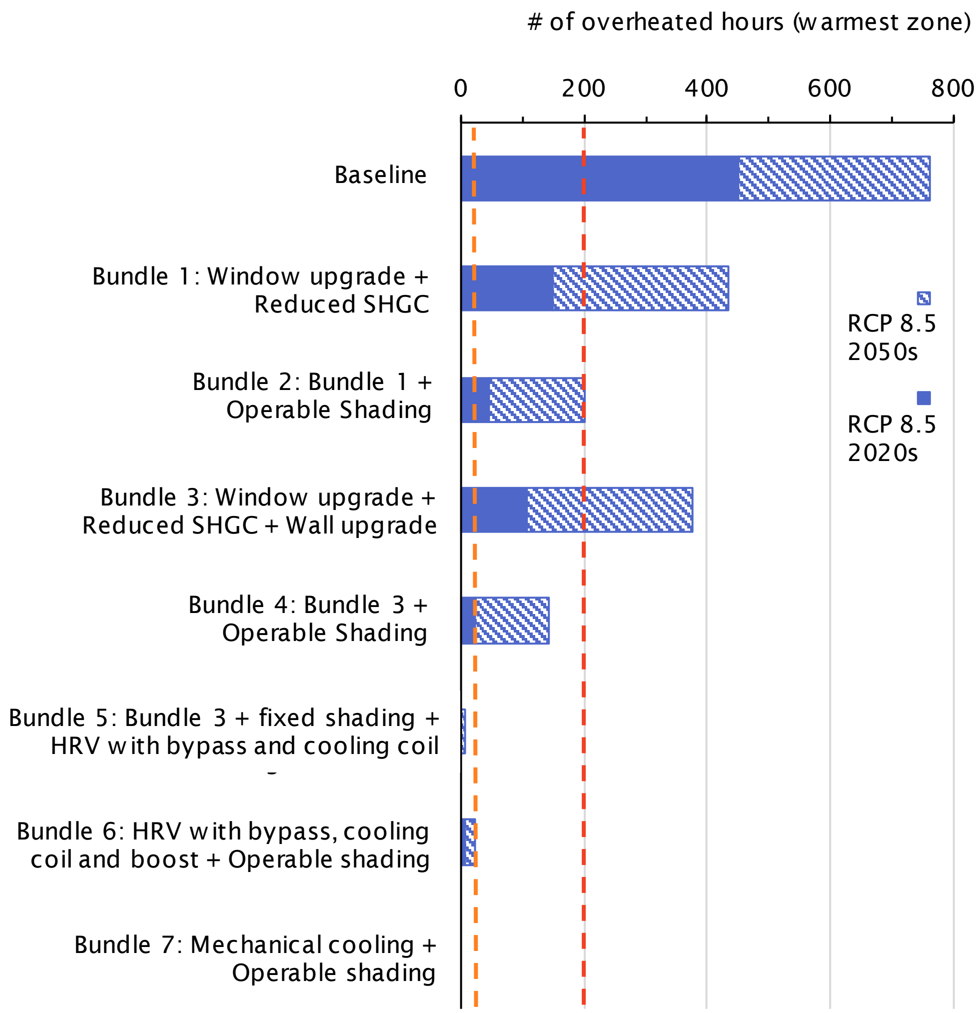

Figure 3.35 Number of overheated hours for the warmest suite for each modelled bundle. The red dashed line illustrates the 200 hour limit, the orange dashed line illustrates the 20 hour limit for vulnerable population.

TABLE 3.32 NUMBER OF OVERHEATED HOURS FOR THE WARMEST SUITE FOR THE LOW RISE EXISTING BUILDING BUNDLE ARCHEYTPES

	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4	Bundle 5	Bundle 6	Bundle 7
RCP-8.5 2020s	452	148	43	106	21	0	5	0
RCP-8.5 2050s	761	433	200	375	143	4	21	0

Figure 3.35 shows that all bundles meet the 200 hour limit based on the RCP-8.5 2020s climate file. With the RCP-8.5 2050s climate file, however, the passive bundles without exterior shading (Bundle 1 and Bundle 3) exceed the 80% acceptability limit, with all other bundles below the threshold. Table 3.32 summarizes the results shown in Figure 3.35.

Table 3.33 summarizes the overall building thermal comfort results for the passive bundles.

TABLE 3.33 SUMMARY OF PASSIVE BUNDLE THERMAL COMFORT RESULTS FOR THE LOW RISE EXISTING BUILDING BASED ON RCP-8.5 2050S CLIMATE FILE

	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
# of zones > 80% acceptability limit	22	14	0	11	0
% of zones > 80% acceptability limit	69%	44%	0%	34%	0%
Highest # of overheated hours[2]	761	433	200	242	143
Peak operative temperature (°C)	37	35	33	33	32
Suite with highest peak operative temperature	South-west facing corner suite on top floor				

As shown, all passive bundles reduce the risk of overheating significantly, though only Bundle 2 and Bundle 4 reduce the number of overheated hours below the 200 threshold. Bundle 4, which consists of operable shading and an enclosure (window and wall) upgrade, shows a higher reduction in number of overheated hours and peak operative temperature than Bundle 2 (operable shading and window upgrade only). This suggests that in combination with solar heat gain reduction design measures, a higher performing enclosure has a positive impact on thermal comfort.

Table 3.34. summarize the thermal comfort results for the combined bundles.

TABLE 3.34 SUMMARY OF COMBINED BUNDLE THERMAL COMFORT RESULTS FOR THE LOW RISE EXISTING BUILDING BASED ON RCP-8.5 2050S CLIMATE FILE

	Bundle 5	Bundle 6	Bundle 7
# of zones > 80% acceptability limit	0	0	0
% of zones > 80% acceptability limit	0%	0%	0%
Highest # of overheated hours (Zone level)	4	21	0
Peak operative temperature (°C)	29	30	27
Suite with highest peak operative temperature	South-west facing corner suite on top floor		

All three combined bundles are close to or below the 20-hour threshold for vulnerable population. Bundle 7 (full mechanical cooling + operable shading) reduces all overheated hours and shows the lowest peak operative temperature. The effect of the addition of cooling energy on the building's energy performance and GHG emissions is presented in the next section.

Figure 3.36 shows the modelled operative temperature for the low rise existing building baseline and the bundles that meet the thermal comfort target based on the RCP-8.5 2050s climate fie, i.e. Bundle 2, 4, 5, 6 and 7. The interior temperatures are shown for the hottest summer week and are modelled with the RCP-8.5 2050s climate file. The red dashed line illustrates the 80% acceptability limit for July.

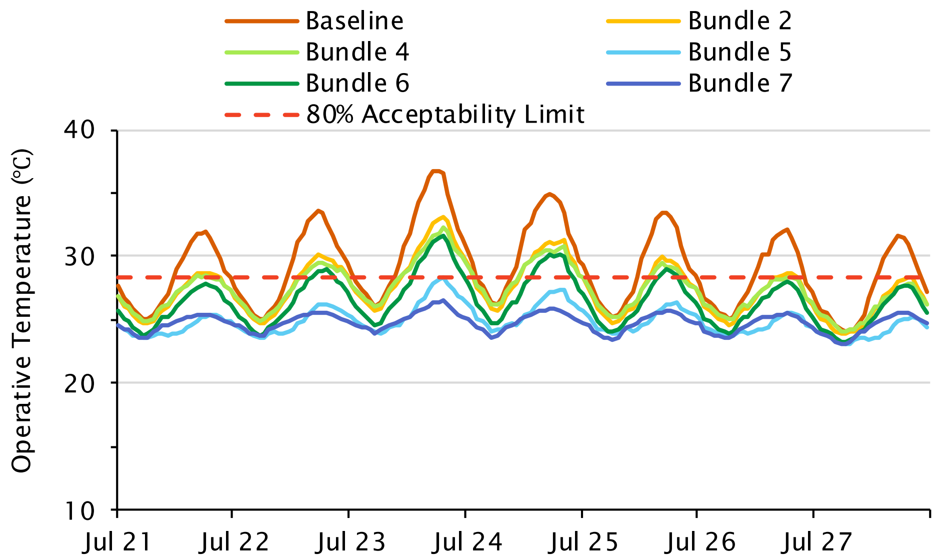

Figure 3.36 Modelled operative temperature (°C) for the warmest suite for the low rise existing building baseline and bundles based on the RCP-8.5 2050s climate file, shown for the hottest summer week.

Energy and Emission Analysis

Table 3.35 summarizes the energy and GHG results for the baseline and passive bundles based on the RCP-8.5 2050s climate file. Note that Bundle 1 and Bundle 3 do not meet the 200 hr threshold based on the 2050s scenario; however, the energy and emission results are included for comparison.

TABLE 3.35 SUMMARY OF PASSIVE BUNDLE ENERGY AND EMISSION RESULTS FOR THE LOW RISE EXISTING BUILDING BASED ON RCP-8.5 2050S CLIMATE

	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
TEUI (kWh/m^{2}a)	131	121	123	106	107
TEDI (kWh/m^{2}a)	49	40	41	27	27
Peak heating demand[1] (W/m^2)	35	27	27	18	18
GHGI[2] (kgCO_2e/m^{2}a)	4	3	3	3	3

[1]Peak heating demand on the grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

The results show that all passive bundles reduce the archetype's energy consumption and peak heating demand. Bundle 2 and 4 build on Bundle 1 (window upgrade) and Bundle 3 (window and wall upgrade), respectively, with the addition of exterior operable shading. As discussed previously, the operable shading reduces the solar heat gains to the space, and therefore the TEDI is slightly higher for the bundles including operable shading. These passive bundles (Bundle 2 and 4) both reduce the number of overheated hours below the 200-hour threshold based on the RCP-8.5 2050s climate file, as well as improve the energy performance and reduce the GHG emissions compared to the baseline.

Table 3.36 summarizes relevant metrics for the combined bundles based on the RCP-8.5 2050s climate file. For comparison, the results for full mechanical cooling are included, i.e. excluding any passive measures. Note that the individual active measure for the partial cooling bundles (Bundle 5 and 6) is not included for comparison since it does not meet the thermal comfort criteria.

TABLE 3.36 SUMMARY OF COMBINED BUNDLE ENERGY AND EMISSION RESULTS FOR LOW RISE EXISTING BUILDING BASED ON RCP-8.5 2050S CLIMATE FILE

	Baseline	HRV with bypass, cooling coil, and boost as needed		Full mechanical cooling	
		With passive measures (Bundle 5)	**With** passive measures (Bundle 6)	**Without** passive measures	**With** passive measures (Bundle 7)
TEUI (kWh/m^2a)	131	113	135	118	117
TEDI (kWh/m^2a)	49	21	35	49	51
CEDI (kWh/m^2a)	n/a	9	10	21	15
TEDI + CEDI (kWh/m^2a)	49	30	45	70	66
Peak heating demand[1] (W/m^2)	35	24	31	18	18
Peak cooling demand[1] (W/m^2)	n/a	5	7	14	11
Peak operative temperature (°C)	37	29	30	28	27
GHGI[2] ($kgCO_2e/m^2a$)	4	3	3	3	3

[1]Peak heating/cooling demand on the grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

The results show that the passive measure (operable shading) included in Bundle 7 significantly lowers the CEDI (by 28%) and peak cooling demand (by 21%) compared to installing full mechanical cooling with no passive measures.

Bundle 6 results in a small increase in total energy use (TEUI) compared to the baseline. This is due to the addition of cooling energy and increased fan power. Even though Bundle 5 and Bundle 7 also include addition of cooling energy, both bundles result in a reduction in TEUI. The reduced TEUI for Bundle 5 is a result of the enclosure upgrade, and the reduced TEUI seen for Bundle 7 is a result of the higher efficiency of the heating system (air source heat pump) compared to the baseline heating system (electric baseboard).

Costing Analysis

This section summarizes the costing analysis of the low rise existing building bundles, including the incremental capital cost ($/m²) and annual energy cost ($/m²). Note that Bundle 1 and Bundle 3 are not included in the costing analysis since they do not meet the thermal comfort criteria based on the RCP-8.5 2050s climate. Additional costing data are provided in Appendix C.

Figure 3.37 shows the incremental cost at the building level for the bundles. The incremental cost is shown together with the number of overheated hours. The error bars illustrate the high and low bundle cost.

Figure 3.38 shows the annual energy cost for the Step 3 baseline and bundles. Table 3.37 summarizes the energy cost savings compared to the baseline.

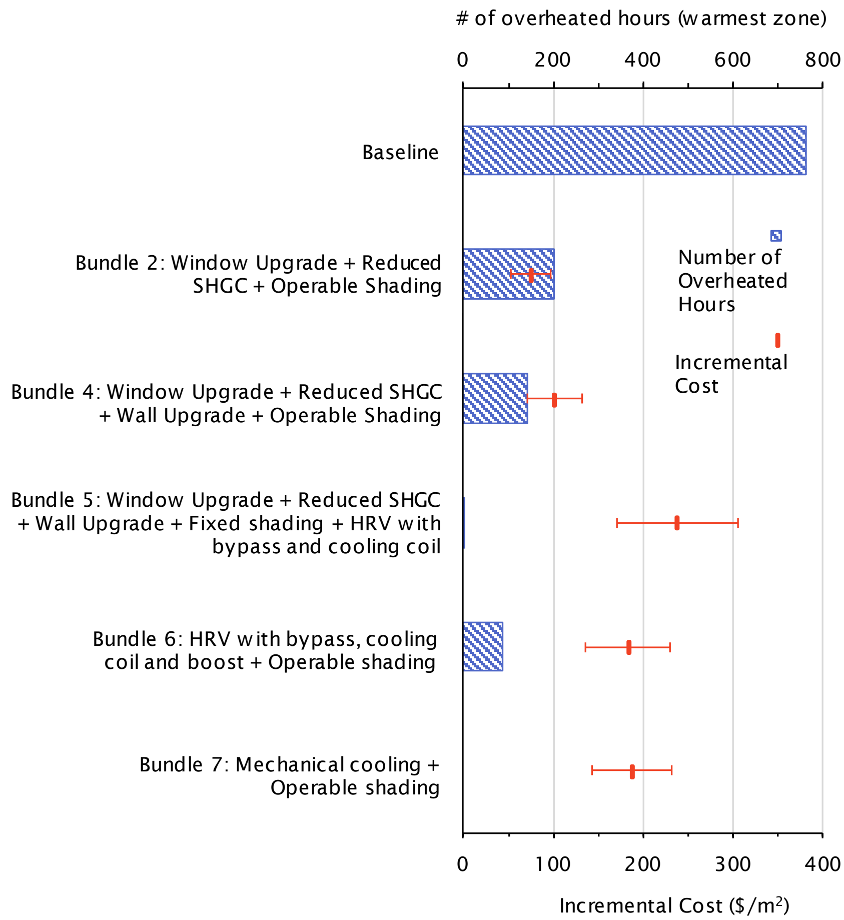

Figure 3.37 Incremental cost ($/m²) for the bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

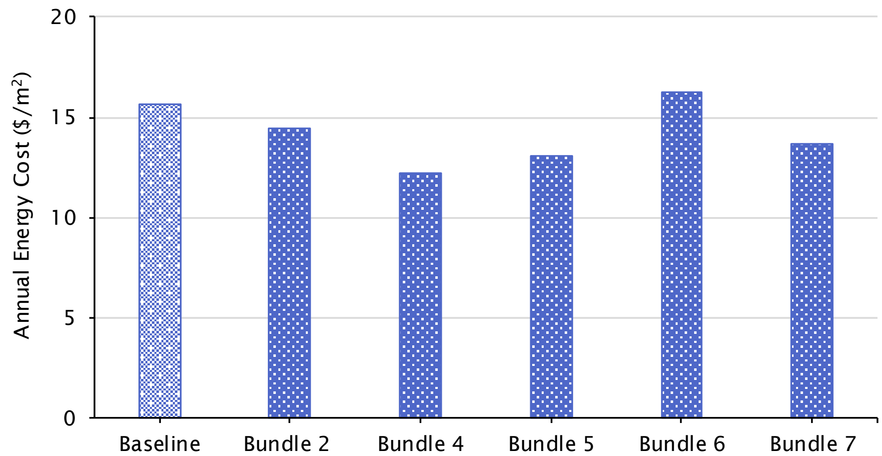

Figure 3.38 Annual energy cost ($/m²) for the baseline and bundles.

TABLE 3.37 ENERGY COST SAVINGS COMPARED TO BASELINE					
	Bundle 2	Bundle 4	Bundle 5	Bundle 6	Bundle 7
Energy Cost Savings (%)	8%	22%	16%	-4%	12%

The results show that the most cost-effective strategy (in terms of incremental capital cost) to reduce the number of overheated hours below the 200 hour threshold is to upgrade to high performance windows with a low SHGC and install exterior operable shading (Bundle 2) to reduce the solar heat gains to the space. The addition of a wall upgrade included in Bundle 4 results in a slightly higher incremental cost, though it further reduces the risk of overheating, reduces the building's energy consumption, and improves the resiliency of the building.

The results suggest that the incremental cost of installing a high efficiency HRV, with bypass and a cooling coil downstream of the HRV (Bundle 6) and adding full mechanical cooling via a ductless air source heat pump are comparable (Bundle 7). However, a heat pump system on its own does not provide ventilation, so if filtered ventilation air is a priority for resiliency or other reasons, the HRV + cooling coil option may be preferred. Alternatively, an HRV (without coil) and heat pump could both be installed over time. The heat pump would efficiently provide both heating and cooling, while the HRV would efficiently provide filtered, tempered outdoor air.

All bundles except Bundle 6 (HRV with bypass, boost and cooling coil + operable shading) result in energy cost savings compared to the baseline archetype. The small increase in annual energy cost seen for Bundle 6 is due to the increase in total energy use as discussed in the *Energy and Emission Analysis* section.

The highest reduction in annual energy cost is seen for Bundle 4 (window and wall upgrade + operable shading), which is a result of the energy savings from the enclosure upgrade, and demonstrates the positive impact of passive climate adaptation and mitigation measures.

3.3.4 Key Findings – Low Rise Existing Building

→ Given the typically poor performance of windows in this building type, any passive measures that reduce direct solar heat gain will lead to a significant reduction of overheated hours. If resources are limited, such efforts could focus on the south and west facing elevations where the solar heat gains are most impactful.

→ The most cost-effective (in terms of incremental capital cost) strategy to reduce the number of overheated hours below the 200-hour threshold is to upgrade to higher performance windows with a low SHGC and to install exterior operable shading (Bundle 2). Besides improving the thermal comfort and resiliency of the building, this upgrade also results in a decrease in space heating demand, and therefore a reduction of the overall energy use, annual energy cost and GHG emissions compared to the baseline.

→ Even greater energy and energy cost savings as well as thermal comfort improvements can be reached by also improving the enclosure (Bundle 4), which is recommended for inclusion when an enclosure renewal is already planned.

→ The cost of installing a high efficiency HRV with bypass and a cooling coil downstream of the HRV, or adding full mechanical cooling via a ductless air source heat pump, is roughly comparable. However, air source heat pumps provide heating and cooling by recirculating air but do not provide any ventilation. The co-benefit to installing HRVs in existing buildings is that it provides filtered outdoor air, which can be desirable during a poor air quality event, or in response to noise or safety concerns, when occupants want to keep windows closed.

→ Combined in-suite HRV heat pumps are a promising emerging technology for this building type, especially for condominium buildings that have individual suite metering and ownership. The performance would be analogous to the modeled HRV + cooling coil, but would allow building owners to address heating, cooling and ventilation via a single piece of equipment. Passive upgrades may also be required to increase the likelihood that the equipment could meet the heating and cooling demand.

→ Installing a high efficiency HRV with bypass and a cooling coil downstream of the HRV may result in a small increase in annual energy cost and total energy use of the building, due to the addition of cooling energy and additional fan power. If the goal is to achieve the 200-hour threshold *and* reduce energy demand, then the installation of this system is recommended to be bundled with design strategies such enclosure upgrades to achieve energy, GHG emissions, and energy cost savings (as well as improved thermal comfort and resilience).

→ If mechanical cooling is installed in an existing building with high SHGC glazing, it is recommended to add exterior shading and/or upgrade the windows to limit excessive cooling energy demand and peak cooling loads.

3.4 Existing Building High Rise

This section summarizes the results for the existing building high rise archetype. The baseline archetype was developed to reflect a high rise existing building typical of the 1980s-90s. Key findings are summarized at the end of the section (Section 3.4.4).

3.4.1 Baseline Results

Thermal Comfort Analysis

The high rise existing building baseline is a non-mechanically cooled archetype. To understand the level of thermal comfort and increased risk of overheating under future climate conditions, the number of overheated hours, as defined in ASHRAE 55-2010 Section 5.3, is reported together with modelled peak operative temperature. Although there is currently no limit for number of overheated hours for existing buildings, the BC ESC compliance limit of 200 hours is used to guide CAMM evaluation and bundle design.

Figure 3.39 shows the number of hours per year that exceed the 80% acceptability limit. The layout of the floor plate is shown, with the colour coding used to illustrate the variation in number of overheated hours.

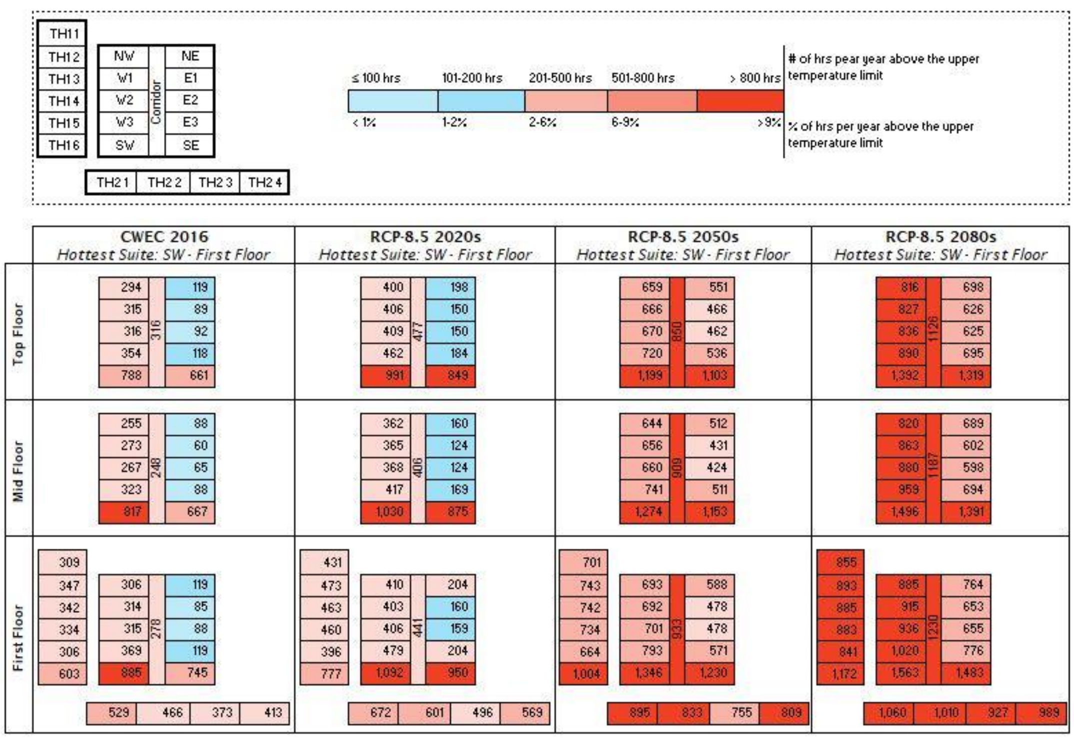

Figure 3.39 Number of hours that exceed the 80% acceptability limit reported at suite level for representative floors of the high rise existing building baseline. The suites that do not exceed the limit of 200 overheated hours are shown as blue, and the suites that exceed the 200-hour limit are colour coded as different shades of red, a darker shade of red indicate a higher number of overheated hours.

The baseline thermal comfort results show that, based on the CWEC 2016 climate file, the south and south-west facing tower suites exceed the 80% acceptability limit for more than 200 hours. Based on the 2020s file 68% of the suites exceed the 200-hour limit, and for the 2050s and 2080s files all suites exceed the 200 hour limit.

Figure 3.40 shows modelled peak operative temperature for the high rise existing building, also in a building zone format with colour coding used to illustrate the variation in peak operative temperature. The date and time of the hottest hour is also included. The modelled operative peak temperature is higher for the south-west and south-east facing corner suites.

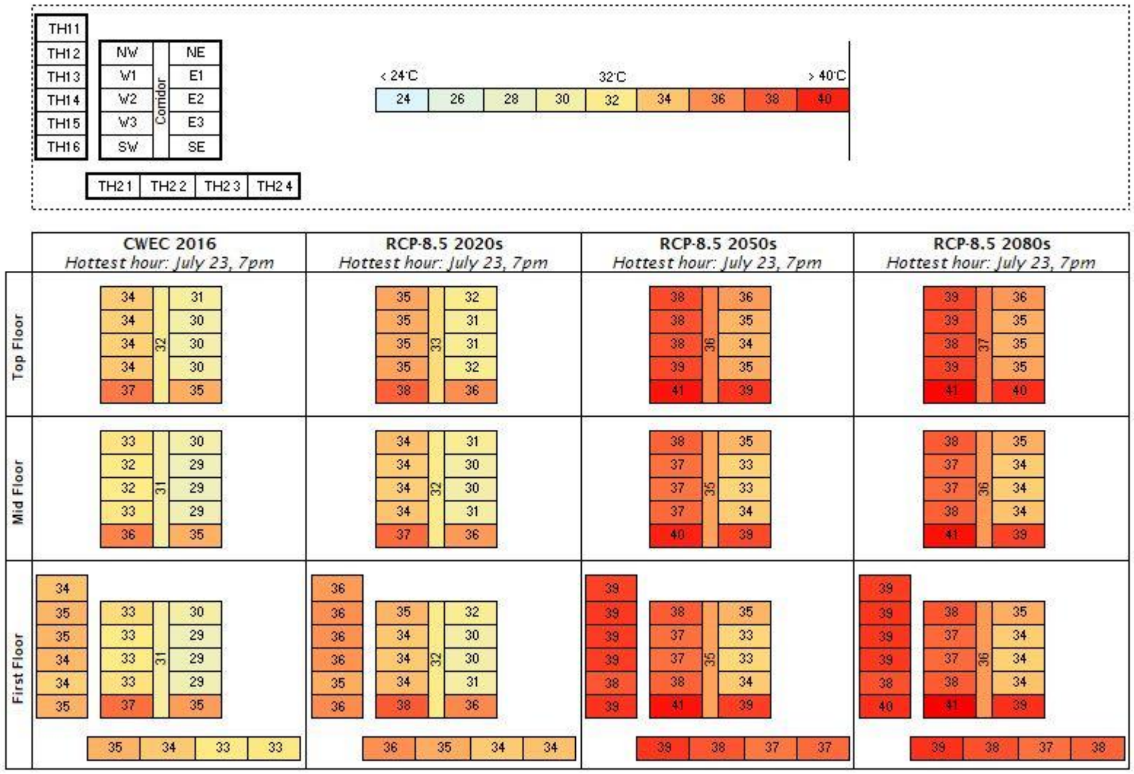

Figure 3.40 Modelled peak operative temperature (°C) for each suite and climate file. The zones are colour coded to illustrate the variation in peak operative temperature. A darker shade of red indicates a higher modelled peak temperature.

The thermal comfort results shown in Figure 3.39 and Figure 3.40 are summarized in Table 3.38. The results indicate that the existing baseline building does not meet the thermal comfort criteria as defined for new construction in the BC ESC under any climate scenario including our current one. The results show that as the climate gets warmer, the number of overheated hours and peak temperatures increase significantly.

TABLE 3.38 SUMMARY OF BASELINE THERMAL COMFORT RESULTS FOR THE HIGH RISE EXISTING BUILDING ARCHETYPE				
	CWEC 2016	RCP-8.5 2020s	RCP-8.5 2050s	RCP-8.5 2080s
# of suites > 80% acceptability limit	87	95	140	140
% of suites > 80% acceptability limit	62%	68%	100%	100%
Highest # of overheated hours (zone level)	885	1,092	1,346	1,563
Suite with highest # of overheated hours	South-west facing corner suite (tower) on first floor			
Peak Operative Temperature (°C)	38	39	42	42
Suite with highest peak operative temperature	South-west facing corner suite (tower) on first floor			

Figure 3.41 shows the modelled hourly operative temperature for the warmest suite during the warmest week for the high rise existing building baseline. The operative temperature is shown based on the CWEC 2016 climate file and RCP-8.5 2020s, 2050s and 2080s. The red dashed line illustrates the 80% acceptability limit based on the CWEC 2016 file.

As the figure shows, the operative temperature based on the 2020s climate file is slightly warmer than CWEC 2016, though the modelled temperature is moderately warmer based on the 2050s and 2080s climate.

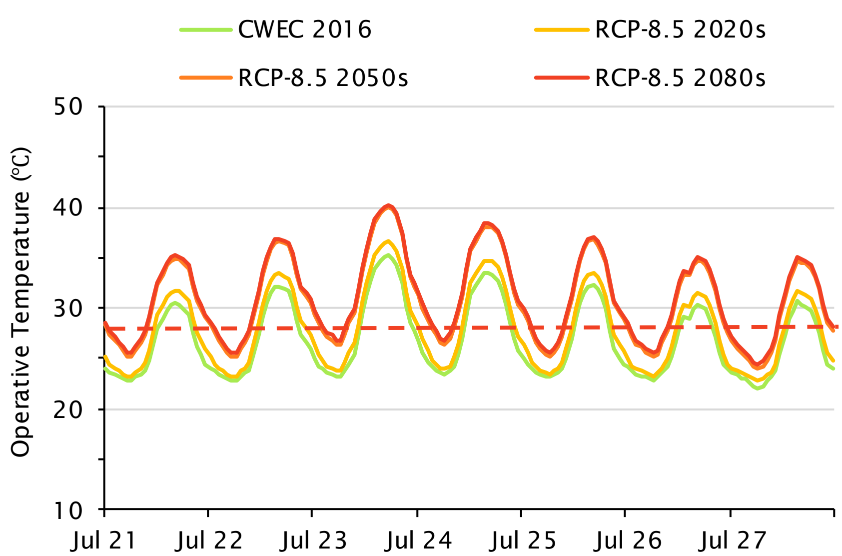

Figure 3.41 Modelled operative temperature (°C) for the warmest suite for the high rise existing building baseline. The interior temperature is shown for one summer week, based on the CWEC 2016, RCP-8.5 2020s, 2050s and 2080s climate files. The red dashed line illustrates the 80% acceptability limit based on the CWEC 2016 climate file.

Energy and Emission Analysis

Figure 3.42 summarizes annual total energy use intensity (TEUI) and thermal energy demand intensity (TEDI) for the high rise existing building baseline.

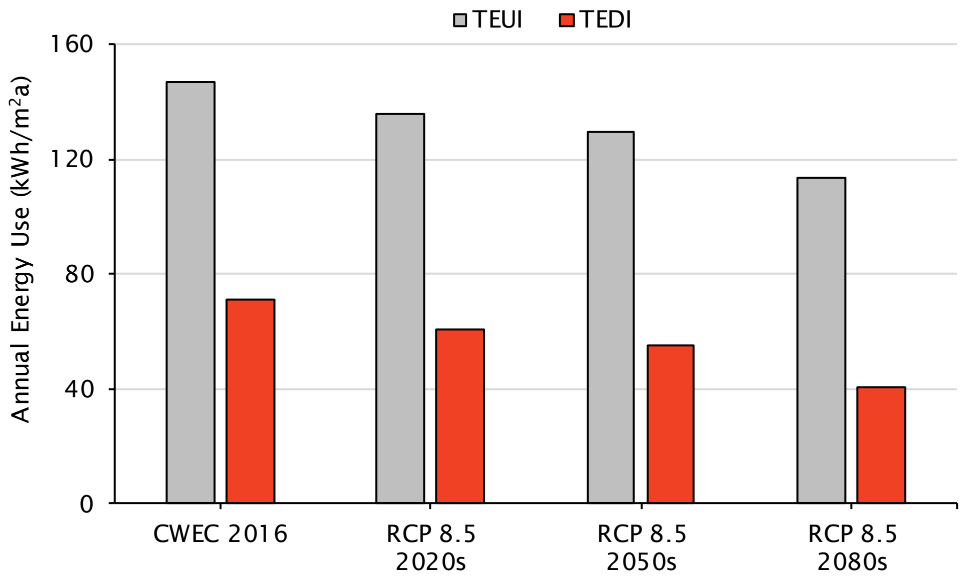

Figure 3.42 Annual total energy use intensity (TEUI) and thermal energy demand intensity (TEDI) results for the high rise existing building baseline.

The Step Code energy and City of Vancouver emission metrics are reported for the high rise existing building baseline to allow for comparison between the new and existing archetypes. Table 3.39 summarizes the baseline results from the energy and emission analysis. Similar to the other non-mechanically cooled archetypes, the three energy related metrics (TEUI, TEDI, and peak heating demand) decrease as the climate gets warmer, due to the decreased space heating demand.

TABLE 3.39 HIGH RISE EXISTING BUILDING BASELINE RESULTS

	CWEC 2016	RCP-8.5 2020s	RCP-8.5 2050s	RCP-8.5 2080s
TEUI (kWh/m^2a)	147	136	130	113
TEDI (kWh/m^2a)	71	61	55	41
Peak heating demand[1] (W/m^2)	47	45	45	41
GHGI[2] – Current ($kgCO_2e/m^2a$)	7	6	6	6
GHGI[2] – Future ($kgCO_2e/m^2a$)	3	3	3	3

[1]Peak heating demand on the grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the current emission factor (GHGI – Current) for the UBC district energy system as well as the emission factor for the future district energy system (GHGI – Future) that is planned to consist of 60% renewable energy by 2024.

3.4.2 Climate Adaptation + Mitigation Measures

This section summarizes the thermal comfort results for the CAMMs for the high rise existing building. A detailed description of each measure is provided in Appendix B.

Thermal Comfort Analysis

Figure 3.43 shows the number of overheated hours for the warmest suite for the baseline archetype and each CAMM, based on the RCP-8.5 2050s climate file. The red dashed line illustrates the 200 hour limit, and the black dashed line presents the baseline results.

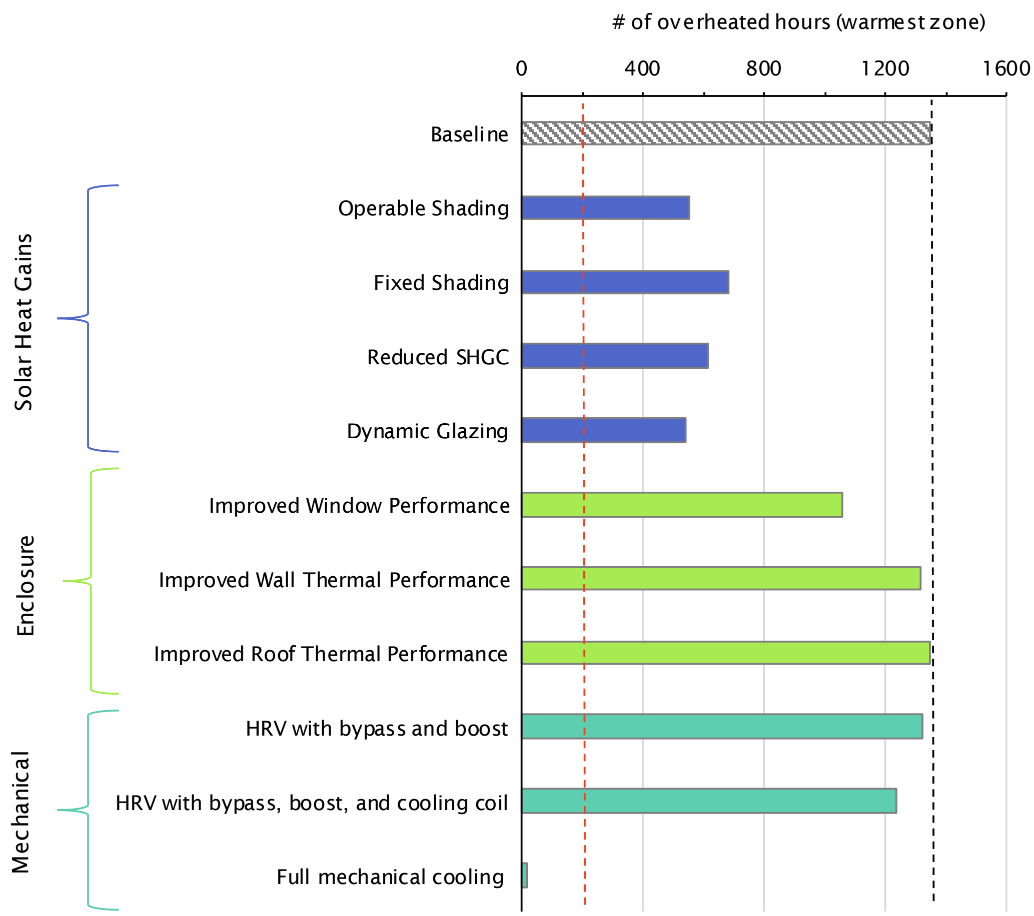

Figure 3.43 Number of overheated hours for the warmest suite and each individual climate adaptation measure, modelled with the RCP-8.5 2050s climate file. The red dashed line illustrates the 200 hour limit, and the black dashed line presents the baseline results.

Similar to the low rise existing building, the results show that any of the solar heat gain reduction measures significantly reduce the number of overheated hours, due to the high baseline SHGC.

As seen for the low rise existing building, partial cooling (HRV with cooling coil) is not enough on its own to meet the thermal comfort criteria, due to the high solar heat gains.

Costing Analysis

The incremental cost compared to the baseline is presented in Figure 3.44together with the thermal comfort results shown in the previous section. The red lines show the average and range of incremental cost ($/m²) at the building level. Appendix C provides additional costing data.

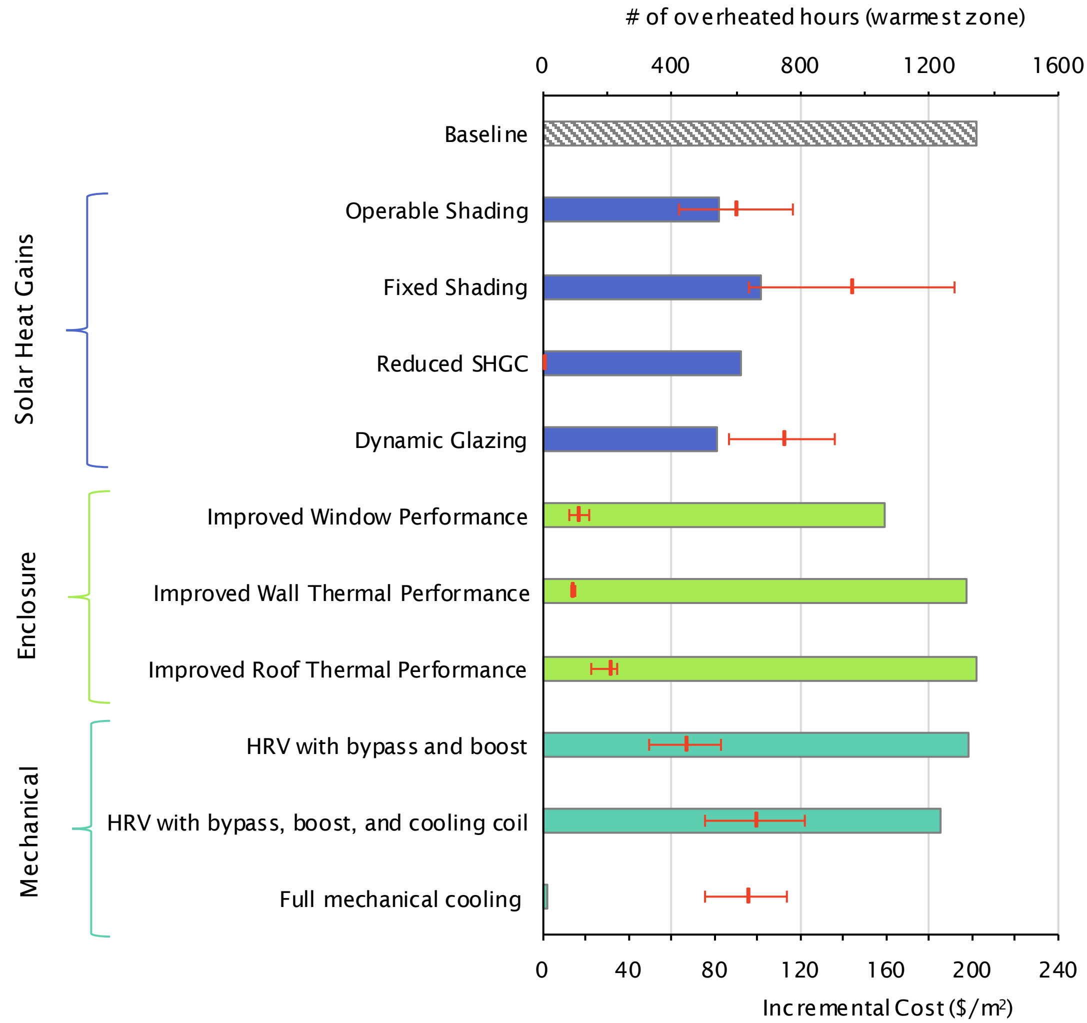

Figure 3.44 The red lines show the incremental cost ($/m²) on building level, the error bars show the high and low cost. The number of overheated hours is shown for the warmest suite based on RCP-8.5 2050s climate file.

The reduction in risk of overheating shown for operable shading is comparable to dynamic glazing and has an approximately 20% lower incremental capital cost.

Similar to the low rise existing building, the incremental cost of installing partial cooling (HRV with cooling coil) and full mechanical cooling (ductless air source heat pump) are comparable, though full mechanical cooling meets the thermal comfort criteria on its own, whereas partial cooling would need to be bundled with solar heat gain reducing measures to meet the thermal comfort criteria. And as noted with the low rise existing archetype, mechanical cooling via heat pumps does not provide a ventilation function.

3.4.3 CAMM Bundles

Bundles were selected based on the individual CAMM analysis. The modelled bundles for the high rise existing building archetype are summarized in Table 3.40. Four passive bundles (Bundle 1-4), and 3 combined bundles (Bundle 5-7) were modelled.

Bundle 1 and 2 consist of solar heat gain reduction measures with a focus on improving thermal comfort. Bundle 3-5 represent comprehensive enclosure renewal scenarios, in which an enclosure renewal is already planned and measures that improve thermal comfort are considered. Bundle 5 also adds mechanical ventilation to the suites, with partial cooling though the ventilation system. Even though fixed shading shows a higher average incremental cost and lower reduction in overheating compared to the operable shading, fixed shading has other benefits (as discussed in Section 3.1.3) and is therefore included in the bundle analysis.

Bundle 6 and 7 represent scenarios where an enclosure upgrade may not be feasible or is not planned in the near future, so the focus is on non-enclosure measures.

TABLE 3.40 MODELLED BUNDLES FOR HIGH RISE EXISTING BUILDING ARCHETYPE

		Description
Passive	Bundle 1 – Thermal Comfort Upgrade	→ Improved window thermal performance (USI-1.14) → Reduced SHGC to 0.28
	Bundle 2 – Thermal Comfort Upgrade	Bundle 1 + → Operable shading
	Bundle 3 – Enclosure Renewal Bundle	→ Improved window thermal performance (USI-1.14) → Reduced SHGC to 0.28 → Improved wall thermal performance
	Bundle 4 – Enclosure Renewal Bundle	Bundle 3 + → Operable shading
Combined	Bundle 5 – Renewal/Resilience Bundle	Bundle 3 + → Fixed shading → HRV with bypass, cooling coil and boost
	Bundle 6 – Resilience Bundle	→ HRV with bypass, cooling coil and boost → Operable shading
	Bundle 7 – Active Thermal Comfort Upgrade	→ Full mechanical cooling → Operable shading

Thermal Comfort Analysis

Figure 3.45 shows the number of overheated hours for the warmest suite in the high rise existing building baseline and bundle archetypes. The modelled risk of overheating is shown based on the RCP-8.5 2020s and 2050s climate files. The red dashed line illustrates the 200-hour limit, and the orange dashed line illustrates the 20-hour limit for vulnerable population.

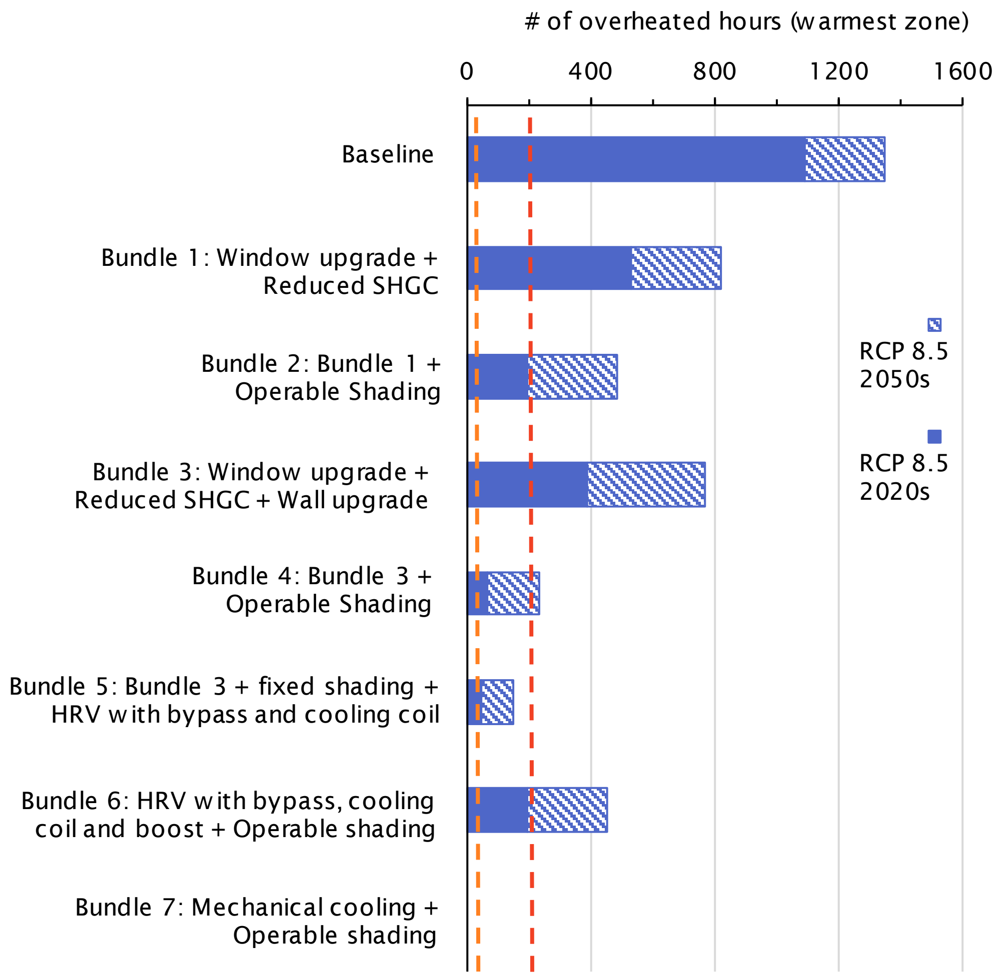

Figure 3.45 Number of overheated hours for the warmest suite for each modelled bundle. The red dashed line illustrates the 200 hour limit, the orange dashed line illustrates the 20 hour limit for vulnerable population.

Figure 3.45 shows that all bundles except those without exterior shading (Bundle 1 and Bundle 3) meet the 200-hour limit based on the RCP-8.5 2020s climate file. The results for the RCP-8.5 2050s climate file, however, show that only Bundle 5 and Bundle 7 are below the 200-hour threshold, suggesting that, in the RCP-8.5 2050s scenario, some level of mechanical cooling will be required to meeting the threshold. The fully passive Bundle 4 comes close and could be an option in a planned enclosure renewal scenario. Table 3.41 summarizes the results shown in Figure 3.45.

TABLE 3.41 NUMBER OF OVERHEATED HOURS FOR THE WARMEST SUITE FOR THE HIGH RISE EXISTING BUILDING BUNDLE ARCHETYPES								
	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4	Bundle 5	Bundle 6	Bundle 7
RCP-8.5 2020s	1092	525	191	385	64	47	194	0
RCP-8.5 2050s	1346	814	480	766	231	148	451	4

Table 3.42 summarizes the overall building thermal comfort results for the passive bundles modelled with the RCP-8.5 2050s climate file.

TABLE 3.42 SUMMARY OF PASSIVE BUNDLE THERMAL COMFORT RESULTS FOR THE HIGH RISE EXISTING BUILDING BASED ON RCP-8.5 2050S CLIMATE FILE					
	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
# of zones > 80% acceptability limit	140	111	28	90	2
% of zones > 80% acceptability limit	100%	79%	20%	64%	1%
Highest # of overheated hours	1,346	817	480	766	231
Peak operative temperature (°C)	42	38	36	37	34
Suite with highest peak operative temperature	South-west facing corner suite on first floor				

Bundle 4 (window and wall upgrade + operable shading) is the passive bundle that reduces the risk of overheating the most, followed by Bundle 2 (window upgrade + operable shading). Even though Bundle 1 and Bundle 3 include a window upgrade (with low SHGC), the bundles do not include exterior shading and do not achieve comparable thermal comfort improvements to Bundle 2 and 4. The greater reduction in number of overheated hours shown for Bundle 4 compared to Bundle 2 suggests that in combination with solar heat gain reduction design measures, a better insulated enclosure has a positive impact on thermal comfort.

Table 3.43 summarizes the overall building thermal comfort results for the combined bundles modelled with the RCP-8.5 2050s climate file.

TABLE 3.43 SUMMARY OF BUNDLE THERMAL COMFORT RESULTS FOR THE LOW RISE EXISTING BUILDING BASED ON RCP-8.5 2050S CLIMATE FILE			
	Bundle 5	Bundle 6	Bundle 7
# of zones > 80% acceptability limit	0	44	0
% of zones > 80% acceptability limit	0%	31%	0%
Highest # of overheated hours (Zone level)	148	451	4
Peak operative temperature (°C)	33	35	27
Suite with highest peak operative temperature	South-west facing corner suite on first floor		

Bundle 6 (HRV with cooling coil + operable shading) exceeds the 200-hr threshold based on the RCP-8.5 2050s climate file, though in combination with an enclosure upgrade (window and wall upgrade) (Bundle 5) the 200-hr limit is met.

If an enclosure upgrade is not feasible, the results suggest that for the high rise existing archetype, installing full mechanical cooling and operable shading may be most promising solution to meet the thermal comfort criteria in a future climate, although this strategy may not meet other goals, such as providing ventilation.

Figure 3.46 shows the modelled operative temperature for the high rise existing building baseline and the bundles that meet the thermal comfort target based on the RCP-8.5 2050s climate fie, i.e. Bundle 5 and 7. The interior temperature is shown for the hottest summer week in the warmest suite and is modelled with the RCP-8.5 2050s climate file. The red dashed line illustrates the 80% acceptability limit for July.

The results show that even though bundle 5 reduces almost all overheated hours, the interior temperature is moderately higher compared to the full mechanical cooling bundle (Bundle 7).

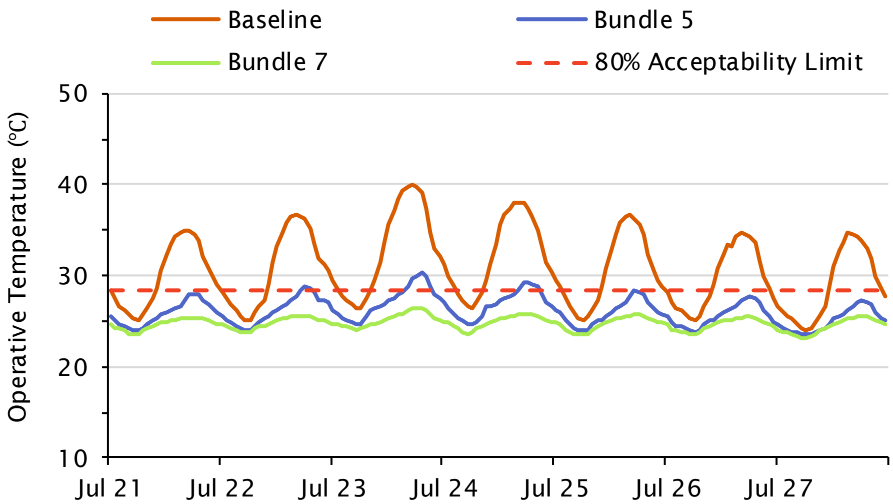

Figure 3.46 Modelled operative temperature (°C) for the warmest suite for the high rise existing building baseline and bundles based on the RCP-8.5 2050s climate file, shown for one summer week.

Energy and Emission Analysis

Table 3.44 summarizes the energy and GHG results for the baseline and passive bundles based on the RCP-8.5 2050s climate file. Note that none of the passive bundles meet the thermal comfort criteria under the 2050s climate; however, the energy and emission results are included for comparison.

TABLE 3.44 SUMMARY OF PASSIVE BUNDLE ENERGY AND EMISSION RESULTS FOR THE HIGH RISE EXISTING BUILDING BASED ON RCP-8.5 2050S CLIMATE FILE

	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
TEUI (kWh/m^2a)	130	115	115	106	107
TEDI (kWh/m^2a)	55	42	42	34	35
Peak heating demand[1] (W/m^2)	45	36	36	31	32
GHGI[2] ($kgCO_2e/m^2a$)	3	3	3	3	3

[1]Peak heating demand on the grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

Similar to the low rise existing building, all passive bundles reduce the archetype's energy consumption and peak heating demand. As discussed previously, the operable shading reduces the solar heat gains to the space, and therefore the TEDI is slightly higher for the bundles including operable shading, but still lower than the baseline. All passive bundles reduce the number of overheated hours and improve the energy performance of the archetype compared to the baseline. Even though all passive bundles reduce the energy consumption and peak heating demand, none of the bundles meet the 80% acceptability limit. The results suggest that further solar reduction design measures or active cooling would be required if this existing building archetype were to meet the new building thermal comfort criteria under future climate conditions.

Table 3.45 summarizes the energy and GHG results for the combined bundles based on the RCP-8.5 2050s climate file. For comparison, the results for the individual active measures are included, i.e. the bundles without passive measures. Note that Bundle 6 and the individual active measure for Bundle 5 (HRV with cooling coil) are not included, since they do not meet the comfort criteria.

TABLE 3.45 SUMMARY OF COMBINED BUNDLE ENERGY AND EMISSION RESULTS FOR THE HIGH RISE EXISTING BUILDING BASED ON RCP-8.5 2050S CLIMATE

	Baseline	HRV with bypass, cooling coil, and boost as needed	Full mechanical cooling	
		With passive measures (Bundle 5)	**Without** passive measures	**With** passive measures (Bundle 7)
TEUI (kWh/m^2a)	130	128	113	109
TEDI (kWh/m^2a)	55	20	55	59
CEDI (kWh/m^2a)	n/a	9	35	19
TEDI + CEDI (kWh/m^2a)	55	29	90	78
Peak heating demand[1] (W/m^2)	45	26	27	33
Peak cooling demand[1] (W/m^2)	n/a	9	21	14
Peak operative temperature (°C)	42	33	28	27
GHGI[2] ($kgCO_2e/m^2a$)	3	3	3	3

[1]Peak heating/cooling demand on the grid (accounts for system efficiency), see Table 2.5 for full description. [2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

As shown, both Bundle 5 and Bundle 7 result in lower TEUI compared to the baseline, despite the addition of cooling energy. Bundle 7 includes installation of air source heat pumps that provide heating and cooling to the suites. The reduction in TEUI is due to the higher efficiency for the heating system compared to the baseline heating system (electric baseboards). Bundle 5 results in a significant reduction in TEDI (63%) due to the enclosure upgrade and heat recovery

Costing Analysis

This section summarizes the costing analysis of the high rise existing building bundles, including the incremental capital cost ($\$/m^2$) and annual energy cost ($\$/m^2$). Note that only the bundles that meet the thermal comfort criteria are included in the costing analysis. Additional costing data are provided in Appendix C.

Figure 3.47 shows the incremental cost on building level for the bundles. The incremental cost is shown together with the number of overheated hours based on the RCP-8.5 2050s climate file. The error bars illustrate the high and low bundle cost.

Figure 3.48 shows the annual energy cost for the Step 3 baseline and bundles. Table 3.46 summarizes the energy cost savings compared to the baseline.

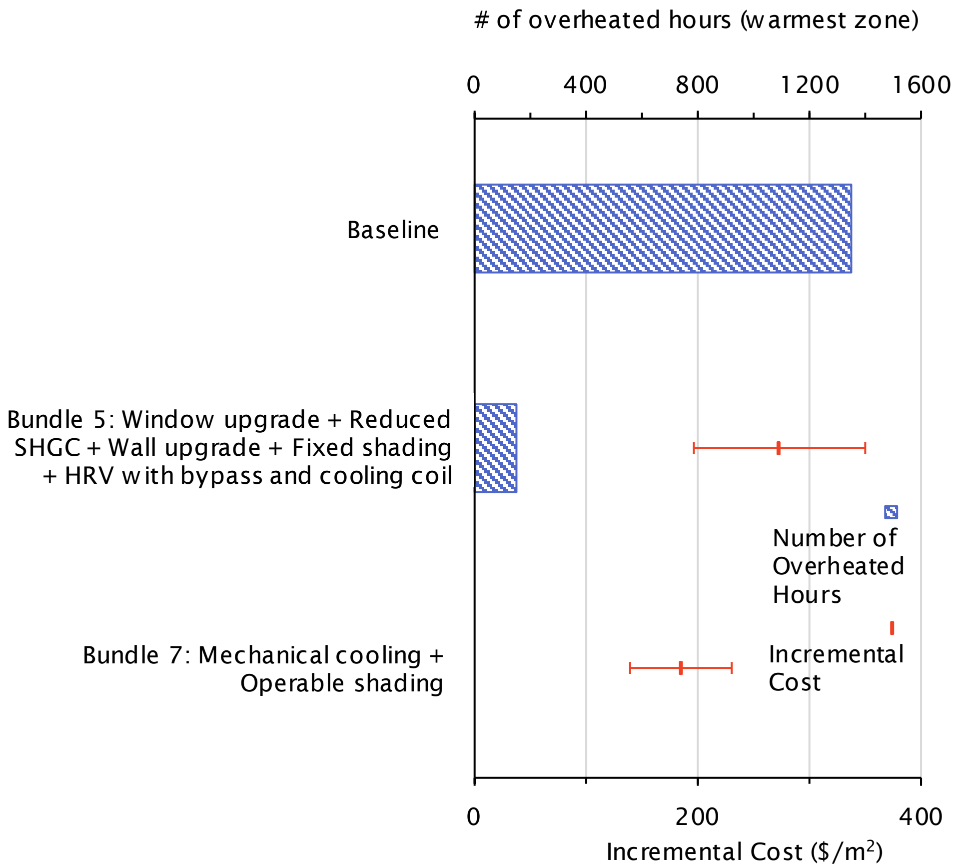

Figure 3.47 Incremental cost ($/m²) for the bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

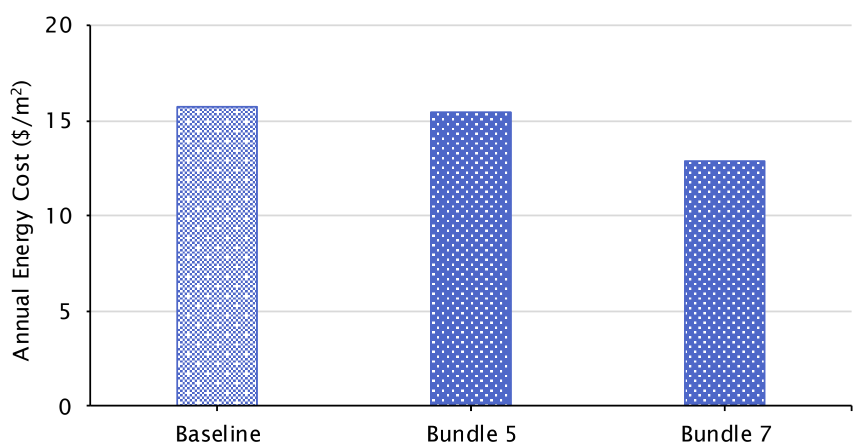

Figure 3.48 Annual energy cost ($/m²) for the baseline and bundles.

TABLE 3.46 ENERGY COST SAVINGS COMPARED TO BASELINE		
	Bundle 5	Bundle 7
Energy cost savings (%)	1%	18%

The results show that the most cost-effective strategy (in terms of incremental capital cost) to reduce the number of overheated hours below the 200-hour threshold, based on the RCP-8.5 2050s climate, is to install full mechanical cooling via in-suite ductless air source heat pumps, and operable shading. Having said this, the upper range of Bundle 7 (full cooling + operable shading) is in line with the lower range of Bundle 5 (enclosure renewal + HRV with cooling coil + fixed shading). If an enclosure renewal is already being considered and/or if providing mechanical ventilation is a priority, then Bundle 5 should be considered. Given limited current options, it is difficult to conclude whether fixed or operable exterior shades are definitively more or less expensive. This is likely to change over time as more products become available.

As shown, both bundles result in a decrease in annual energy cost. Bundle 7 results in a larger decrease, due to the higher equipment efficiency and therefore lower heating and cooling energy use.

3.4.4 Key Findings – High Rise Existing Building

→ The high rise existing archetype baseline performs the worst of all the archetypes from an overheating perspective, due to the combined effect of high solar gains through poor performing glazing and high window to wall ratio; high occupant density, and lack of mechanical ventilation and cooling.

→ Any passive measures that reduce solar heat gain will significantly improve comfort performance with this archetype and should be encouraged at every opportunity (e.g. at time of window replacement).

→ However, the modeling suggests that full or partial cooling is necessary to maintain thermal comfort as the outdoor air temperature increases. Adding passive measures *in combination with mechanical cooling* is recommended to increase the likelihood that an added cooling system will be able to meet the peak cooling load, and to reduce the annual cooling energy consumption.

→ Only two bundles meet the 200-hour threshold based on the RCP-8.5 2050s climate. Of the two bundles, full mechanical cooling + operable shading is the most cost-effective strategy in terms of incremental capital cost and annual energy cost, although it does not address ventilation.

→ The other bundle that meets the 200-hour threshold based on the RCP-8.5 2050s climate consists of a window upgrade (with reduced SHGC), wall upgrade, fixed exterior shading and installation of HRVs that allows for bypass and boost as needed, and a cooling coil downstream of the HRV. Even though this bundle is more costly, it should be considered if an enclosure renewal is already being considered and if providing mechanical ventilation is a priority.

→ Besides improving the archetype's resilience to increasing outdoor air temperatures, installing air source heat pumps for heating and cooling also reduces the total energy use of the building (due to the higher equipment efficiency).

→ Combined in-suite HRV heat pumps are a promising emerging technology for this building type, especially for condominium buildings that have individual suite metering and ownership. The performance would be analogous to the modeled HRV + cooling coil, but would allow building owners to address heating, cooling and ventilation via a single piece of equipment. Passive upgrades may also be required to increase the likelihood that the equipment could meet the heating and cooling demand.

4 Sensitivity Analysis

Sensitivity analysis was performed to test modelling assumptions that are known to have considerable potential impact on results, and to test our best performing bundles against external climate related events. The ideal solutions not only provide adequate thermal comfort in a cost-effective, energy- and emissions-efficient manner, but they are also resilient to disruptive events such as wildfires and power outages.

4.1 Internal Heat Gains

To understand how the model assumptions for internal heat gains (IHGs) affect the modelled risk of overheating, a sensitivity analysis was carried out based on the new building low rise as described in Section 2.5.1. The analysis was completed using the baseline archetype and Bundle 1 (reduced WWR, exterior fixed shading and reduced SHGC), which meets the 80% acceptability limit based on the RCP-8.5 2050s climate file.

Figure 4.1 shows the number of overheated hours for the warmest suite for the low and high IHG scenario, along with the baseline assumption (NECB 2011).

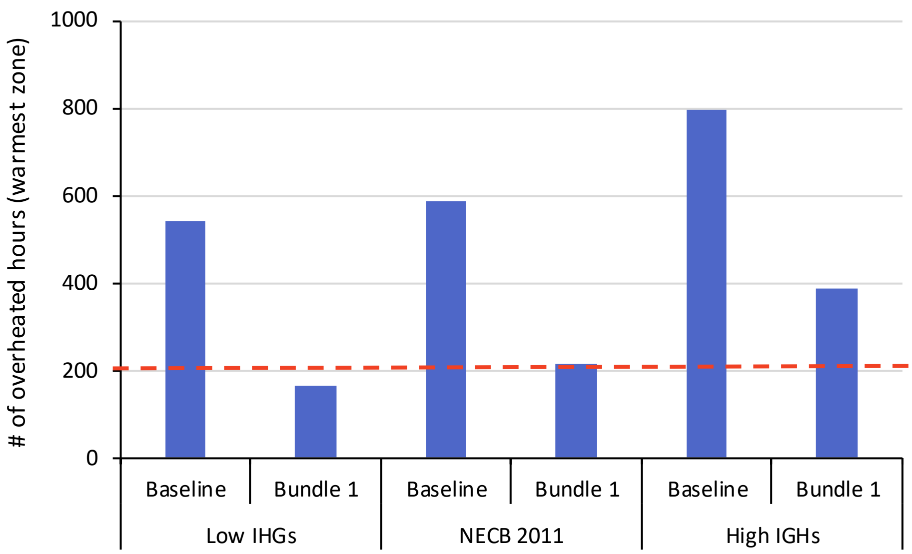

Figure 4.1 Sensitivity analysis of internal heat gains based on new building low rise archetype and Bundle 1, modelled with the RCP-8.5 2050s climate file.

The results suggest that if the IHGs were to be higher than predicted when designing Bundle 1, the number of overheated hours would exceed the 200 hour limit in the RCP-8.5 2050s scenario. In this scenario, the number of overheated hours roughly doubles over the NECB 2011 baseline. This suggests that both the baseline and Bundle 1 are quite sensitive to high IGHs (e.g. a densely occupied suite).

4.2 Natural Ventilation

In this study the modelled natural ventilation is based on the assumption that occupants open their windows as needed for optimized thermal comfort, though occupants may not open their windows due to reasons such as poor air quality, bugs, noise, or safety reasons. Part of the rationale for this sensitivity analysis is to test CAMM bundles for their resilience against air quality events such as wildfires.

Two bundles were analyzed for the low rise new building:

→ Bundle 1: reduced WWR, exterior fixed shading and reduced SHGC

→ Bundle 3: high efficiency HRV with cooling coil and boost as needed, and operable shading.

Recall that Bundle 1 has a minimum efficiency HRV (per the baseline) with no mechanical cooling.

Figure 4.2 shows the modelled operative temperature for the Step 3 (baseline) low rise new building baseline and the two bundles in the event of no natural ventilation (i.e. windows are kept closed), based on the RCP-8.5 2050s climate file. The interior temperatures are shown for a summer week, together with the outdoor dry-bulb (2050s) for the same period.

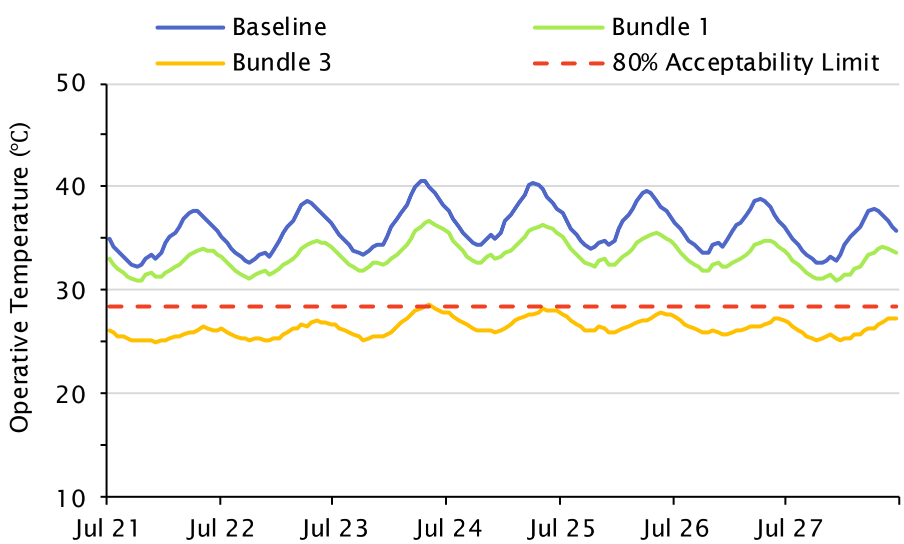

Figure 4.2 Modelled operative temperature for low rise new building Step 3 baseline, bundle 1 and bundle 3 in the event of no natural ventilation, based on the RCP-8.5 2050s climate file. The indoor temperatures are shown together with dry-bulb outdoor temperature for a summer week. The red dashed line illustrates the 80% acceptability limit.

As shown in the figure, both the baseline and Bundle 1 exceed the 80% acceptability limit for the whole week. However, Bundle 3 successfully keeps the operative temperature below the acceptability limit, and therefore shows higher resilience against wildfire smoke events and other events that may influence occupants to keep windows closed. This is primarily due to the addition of a cooling coil to the heat recovery ventilation system. Heat recovery ventilation systems also typically have filters that provide additional resilience against air quality related events (although units will not necessarily be equipped with filters that will remove the fine particulate matter from wildfire smoke[28]).

[28] MERV-8 filters are an industry standard, although MERV-13 or higher is recommended for better protection against particulates from wildfire smoke. http://www.bccdc.ca/resource-gallery/Documents/Guidelines%20and%20Forms/Guidelines%20and%20Manuals/Health-Environment/WFSG_EvidenceReview_FiltrationinInstitutions_FINAL_v3_edstrs.pdf

4.3 Power Outage

A sensitivity analysis was carried out to further understand how a mechanically cooled archetype may perform in the event of a power outage. The sensitivity analysis was based on the Step 4 high rise new building baseline and Bundle 2 (operable shading and reduced SHGC) – in other words, one scenario with no additional cooling-focused passive measures and one with cooling focused passive measures.

Figure 4.3 shows the modelled operative temperature for the Step 4 baseline and Bundle 2 during normal operation, and for a power outage event during a summer week (i.e. no cooling, plug loads, ventilation, etc.).

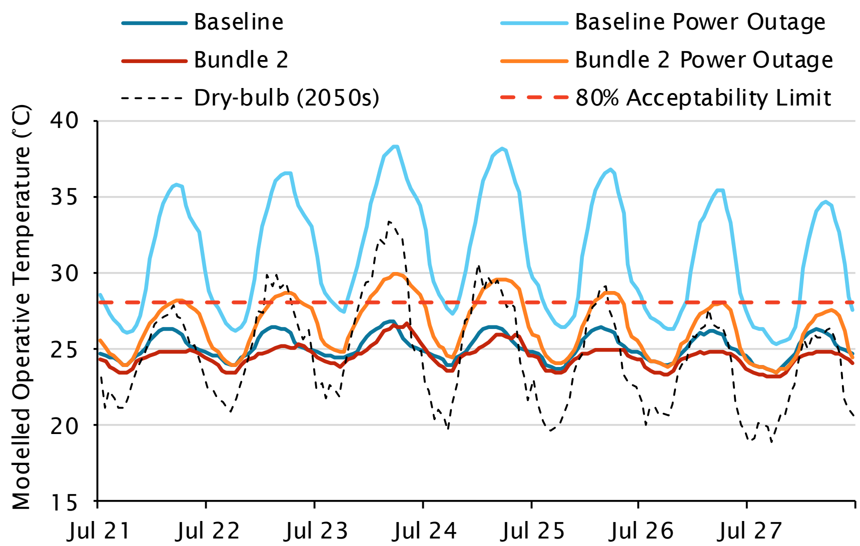

Figure 4.3 Modelled operative temperature for the Step 4 high rise new building baseline and Bundle 2, during normal operation and during a power outage event for a summer week.

As shown in the figure, the passive measures make a substantial difference to the thermal comfort in the event of a power outage, demonstrating the additional resiliency benefit of incorporating cooling focused passive measures into a building with full mechanical cooling.

4.4 RCP-8.5 2080s

A sensitivity analysis was carried out to further understand how new building archetypes that are designed to meet the thermal comfort criteria based on the RCP-2050s climate conditions would perform later in the century, or if the RCP-8.5 2080s climate conditions were to occur earlier than predicted. This sensitivity analysis can also be seen as a 2050s 'hot summer' stress test of the archetypes.

For the low rise new building, the baseline, Step 3 and Step 4 passive bundles were modelled with the RCP-8.5 2080s climate as follows:

- Bundle 1 - Step 3: Reduced window to wall ratio + Reduced SHGC + Fixed shading
- Bundle 2 - Step 3: Reduced SHGC + Operable shading
- Bundle 1 - Step 4: Reduced window to wall ratio + Fixed shading
- Bundle 2 - Step 4: Operable shading

Recall that the adjustments that were made to the Step 3 baseline to meet Step 4 were as follows:

→ Reduced SHGC

→ Higher performing wall assembly

→ High efficiency HRV with bypass

Figure 4.4 shows the number of overheated hours for the warmest zone based on the RCP-8.5 2020s, 2050s, and 2080s climate file. As shown, the risk of overheating increases significantly for both the Step 3 and Step 4 baseline archetypes, illustrating the need for design strategies beyond simply meeting the current BC ESC metrics to address future thermal comfort.

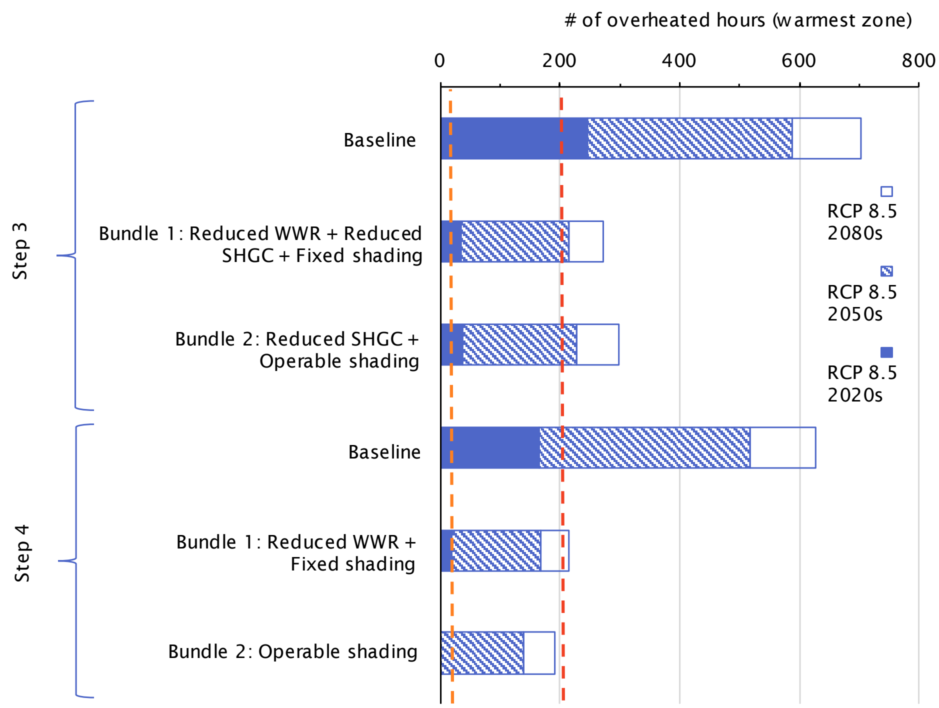

Figure 4.4 Number of overheated hours for the warmest zone, modelled with the RCP-8.5 2020s, 2050s, and 2080s climate files. The red dashed line illustrates the 200 hour threshold, and the orange dashed line illustrates the 20 hour threshold for vulnerable populations.

The passive bundles show a significant reduction in the risk of overheating for the RCP-8.5 2080s climate file, although the only bundle that meets the 200-hour limit is the Step 4 archetype with operable shading. These results demonstrate the benefit of a higher performing enclosure.

For the high rise new building both bundles were modelled for the Step 3 and 4 archetype. Recall that the high rise new building includes mechanical cooling in the baseline and that the Step 4 baseline includes a higher performing wall assembly than the Step 3 archetype.

→ Bundle 1 - Step 3 and 4: Reduced window to wall ratio + Reduced SHGC + Fixed shading

→ Bundle 2 – Step 3 and 4: Reduced SHGC + Operable shading

Figure 4.5 shows the CEDI at the building level for the Step 3 and Step 4 high rise new building and bundles, modelled with the RCP-8.5 2020s, 2050s and 2080s climate file. The red dashed line illustrates the PHI cooling energy demand limit of 15 kWh/m²a.

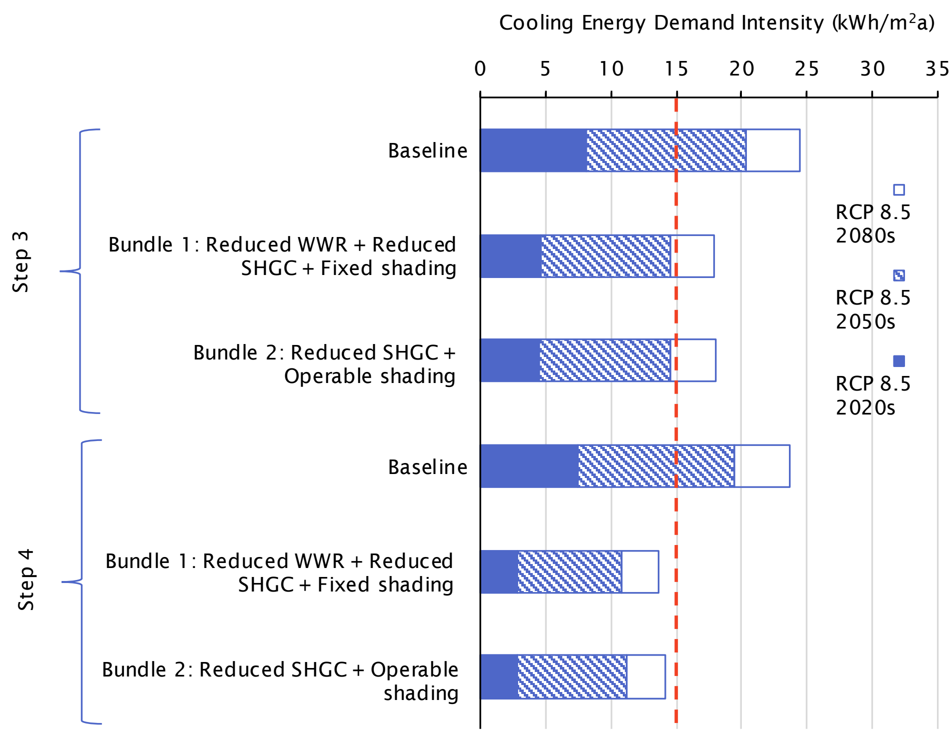

Figure 4.5 Cooling energy demand intensity (CEDI) for new high rise at building level, modelled with the RCP-8.5 2020s. 2050s, and 2080s climate files. The red dashed line illustrates the PHI limit of 15 kWh/m²a.

As shown, all bundles exceed the PHI limit based on the RCP-8.5 2080s climate file. As seen for the low rise new building, the Step 4 bundles perform better than the Step 3 ones, again demonstrating the benefit of a higher performing enclosure towards reducing cooling energy use.

5 Recommendations for Methods and Standards

Drawing on the study results, a number of design strategies and modelling recommendations are offered, with the intent of informing future analysis, program and policy development.

5.1 Design Strategies

*For **new** multi-family residential buildings:*

→ Designing for reduced WWR and SHGC are both promising strategies given that they reduce the risk of overheating with either a negligible or positive impact on incremental costs. It is recommended that these be considered as core design considerations in the near term. However, both strategies may reduce winter solar gains and increase thermal energy demand, and as such, each strategy must be evaluated within the context of a specific project and its other performance metrics.

→ Dramatically improving window thermal performance (e.g. to Passive House level) without also addressing solar heat gain, via a reduced SHGC and/or shading measures, can put the building at risk of overheating. This leads the team to recommend that as building designs progress toward the highest steps of the BC ESC that solar heat gain reduction measures also be required. Reduced SHGC targets beyond what is already required by code would be one way to address this, or inclusion of exterior shading.

→ For the low-rise new archetype, the results indicate that upgrading the ventilation system to include a high efficiency HRV (with boost and bypass modes), plus a cooling coil downstream of the HRV, meets the thermal comfort criteria based on RCP-8.5 2050s climate. This suggests that a separate mechanical cooling system is not generally required for this archetype in the 2050s climate, provided we accept the 200-hr 80% acceptability limit.

→ If not constrained to use a district heating system, heat pumps could also be installed at the time of construction to efficiently provide both heating and cooling.

→ If centralized HRVs are used, distribution ducts could be oversized during design to allow additional capacity for cooling in the future. Current best practice for high efficiency HRVs is to size at 150-160% capacity, which enables boost airflow and additional cooled air to be circulated when needed.

→ Combined in-suite HRV heat pumps are an emerging technology that may be suitable for condominium buildings that have individual suite metering and ownership.

→ Further work could include the development of design guidelines for a range of cooling (or ‘partial’ cooling) strategies as we prepare buildings for future climate conditions.

→ In order to meet thermal comfort in the current and future climate without sacrificing energy demand reduction targets, it is recommended that any building that includes partial or full mechanical cooling also include design elements to mitigate solar heat gain (such as exterior shading and/or low SHGC) and thereby manage cooling equipment loads. This will also reduce annual energy costs, electricity demand charges and provide greater resiliency to power outages and poor air quality events such as forest fires.

- → A well-insulated, airtight enclosure, paired with passive cooling strategies, is shown to be beneficial for mechanically cooled archetypes in terms of reducing peak cooling demand and annual cooling demand. It is also shown to be beneficial for non-mechanically cooled buildings in terms of improving thermal comfort. A high performance enclosure also reduces the total building energy use, greenhouse gas emissions and annual energy cost.
- → A Cooling Energy Demand Intensity (CEDI) metric is used in this study to quantify the cooling demand in the current and future climate scenarios. Peak cooling demand is also used. The Passive House Institute cooling demand intensity metric is included as a theoretical reference point for the CEDI[29]. As our climate shifts from heating dominated to cooling dominated, a target for cooling demand intensity and/or peak cooling demand will likely be desired. These targets will guide design professionals toward cooling strategies that consider not just comfort, but also overall energy reduction and resiliency goals.

*For **existing** buildings:*

- → Generally speaking, for upgrades to existing building assets, the most cost-effective time to accommodate CAMMs is during a planned renewal. For example, adding exterior shading during a comprehensive cladding and window renewal means that the work can be designed at the same time for a cohesive appearance and proper detailing, and can make use of the same site mobilization such as scaffolding and on-site trades that can accomplish multiple scopes of work. The bundles were selected and costed with this approach in mind, and where applicable, basic renewal with like-for-like components was assumed as a starting point for the incremental costing.
- → As a corollary to the first point, if we *do not* address climate adaptation and mitigation at the time of renewal, there is a lost opportunity cost, as major building assets such as windows and siding are typically only renewed once every 40 or 50 years. There is therefore some urgency with which programs and policies may be developed to support this type of work for existing buildings.
- → A primary focus for retrofitting existing buildings (both low and high rise) in the near term should be on mitigating direct solar heat gain through existing high solar gain windows. Any passive measures that reduce solar heat gain are shown to significantly improve thermal comfort performance with this archetype and should be encouraged at every opportunity. If resources are limited, such efforts could focus on the south and west facing elevations where the solar heat gains are most impactful.
- → Further to the first point, it is recommended that any existing building that is considering adding full mechanical cooling also incorporate passive solar heat gain mitigation measures (e.g. exterior shading). This will increase the likelihood that an added cooling system will actually be able to meet the peak cooling load. This will also reduce the likelihood that the existing electrical capacity is exceeded with the

[29] PHI's cooling demand intensity requirement is not climate specific, while Passive House Institute US (PHIUS) varies its target based on location, building size, and occupant load.

addition of new equipment. While not evaluated in this study, it is possible that the cost of adding passive heat gain mitigation measures would be less than the cost to upgrade a building's electrical service.

- → Combined in-suite HRV heat pumps are an emerging technology that may be suitable for existing condominium buildings that have individual suite metering and ownership. This type of equipment would enable existing buildings, which typically have neither mechanical cooling nor mechanical ventilation, to address efficient heating, cooling and ventilation needs in a single piece of equipment, although passive measures would likely also be required (similar to the HRV + cooling coil case). Additional analysis is recommended to evaluate the best applications, available products, and demand reduction measures for this technology.

5.2 Modelling considerations and recommendations

- → Current modelling guidelines prescribe the use of CWEC 2016 weather files, which are based on historical data. As this study has shown, the use of future climate models dramatically changes the modelled results for the key overheating metrics. With the understanding that the climate will continue to change throughout a building's lifetime, it is strongly recommended that the modeling and design of new buildings incorporate future climate considerations.
- → The historical CWEC files upon which the future climate files are built, are provided in TMY format and are created by combining twelve statistical median months chosen from a continuous 15-30-year period of historical data. This approach results in a file that represents the average climate and does not include events such as cold snaps or heat waves. There is currently no requirement to use climate files that represents warmer (or colder) conditions than average, to stress test archetypes for Step Code compliance.

  As such, it is recommended that further analysis is conducted to identify a reasonable set of current and future climate files that modellers can use to test the resilience of new building designs to extreme temperature events.
- → The definition of overheating outlined in the City of Vancouver Energy Modelling Guideline v.2.0. was followed in this study for non-mechanically cooled buildings. The upper temperature limit used to determine an overheated hour is a function of the mean outdoor air temperature. In this analysis, the upper temperature limit was calculated based on each climate file. As such, the upper temperature limit increases as the climate warms and the number of overheated hours is lower than if the upper temperature limit would have been held constant throughout (based on the CWEC file). Further scope could focus on developing a consistent approach and metrics around overheating design limits.
- → The sensitivity analysis around internal heat gains suggests that higher than expected internal gains can have a significant impact on overheating. Further investigation may be warranted to validate current modelling standard practice and/or designers need to be aware of projects that are likely to have higher occupant loads or other internal gains and accommodate those in the modelling.
- → There is currently no standard available for modelling of natural ventilation. For consistency within the industry, further scope is recommended to focus on

developing a guideline for modelling of natural ventilation as overheating studies becomes more common.

6 Closure

We trust this report fulfills the expectations as laid out in RFP #2018010204: Design Climate Resilient Buildings Services. We look forward to supporting the next phases of work as they are developed.

Yours truly,

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Appendix A

Key Modelling Inputs

TABLE A.1 MODEL INPUTS FOR LOW RISE NEW BUILDING BASLEINE			
GENERAL DESCRIPTION			
This archetype is a 6-storey, 4,700 m^2 (51,000 ft^2), low rise multi-unit residential building, with a 2-level 1,600 m^2 (17,000 ft^2) parkade. The archetype has hydronic in-floor radiant heating, connected to the district energy system. The archetype has in-suite minimum efficiency HRVs, and a constant volume make-up air unit supply tempered air for corridor pressurization. This archetype does not have a mechanical cooling system. Domestic hot water is heated by district heating.			
	Units	Baseline	Notes & References
ARCHITECTURAL			
Storeys	-	Residential: 6 Parkade: 2	
Breakdown of Space Type	-	48 Suites Corridors Parkade	
Gross Floor Area	m^2 (ft^2)	4,700 (50,600)	
Average Suite Size	m^2 (ft^2)	88 (950)	
Shading	-	Interior blinds	
BUILDING ENCLOSURE			
Exterior Walls – Above Grade – RSI-Value (R-value)	m^2K/W (hr-sf^2-F/Btu)	RSI-2.75 (R-15.6)	ASHRAE 90.1-2010 CZ4 Residential Wood-Framed
Floors – Above Parkade – RSI-Value (R-value)	m^2K/W (hr-sf^2-F/Btu)	RSI-0.53 (R-3.0)	Based on 6” concrete, uninsulated
Roofs – RSI-Value (R-value)	m^2K/W (hr-sf^2-F/Btu)	RSI-3.66 (R-20.8)	ASHRAE 90.1-2010 CZ4 Residential Insulation Above Deck
Infiltration Rate	L/s/m^2 @ 50Pa	0.20	City of Vancouver Energy Modelling Guideline v.2.0
Infiltration Schedule	-	Fractional	Always on
Window-to-Wall Ratio (WWR)	%	40	
Window – USI-Value (U-value)	W/m^2K (Btu/hr-sf^2-F)	USI-2.0 (U-0.35)	ASHRAE 90.1-2010 CZ4 Operable Window Residential Prescriptive Maximum. Non-metal framing.
Window – SHGC	-	0.36	ASHRAE 90.1-2016 CZ4 Residential Prescriptive Maximum.
MECHANICAL SYSTEMS			
MAKE-UP AIR UNIT			
Supply Air Temperature	˚C	18	Tempering Only
Flow rate	cfm (m^3/s)	1200 (0.57)	25 cfm/door
Outdoor Air Volume Control	-	100% Outdoor Air	
Fan Type	-	Constant Air Volume	
Fan Power	W/cfm	0.76	
Economizer	-	None	
Heating Type	-	District Energy	
Schedule	-	Always On	

SUITE VENTILATION			
Heat Recovery Ventilator			
Flow Rate	cfm/suite (m³/s/suite)	65 (0.031)	15 cfm/person (living area), 20 cfm/bathroom (continuous) ASHRAE 62.1-2001. Assumed 3 ppl/suite + 1 bathroom
Fan total Efficiency	%	60%	
Fan Pressure Rise	Pa	1258	
Fan Power	W/cfm	1.0	
Heat Recovery Effectiveness	%	60%	
Schedule	-	Always On	
Intermittent kitchen exhaust fan			
Flow Rate	cfm/suite (m³/s/suite)	100 (0.047)	ASHRAE 62.1 2001
Fan Total Efficiency	%	60%	
Fan Pressure Rise	Pa	445	
Fan Power	W/cfm	0.35	
Fan Schedule	-	7-8am 5-6m	
PARKADE VENTILATION			
Flow Rate	l/s/m²	3.7	ASHRAE 62.1 2001
Fan Total Efficiency	%	60%	
Fan Pressure Rise	Pa	254	
Fan Power	W/cfm	0.2	
Fan Schedule	-	4 hrs per day	
HEATING/COOLING DISTRIBUTION			
Heating Distribution	-	In-floor radiant heating	
Design Heating Capacity	W	Autosized	
Supply Temperature	°C	36	
Pump Power	W/gpm	19	ASHRAE 90.1-2010
DOMESTIC HOT WATER			
Heating Source	-	District Energy	
DHW Load	l/s/person	0.0016	City of Vancouver Energy Modelling Guideline
Supply Temperature	°C	60	
Storage Tank	-	Autosized	
Pumping	-	Variable Speed Pumps	
Pump Power	W/gpm	20	
OPERATION			
LIGHTING			
Lighting Power Density – Suites	W/m²	5	City of Vancouver Energy Modelling Guideline

Schedule - Suites	-	NECB 2011 Schedule G	
Lighting Power Density – Corridor	W/m²	8.4	NECB 2011
Schedule – Corridor	-	Always On	
Lighting Power Density – Parkade	W/m²	1.8	ASHRAE 90.1-2010
Lighting Controls – Parkade	-	10% LPD Reduction	ASHRAE 90.1-2010 9.4.1.3
Schedule - Parkade	-	Always On	
PROCESS LOADS			
Plug Loads – Suites	W/m²	5	City of Vancouver Energy Modelling Guidelines
Schedule	-	NECB 2011 Schedule G	
Elevator Load	-	2 @ 3kW	3 kW per elevator (City of Vancouver Energy Modelling Guideline), assumed 2 elevators.
Elevator Schedule	-	BC Hydro Elevator Schedule	
OCCUPANCY			
Occupancy Density - Suites	m²/person	29.3	2 ppl for the 1st bedroom, 1 additional person for each bedroom thereafter (City of Vancouver Energy Modelling Guideline). Assumed 3 ppl per typical suite
Occupancy Schedule – Suites	-	NECB 2011 Schedule G	
Occupancy Density - Corridor	m²/person	100	NECB 2011
Occupancy Schedule – Corridor	-	NECB 2011 Schedule G	
Occupancy Density - Parkade	m²/person	1,000	NECB 2011
Occupancy Schedule – Parkade	-	NECB 2011 Schedule H	

TABLE A.2 MODEL INPUTS FOR HIGH RISE NEW BUILDING BASLEINE			
GENERAL DESCRIPTION			
This archetype is a high rise multi-unit residential complex with townhouses. The archetype consists of a 22-storey, 24,100 m^2 (260,000 ft^2) high rise multi-unit residential building, and sixteen 2-storey, 150 m^2 (1,600 ft^2) townhouses built on an 8,430 m^2 (90,000 ft^2) two-level parkade. Suite fan coil units provide heating, cooling. The archetype has in-suite minimum efficiency HRVs, tempered air is provided by a make-up air unit to pressurize the corridors. Domestic hot water is heated by district heating.			
	Units	Baseline	Notes & References
ARCHITECTURAL			
Storeys	-	Tower: 22 Townhouse: 2 Parkade: 2	
Breakdown of Space Type	-	Tower Suites Tower Corridors Townhouse Parkade	
Gross Floor Area	m^2 (ft^2)	25,000 (270,000)	
Average Suite Size	m^2 (ft^2)	Tower: 80 (850) Townhouse: 150 (1,600)	
Shading	-	Interior blinds	
BUILDING ENCLOSURE			
Exterior Walls – Above Grade – RSI-Value (R-value)	m^2K/W (hr-sf^2-F/Btu)	RSI-2.75 (R-15.6)	Spandrel panels. Note performance below ASHRAE 90.1-2010 prescriptive value is trade off when model includes HRVs
Floors – Above Parkade – RSI-Value (R-value)	m^2K/W (hr-sf^2-F/Btu)	RSI-0.53 (R-3.0)	Based on 6" concrete, uninsulated
Roofs – RSI-Value (R-value)	m^2K/W (hr-sf^2-F/Btu)	RSI-3.66 (R-20.8)	ASHRAE 90.1-2010 CZ4 Residential Insulation Above Deck
Infiltration Rate	L/s/m^2 @ 50Pa	0.20	City of Vancouver Energy Modelling Guideline v.2.0
Infiltration Schedule	-	Fractional	Always on
Window-to-Wall Ratio (WWR)	%	55	
Window – USI-Value (U-value)	W/m^2K (Btu/hr-sf^2-F)	USI-2.61 (U-0.46)	ASHRAE 90.1-2010 CZ4 Operable Window Residential Prescriptive Maximum. Metal framing.
Window – SHGC	-	0.36	ASHRAE 90.1-2016 CZ4 Residential Prescriptive Maximum
MECHANICAL SYSTEMS			
MAKE-UP AIR UNIT			
Supply Air Temperature	˚C	18	Tempering Only
Flow rate	cfm (m^3/s)	5,500 (2.6)	25 cfm/door
Outdoor Air Volume Control	-	100% Outdoor Air	
Fan Type	-	Constant Air Volume	
Fan Power	W/cfm	0.76	
Economizer	-	None	

Heating Type	-	District Energy	
Cooling Type	-	Water cooled chilled	
Schedule	-	Always On	
SUITE VENTILATION			
Heat Recovery Ventilator			
Flow Rate	cfm/suite (m^3/s/suite)	Tower: 65 (0.031) Townhouse: 100 (0.047)	15 cfm/person (living area), 20 cfm/bathroom (continuous) ASHRAE 62.1-2001. Assumed 3 ppl/suite + 1 bathroom for tower, and 4 ppl/suite + 2 bathrooms for townhouse
Fan total Efficiency	%	60%	
Fan Pressure Rise	Pa	1258	
Fan Power	W/cfm	1.0	
Heat Recovery Effectiveness	%	60%	
Schedule	-	Always On	
Intermittent kitchen exhaust fan			
Flow Rate	cfm/suite (m^3/s/suite)	100 (0.047)	ASHRAE 62.1 2001
Fan Total Efficiency	%	60%	
Fan Pressure Rise	Pa	445	
Fan Power	W/cfm	0.35	
Fan Schedule	-	7-8am 5-6m	
PARKADE VENTILATION			
Flow Rate	$l/s/m^2$	3.7	ASHRAE 62.1 2001
Fan Total Efficiency	%	60%	
Fan Pressure Rise	Pa	254	
Fan Power	W/cfm	0.2	
Fan Schedule	-	4 hrs per day	
HEATING/COOLING DISTRIBUTION			
Heating/Cooling Distribution	-	Suite fan coil units	
Design Heating Capacity	W	Autosized	
Fan Power	W/cfm	0.3	
DOMESTIC HOT WATER			
Heating Source	-	District Energy	
DHW Load	l/s/person	0.0016	City of Vancouver Energy Modelling Guideline
Supply Temperature	°C	60	
Storage Tank	-	Autosized	
Pumping	-	Variable Speed Pumps	

Pump Power	W/gpm	20	
OPERATION			
LIGHTING			
Lighting Power Density – Suites	W/m²	5	City of Vancouver Energy Modelling Guideline
Schedule - Suites	-	NECB 2011 Schedule G	
Lighting Power Density – Corridor	W/m²	8.4	NECB 2011
Schedule – Corridor	-	Always On	
Lighting Power Density – Parkade	W/m²	1.8	ASHRAE 90.1-2010
Lighting Controls – Parkade	-	10% LPD Reduction	ASHRAE 90.1-2010 9.4.1.3
Schedule - Parkade	-	Always On	
PROCESS LOADS			
Plug Loads – Suites	W/m²	5	City of Vancouver Energy Modelling Guidelines
Schedule	-	NECB 2011 Schedule G	
Elevator Load	-	2 @ 3kW	3 kW per elevator (City of Vancouver Energy Modelling Guideline), assumed 2 elevators.
Elevator Schedule	-	BC Hydro Elevator Schedule	
OCCUPANCY			
Occupancy Density - Suites	m²/person	Tower: 34.95 Townhouse: 59.46	2 ppl for the 1st bedroom, 1 additional person for each bedroom thereafter (City of Vancouver Energy Modelling Guideline). Assumed 3 ppl per typical tower suite, and 4 ppl per typical townhouse unit
Occupancy Schedule – Suites	-	NECB 2011 Schedule G	
Occupancy Density - Corridor	m²/person	100	NECB 2011
Occupancy Schedule – Corridor	-	NECB 2011 Schedule G	
Occupancy Density - Parkade	m²/person	1,000	NECB 2011
Occupancy Schedule – Parkade	-	NECB 2011 Schedule H	

TABLE A.3 MODEL INPUTS FOR LOW RISE EXISTING BUILDING BASLEINE			
GENERAL DESCRIPTION			
This archetype is a 4-storey wood frame multi-unit residential building with assemblies, and systems typical of the 1980s to 1990s. The proposed archetype characteristics are based on a previous existing building study carried out by RDH[1]. The building enclosure consists of 2x4 wood framing with batt insulation, with an overall effective wall R-value of R-11. The windows are double-glazed with non-thermally broken aluminum frames (U-0.62, SHGC-0.66). The suites are heated bye electric baseboards. Ventilation is provided by make-up air unit to pressurize the corridor, with occupant-controlled bathroom and kitchen exhaust fans in suites.			
	Units	Baseline	Notes & References
ARCHITECTURAL			
Storeys	-	Residential: 4 Parkade: 2	
Breakdown of Space Type	-	32 Suites Corridors Parkade	
Gross Floor Area	m^2 (ft^2)	3,100 (33,700)	
Average Suite Size	m^2 (ft^2)	88 (950)	
Shading	-	Interior blinds	
BUILDING ENCLOSURE			
Exterior Walls – Above Grade – RSI-Value (R-value)	m^2K/W (hr-sf²-F/Btu)	RSI-1.9 (R-11)	Based on 2x4 wood framing with batt insulation and balconies
Floors – Above Parkade – RSI-Value (R-value)	m^2K/W (hr-sf²-F/Btu)	RSI-1.8 (R-10)	Based on 6" concrete with 2" insulation
Roofs – RSI-Value (R-value)	m^2K/W (hr-sf²-F/Btu)	RSI-3.3 (R-19)	Based on R-20 batt in low-slope roof
Infiltration Rate	L/s/m² @ 50Pa	0.78	
Infiltration Schedule	-	Always On	
Window-to-Wall Ratio (WWR)	%	30	
Window – USI-Value (U-value)	W/m^2K (Btu/hr-sf²-F)	USI-3.5 (U-0.62)	Operable windows. Double glazed, non-thermally broken aluminum frames.
Window – SHGC	-	0.66	No low-e coating
MECHANICAL SYSTEMS			
MAKE-UP AIR UNIT			
Supply Air Temperature	˚C	18	Tempering Only
Flow rate	cfm (m^3/s)	2,080 (0.98)	20 cfm/door to supply corridors, 45 cfm/door to supply suites
Outdoor Air Volume Control	-	100% Outdoor Air	
Fan Type	-	Constant Air Volume	
Fan Power	W/cfm	0.76	
Economizer	-	None	
Heating Type	-	Electric	
Schedule	-	Always On	
SUITE VENTILATION			

Intermittent suite exhaust			
Flow Rate	cfm/suite (m^3/s/suite)	150 (0.071)	100 cfm kitchen, 50 cfm bathroom (ASHRAE 62.1 2001)
Fan Total Efficiency	%	60%	
Fan Pressure Rise	Pa	445	
Fan Power	W/cfm	0.35	
Fan Schedule	-	7-8am 5-6m	
PARKADE VENTILATION			
Flow Rate	l/s/m²	3.7	ASHRAE 62.1 2001
Fan Total Efficiency	%	60%	
Fan Pressure Rise	Pa	254	
Fan Power	W/cfm	0.2	
Fan Schedule	-	4 hrs per day	
HEATING/COOLING DISTRIBUTION			
Heating Distribution	-	Electric baseboards	
Design Heating Capacity	W	Autosized	
DOMESTIC HOT WATER			
Heating Source	-	District Energy	
DHW Load	l/s/person	0.0016	City of Vancouver Energy Modelling Guideline
Supply Temperature	°C	60	
Storage Tank	-	Autosized	
Pumping	-	Variable Speed Pumps	
Pump Power	W/gpm	20	
OPERATION			
LIGHTING			
Lighting Power Density – Suites	W/m²	5	City of Vancouver Energy Modelling Guideline
Schedule - Suites	-	NECB 2011 Schedule G	
Lighting Power Density – Corridor	W/m²	8.4	NECB 2011
Schedule – Corridor	-	Always On	
Lighting Power Density – Parkade	W/m²	1.8	ASHRAE 90.1-2010
Lighting Controls – Parkade	-	10% LPD Reduction	ASHRAE 90.1-2010 9.4.1.3
Schedule - Parkade	-	Always On	
PROCESS LOADS			
Plug Loads – Suites	W/m²	5	City of Vancouver Energy Modelling Guidelines

[1] Phase II Strata Energy Study; report prepared for City of Vancouver by RDH, September 2017.

Schedule	-	NECB 2011 Schedule G	
Elevator Load	-	2 @ 3kW	3 kW per elevator (City of Vancouver Energy Modelling Guideline), assumed 2 elevators.
Elevator Schedule	-	BC Hydro Elevator Schedule	
OCCUPANCY			
Occupancy Density - Suites	m²/person	29.3	2 ppl for the 1st bedroom, 1 additional person for each bedroom thereafter (City of Vancouver Energy Modelling Guideline). Assumed 3 ppl per typical suite
Occupancy Schedule – Suites	-	NECB 2011 Schedule G	
Occupancy Density - Corridor	m²/person	100	NECB 2011
Occupancy Schedule – Corridor	-	NECB 2011 Schedule G	
Occupancy Density - Parkade	m²/person	1,000	NECB 2011
Occupancy Schedule – Parkade	-	NECB 2011 Schedule H	

TABLE A.4 MODEL INPUTS FOR HIGH RISE EXISTING BUILDING BASLEINE			
GENERAL DESCRIPTION			
The high rise existing building is a 13-storey multi-unit high rise residential building constructed in the 1980s to 1990s. The proposed archetype characteristics are based on a previous existing building study carried out by RDH[2]. The building enclosure consist of steel stud walls with uninsulated slab edges with an overall effective wall R-value of R-3. The windows are double glazed, non-thermally broken aluminum frames (U-0.62, SHGC-0.66). The suites are heated by electric baseboards. Ventilation is provided by a make-up air unit to pressurize the corridors, with occupant-controlled bathroom and kitchen exhaust fans in suites			
	Units	Baseline	Notes & References
ARCHITECTURAL			
Storeys	-	Tower: 13 Townhouse: 2 Parkade: 2	
Breakdown of Space Type	-	Tower Suites Tower Corridors Townhouse Parkade	
Gross Floor Area	m^2 (ft^2)	3,100 (33,700)	
Average Suite Size	m^2 (ft^2)	88 (950)	
Shading	-	Interior blinds	
BUILDING ENCLOSURE			
Exterior Walls – Above Grade – RSI-Value (R-value)	m^2K/W (hr-sf²-F/Btu)	RSI-0.53 (R-3.0)	Steel stud walls with uninsulated slab edges
Floors – Above Parkade – RSI-Value (R-value)	m^2K/W (hr-sf²-F/Btu)	RSI-0.53 (R-3.0)	Based on 6" concrete, uninsulated
Roofs – RSI-Value (R-value)	m^2K/W (hr-sf²-F/Btu)	RSI-1.7 (R-9.5)	Based on 1.5" rigid foam
Infiltration Rate	L/s/m² @ 50Pa	0.78	
Infiltration Schedule	-	Always On	
Window-to-Wall Ratio (WWR)	%	60	
Window – USI-Value (U-value)	W/m^2K (Btu/hr-sf²-F)	USI-3.5 (U-0.62)	Operable windows. Double glazed, non-thermally broken aluminum frames.
Window – SHGC	-	0.66	No low-e coating
MECHANICAL SYSTEMS			
MAKE-UP AIR UNIT			
Supply Air Temperature	˚C	18	Tempering Only
Flow rate	cfm (m^3/s)	9,450 (4.46)	20 cfm/door to supply corridors, 45 cfm/door to supply tower suites and 100 cfm/door to supply townhouse units
Outdoor Air Volume Control	-	100% Outdoor Air	
Fan Type	-	Constant Air Volume	
Fan Power	W/cfm	0.76	
Economizer	-	None	
Heating Type	-	Electric	

Schedule	-	Always On	
SUITE VENTILATION			
Intermittent suite exhaust			
Flow Rate	cfm/suite (m^3/s/suite)	150 (0.071)	100 cfm kitchen, 50 cfm bathroom (ASHRAE 62.1 2001)
Fan Total Efficiency	%	60%	
Fan Pressure Rise	Pa	445	
Fan Power	W/cfm	0.35	
Fan Schedule	-	7-8am 5-6m	
PARKADE VENTILATION			
Flow Rate	l/s/m²	3.7	ASHRAE 62.1 2001
Fan Total Efficiency	%	60%	
Fan Pressure Rise	Pa	254	
Fan Power	W/cfm	0.2	
Fan Schedule	-	4 hrs per day	
HEATING/COOLING DISTRIBUTION			
Heating Distribution	-	Electric baseboards	
Design Heating Capacity	W	Autosized	
DOMESTIC HOT WATER			
Heating Source	-	District Energy	
DHW Load	l/s/person	0.0016	City of Vancouver Energy Modelling Guideline
Supply Temperature	°C	60	
Storage Tank	-	Autosized	
Pumping	-	Variable Speed Pumps	
Pump Power	W/gpm	20	
OPERATION			
LIGHTING			
Lighting Power Density – Suites	W/m²	5	City of Vancouver Energy Modelling Guideline
Schedule - Suites	-	NECB 2011 Schedule G	
Lighting Power Density – Corridor	W/m²	8.4	NECB 2011
Schedule – Corridor	-	Always On	
Lighting Power Density – Parkade	W/m²	1.8	ASHRAE 90.1-2010
Lighting Controls – Parkade	-	10% LPD Reduction	ASHRAE 90.1-2010 9.4.1.3
Schedule - Parkade	-	Always On	

[2] Exploring Options for 80% GHG Reductions in Downtown Buildings; report prepared for City of Vancouver by RDH, March 2017.

PROCESS LOADS			
Plug Loads – Suites	W/m²	5	City of Vancouver Energy Modelling Guidelines
Schedule	-	NECB 2011 Schedule G	
Elevator Load	-	2 @ 3kW	3 kW per elevator (City of Vancouver Energy Modelling Guideline), assumed 2 elevators.
Elevator Schedule	-	BC Hydro Elevator Schedule	
OCCUPANCY			
Occupancy Density - Suites	m²/person	Tower: 26.7 Townhouse: 37.5	2 ppl for the 1st bedroom, 1 additional person for each bedroom thereafter (City of Vancouver Energy Modelling Guideline). Assumed 3 ppl per typical tower suite, and 4 ppl per typical townhouse unit
Occupancy Schedule – Suites	-	NECB 2011 Schedule G	
Occupancy Density - Corridor	m²/person	100	NECB 2011
Occupancy Schedule – Corridor	-	NECB 2011 Schedule G	
Occupancy Density - Parkade	m²/person	1,000	NECB 2011
Occupancy Schedule – Parkade	-	NECB 2011 Schedule H	

Appendix B

Climate Adaptation and Mitigation Measures

TABLE B.1 MODELLED CLIMATE ADAPTATION + MITIGATION MEASURES FOR THE LOW RISE NEW BUILDING ARCHETYPE

GENERAL DESCRIPTION

This table describes the model assumptions for the CAMMs for the low rise new building archetype.

MEASURE	DESCRIPTION
Reduced Window to Wall Ratio	Modelled 30% WWR
Operable Shading	Modelled operable exterior shades for all windows facing east, west and south. The shades are controlled based on interior temperature, with a setpoint of 22°C. The shares are modelled as slatted blinds positioned at a 45° angle, covering the whole window.
Fixed Shading	Modelled 1m overhangs on east-, south-, and west-facing façade.
Reduced SHGC	Modelled SHGC of 0.28. No change to U-value.
Dynamic Glazing	Installation of double pane dynamic glazing. A SHGC of 0.40 was modelled during heating season, and 0.20 during cooling season, U-value of 1.7 W/m²K.
Improved Window Thermal Performance	Modelled U-value of 0.8 W/m²K for individual CAMM analysis, and Step 4 bundles.
Improved Wall Thermal Performance	Improved wall thermal performance to meet Step 4, modelled effective R-value of 27 hr-sf²-F/Btu.
Improved Roof Thermal Performance	Improved roof thermal performance to meet Step 4, modelled effective R-value of 40 hr-sf²-F/Btu.
HRV with bypass and boosted flow rate as needed	High efficiency HRV (85%) that can operate in boost and bypass mode as needed, corridor pressurization.
HRV with bypass and boosted flow rate as needed, and cooling coil in ventilation system	High efficiency HRV (85%) that can operate in boost and bypass mode as needed, plus a DX cooling coil (SCOP of 2.6) downstream of the HRV, corridor pressurization.
Full mechanical cooling	Air source heat pump providing heating and cooling via hydronic FCUs (SCOP-3.2).

TABLE B.2 MODELLED CLIMATE ADAPTATION + MITIGATION MEASURES FOR THE HIGH RISE NEW BUILDING ARCHETYPE	
GENERAL DESCRIPTION	
This table describes the model assumptions for the CAMMs for the high rise new building archetype.	
MEASURE	**DESCRIPTION**
Reduced Window to Wall Ratio	Modelled 30% WWR
Operable Shading	Modelled operable exterior shades for all windows facing east, west and south. The shades are controlled based on interior temperature, with a setpoint of 22˚C. The shares are modelled as slatted blinds positioned at a 45˚ angle, covering the whole window.
Fixed Shading	Modelled 1m overhangs on east-, south-, and west-facing façade.
Reduced SHGC	Modelled SHGC of 0.28. No change to U-value.
Dynamic Glazing	Installation of double pane dynamic glazing. A SHGC of 0.40 was modelled during heating season, and 0.20 during cooling season, U-value of 1.7 W/m^2K.
Improved Window Thermal Performance	Modelled U-value of U-1.8 W/m^2k for Step 3 bundles, and U-value of 1.14 W/m^2K for Step 4 bundles and individual CAMM analysis.
Improved Wall Thermal Performance	Improved wall thermal performance to meet Step 4 targets, modelled effective R-value of 15.6 $hr\text{-}sf^2\text{-}F/Btu$
Improved Roof Thermal Performance	Improved roof thermal performance to meet Step 4, modelled effective R-value of 40 $hr\text{-}sf^2\text{-}F/Btu$.

TABLE B.3 MODELLED CLIMATE ADAPTATION + MITIGATION MEASURES FOR THE LOW RISE EXISTING BUILDING ARCHETYPE

GENERAL DESCRIPTION

This table describes the model assumptions for the CAMMs for the low rise existing building archetype.

MEASURE	DESCRIPTION
Operable Shading	Modelled operable exterior shades for all windows facing east, west and south. The shades are controlled based on interior temperature, with a setpoint of 22˚C. The shares are modelled as slatted blinds positioned at a 45˚ angle, covering the whole window.
Fixed Shading	Modelled 1m overhangs on east-, south-, and west-facing façade.
Reduced SHGC	Reduced SHGC to 0.28. Modelled to show the impact of a reduced SHGC, only applicable in the case of window upgrade.
Dynamic Glazing	Window replacement to double pane dynamic glazing. A SHGC of 0.40 was modelled during heating season, and 0.20 during cooling season, U-value of 1.7 W/m²K.
Improved Window Performance	Window replacement to a code minimum non-aluminum frame window; USI-1.1 W/m²K, SHGC-0.36
Improved Wall Thermal Performance	Improved wall thermal performance by adding exterior insulation during an enclosure upgrade, modelled effective R-value of 27 hr-sf²-F/Btu.
Improved Roof Thermal Performance	Improved roof thermal performance by adding insulation during a roof upgrade, modelled effective R-value of 40 hr-sf²-F/Btu.
HRV with bypass and boosted flow rate as needed	Installation of high efficiency HRV (85%) that can operate in boost and bypass mode as needed, corridor pressurization.
HRV with bypass and boosted flow rate as needed, and cooling coil in ventilation system	High efficiency HRV (85%) that can operate in boost and bypass mode as needed, plus a DX cooling coil (SCOP of 2.6) downstream of the HRV, corridor pressurization.
Full mechanical cooling	Assumed ductless in-suite air source heat pump providing heating and cooling (SCOP-2.9).

TABLE B.4 MODELLED CLIMATE ADAPTATION + MITIGATION MEASURES FOR THE HIGH RISE EXISTING BUILDING ARCHETYPE	
GENERAL DESCRIPTION	
This table describes the model assumptions for the CAMMs for the high rise existing building archetype.	
MEASURE	**DESCRIPTION**
Operable Shading	Modelled operable exterior shades for all windows facing east, west and south. The shades are controlled based on interior temperature, with a setpoint of 22˚C. The shares are modelled as slatted blinds positioned at a 45˚ angle, covering the whole window.
Fixed Shading	Modelled 1m overhangs on east-, south-, and west-facing façade.
Reduced SHGC	Reduced SHGC to 0.28. Modelled to show the impact of a reduced SHGC, only applicable in the case of window upgrade.
Dynamic Glazing	Window replacement to double pane dynamic glazing. A SHGC of 0.40 was modelled during heating season, and 0.20 during cooling season, U-value of 1.7 W/m^2K.
Improved Window Performance	Window replacement to a code minimum non-aluminum frame window; USI-1.1 W/m^2K, SHGC-0.36
Improved Wall Thermal Performance	Improved wall thermal performance by adding exterior insulation during an enclosure upgrade, modelled effective R-value of 13 hr-sf^2-F/Btu.
Improved Roof Thermal Performance	Improved roof thermal performance by adding insulation during a roof upgrade, modelled effective R-value of 20 hr-sf^2-F/Btu.
HRV with bypass and boosted flow rate as needed	Installation of high efficiency HRV (85%) that can operate in boost and bypass mode as needed, corridor pressurization.
HRV with bypass and boosted flow rate as needed, and cooling coil in ventilation system	High efficiency HRV (85%) that can operate in boost and bypass mode as needed, plus a DX cooling coil (SCOP of 2.6) downstream of the HRV, corridor pressurization.
Full mechanical cooling	Assumed ductless in-suite air source heat pump providing heating and cooling (SCOP-2.9).

Appendix C

Costing Analysis Results

TABLE C.1 TOTAL INCREMENTAL COST RESULTS FOR LOW RISE NEW BUILDING CLIMATE ADAPTATION + MITIGATION MEASURES AND BUNDLES			
	Incremental Capital Cost ($/m² floor area)		
	Low	Mean	High
Climate Adaptation + Mitigation Measures (Based on Step 3 baseline archetype)			
Reduced Window to Wall Ratio	-15	-19	-23
Operable Shading	60	85	108
Fixed Shading	70	106	142
Reduced SHGC	0	0	0
Dynamic Glazing	81	104	128
Improved Window Thermal Performance	12	15	20
Improved Wall Thermal Performance	11	13	16
Improved Roof Thermal Performance	7	12	17
HRV with bypass and boosted flow rate as needed	20	26	30
HRV with bypass and boosted flow rate as needed, and cooling coil in ventilation system	51	64	77
Full mechanical cooling	1	-1	-3
Step 3 Bundles			
Bundle 1	38	62	85
Bundle 2	60	85	108
Bundle 3	111	149	185
Bundle 4	60	83	106
Step 4 Bundles			
Bundle 1	36	57	79
Bundle 2	60	85	108
Bundle 3	89	123	155
Bundle 4	60	83	106

TABLE C.2 ANNUAL ENERGY COST AND SAVINGS FOR THE LOW RISE NEW BUILDING					
Step 3 low rise new building archetype					
	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
Annual energy cost ($/m² floor area)	9.9	9.9	9.9	10.4	11.8
Energy cost savings compared to baseline (%)	-	0%	0%	-5%	-19%
Step 4 low rise new building archetype					
	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
Annual energy cost ($/m² floor area)	9.5	9.5	9.5	9.9	11.1
Energy cost savings compared to baseline (%)	-	0%	0%	-4%	-16%

TABLE C.3 TOTAL INCREMENTAL COST RESULTS FOR HIGH RISE NEW BUILDING CLIMATE ADAPTATION + MITIGATION MEASURES AND BUNDLES			
	Incremental Capital Cost ($/m² floor area)		
	Low	Mean	High
Climate Adaptation + Mitigation Measures (Based on Step 2 archetype)			
Reduced Window to Wall Ratio	-4	-5	-7
Operable Shading	41	79	113
Fixed Shading	109	166	219
Reduced SHGC	0	0	0
Dynamic Glazing	79	102	124
Improved Window Thermal Performance	20	25	29
Improved Wall Thermal Performance	20	25	30
Improved Roof Thermal Performance	10	18	25
Step 3 Bundles			
Bundle 1 (Step 3)	72	109	143
Bundle 2 (Step 3)	64	102	143
Step 4 Bundles			
Bundle 1 (Step 4)	102	143	185
Bundle 2 (Step 4)	83	128	173

TABLE C.4 ANNUAL ENERGY COST AND SAVINGS FOR THE HIGH RISE NEW BUILDING			
Step 3 high rise new building archetype			
	Baseline	Bundle 1	Bundle 2
Annual energy cost ($/m² floor area)	11.3	10.8	11.1
Energy cost savings compared to baseline (%)	-	4%	1%
Step 4 high rise new building archetype			
	Baseline	Bundle 1	Bundle 2
Annual energy cost ($/m² floor area)	10.4	9.6	10.2
Energy cost savings compared to baseline (%)	-	8%	2%

TABLE C.5 TOTAL INCREMENTAL COST RESULTS FOR LOW RISE EXISTING BUILDING CLIMATE ADAPTATION + MITIGATION MEASURES AND BUNDLES

	Incremental Capital Cost ($/m² floor area)		
	Low	Mean	High
Climate Adaptation + Mitigation Measures			
Operable Shading	45	64	83
Fixed Shading	54	80	108
Reduced SHGC	0	0	0
Dynamic Glazing	61	80	96
Improved Window Thermal Performance	9	11	15
Improved Wall Thermal Performance	17	26	35
Improved Roof Thermal Performance	11	12	13
HRV with bypass and boosted flow rate as needed	61	80	102
HRV with bypass and boosted flow rate as needed, and cooling coil in ventilation system	93	118	147
Full Mechanical Cooling - Ductless	99	124	150
Bundles			
Bundle 2	54	73	96
Bundle 4	70	99	131
Bundle 5	172	236	306
Bundle 6	137	182	230
Bundle 7	144	188	230

TABLE C.6 ANNUAL ENERGY COST AND SAVINGS FOR THE LOW RISE EXISTING BUILDING

	Baseline	Bundle 2	Bundle 4	Bundle 5	Bundle 6	Bundle 7
Annual energy cost ($/m² floor area)	15.6	14.4	12.2	13.1	16.2	13.7
Energy cost savings compared to baseline (%)	-	8%	22%	16%	-4%	12%

TABLE C.7 TOTAL INCREMENTAL COST RESULTS FOR HIGH RISE EXISTING BUILDING CLIMATE ADAPTATION + MITIGATION MEASURES AND BUNDLES			
	Incremental Capital Cost ($/m² floor area)		
	Low	Mean	High
Climate Adaptation + Mitigation Measures			
Operable Shading	66	90	114
Fixed Shading	96	144	192
Reduced SHGC	0	0	0
Dynamic Glazing	84	114	138
Improved Window Thermal Performance	13	16	21
Improved Wall Thermal Performance	13	13	15
Improved Roof Thermal Performance	23	31	27
HRV with bypass and boosted flow rate as needed	50	66	84
HRV with bypass and boosted flow rate as needed, and cooling coil in ventilation system	78	96	120
Full Mechanical Cooling - Ductless	78	96	114
Bundles			
Bundle 5	198	270	348
Bundle 7	138	186	228

TABLE C.8 ANNUAL ENERGY COST AND SAVINGS FOR THE HIGH RISE EXISTING BUILDING			
	Baseline	Bundle 5	Bundle 7
Annual energy cost ($/m² floor area)	15.7	15.5	12.8
Energy cost savings compared to baseline (%)	-	1%	18%

Appendix D

Alternate Baseline Modelling Results – New Building Low Rise

Alternate Baseline Modelling Results – New Building Low Rise

Background

The new building low rise baseline is heated via in-floor hydronic heating with district energy connection (no cooling). This system choice aligns with typical new construction at the University of British Columbia (UBC); however, this system choice is less common in other areas of the Lower Mainland. This additional analysis was therefore completed to understand the impact and cost associated with the Climate Adaptation and Mitigation Measures (CAMMs) for a low rise new archetype compared to a more common baseline heating system.

The additional analysis includes assessing the impact of the CAMM Bundles on the GHG and energy metrics, and completing the financial analysis for each CAMM Bundle. The analysis follows the methodology described in Section 2 of the main report, and the bundles described in Section 3.1.3 are modelled with the only difference being the heating system.

Archetype

The low rise new building baseline is a 6-storey wood frame multi-unit residential building with a 2-level below-grade parkade. The archetype in this additional analysis is heated via electric baseboards, while all other characteristics are unchanged, including complying with Step 3 of the BC ESC. The key building characteristics are summarized in Table D.1.

TABLE D.1 ALTERNATE BASELINE LOW RISE NEW BUILDING ARCHETYPE DESCRIPTION	
Floor Area	4,700 m² (approx. 51,000 ft²)
Number of stories	6
Enclosure	Wood frame with batt insulation (R_{eff}–15.6). Double glazed windows in non-metal frames (USI-1.8 [U-0.31], SHGC-0.36), 40% window to wall ratio.
HVAC	Heating provided via electric baseboards. Tempered outdoor air pressurizes the corridors. Outdoor air is provided via minimum efficiency (60%) in-suite HRV units with no by-pass. No mechanical cooling.
DHW	District energy connection[1]

Results

The energy, GHG, and annual energy cost results are summarized below for the Step 3 and Step 4 baselines and bundles, as well as the incremental capital cost associated with each bundle. The thermal

[1] District energy for domestic hot water is a possible system choice for UBC and other regions that have district energy, although central gas-fired boilers or in-suite electric hot water heaters are likely more prevalent across the Metro region. The district DHW option was used across all archetypes for simplicity. Other system choices would possibly impact the total energy consumption and GHGI but because none of the CAMMS modify the domestic hot water system, these choices would not alter the relative analysis in a meaningful way.

comfort results are not included in this appendix since they are unchanged compared to the original analysis (see Section 3.1.3 of the main report for thermal comfort results).

Step 3

As a reminder, the modelled bundles are summarized in Table D.2. Two passive bundles (Bundle 1 and Bundle 2), and two combined passive and active bundles (Bundle 3 and Bundle 4) were modelled. Bundle 3 includes "partial" cooling through the ventilation unit, whereas Bundle 4 consists of full mechanical cooling through an air source heat pump supplying in-suite fan-coil units. The measures included in the bundles are described in further detail in Appendix B.

TABLE D.2 MODELLED BUNDLES FOR STEP 3 LOW RISE NEW BUILDING ARCHETYPE

		Description
Passive	Step 3 – Bundle 1	→ Reduced WWR to 30% (from 40%) → Reduced SHGC to 0.28 (from 0.36) → Fixed shading
	Step 3 – Bundle 2	→ Reduced SHGC to 0.28 (from 0.36) → Operable shading
Combined	Step 3 – Bundle 3	→ High efficiency HRV with bypass, cooling coil and boost as needed → Reduced SHGC to 0.28 (from 0.36) → Operable shading
	Step 3 – Bundle 4	→ Full mechanical cooling → Reduced SHGC to 0.28 (from 0.36) → Operable shading

Energy and Emission Analysis

Table D.3 summarizes the energy and GHG results for the passive bundles for the Step 3 low rise new building archetype based on the RCP-8.5 2050s climate file. The passive bundles for the Step 3 archetype marginally exceed the 200-hour threshold based on the 2050s scenario; however, the energy and emission results for these bundles are still included since they are close to the limit and may still be viable solutions.

TABLE D.3 ENERGY AND GHG RESULTS FOR THE STEP 3 LOW RISE NEW BUILDING PASSIVE BUNDLES BASED ON THE RCP-8.5 2050S CLIMATE FILE			
	Baseline (Step 3)	Bundle 1	Bundle 2
TEUI (kWh/m²a)	103	102	103
TEDI (kWh/m²a)	19	18	19
Peak heating demand[1] (W/m²)	16	14	17
GHGI[2] (kgCO_2e/m²a)	3	3	3

[1]Peak heating demand on grid (accounts for system efficiency), see Table 2.5 of the main report for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

Table D.4 summarize the energy and GHG results for the combined bundles based on the RCP-8.5 2050s climate file. To quantify the impact of passive measures when combined with the active measures, the results for the individual active measures are included, i.e. the bundles without passive measures.

TABLE D.4 ENERGY AND GHG RESULTS FOR THE STEP 3 LOW RISE NEW BUILDING COMBINED BUNDLES BASED ON THE RCP-8.5 2050S CLIMATE FILE					
	Baseline (Step 3)	HRV with bypass, cooling coil, and boost as needed		Full mechanical cooling	
		Without passive measures	**With** passive measures (Bundle 3)	**Without** passive measures	**With** passive measures (Bundle 4)
TEUI (kWh/m²a)	103	103	103	109	104
TEDI (kWh/m²a)	19	13	13	19	19
CEDI (kWh/m²a)	n/a	9	8	16	12
TEDI + CEDI (kWh/m²a)	19	22	21	35	31
Peak heating demand[1] (W/m²)	16	12	12	6	6
Peak cooling demand[1] (W/m²)	n/a	10	7	9	6
Peak operative temperature (°C)	36	31	28	27	27
GHGI[2] (kgCO_2e/m²a)	3	3	3	3	3

[1]Peak heating/cooling demand on grid (accounts for system efficiency), see Table 2.5 of the main report for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

Compared to the hydronic low rise new building archetype with district energy connection for space heating, the total energy use intensity (TEUI) and peak heating demand results are slightly lower for the Step 3 baseline and bundles with electric baseboards. This is because the electric baseboards have a slightly higher modelled efficiency than the district energy connection.

The thermal energy demand intensity, TEDI, represents the heating demand for space conditioning and conditioning of ventilation air, and does not account for the system efficiency. Therefore, TEDI is unchanged compared to the hydronic low rise new building archetype.

Since the space heating is assumed to be all-electric in this analysis, the GHGI is slightly lower compared to the hydronic low rise new building archetype, due to the lower emission factor for electricity compared to the UBC district energy (see Table 2.7 in the main report).

Costing Analysis

This section summarizes the costing analysis of the Step 3 low rise new building bundles, including the incremental capital cost and annual energy cost.

Figure D.1 shows the incremental cost at the building level for the Step 3 bundles. To understand the cost-effectiveness of each bundle the incremental cost is shown together with the number of overheated hours based on the RCP-8.5 2050s climate file. The error bars illustrate the high and low bundle cost. The incremental bundle costs per floor area ($/m²) are summarized in Table D.5.

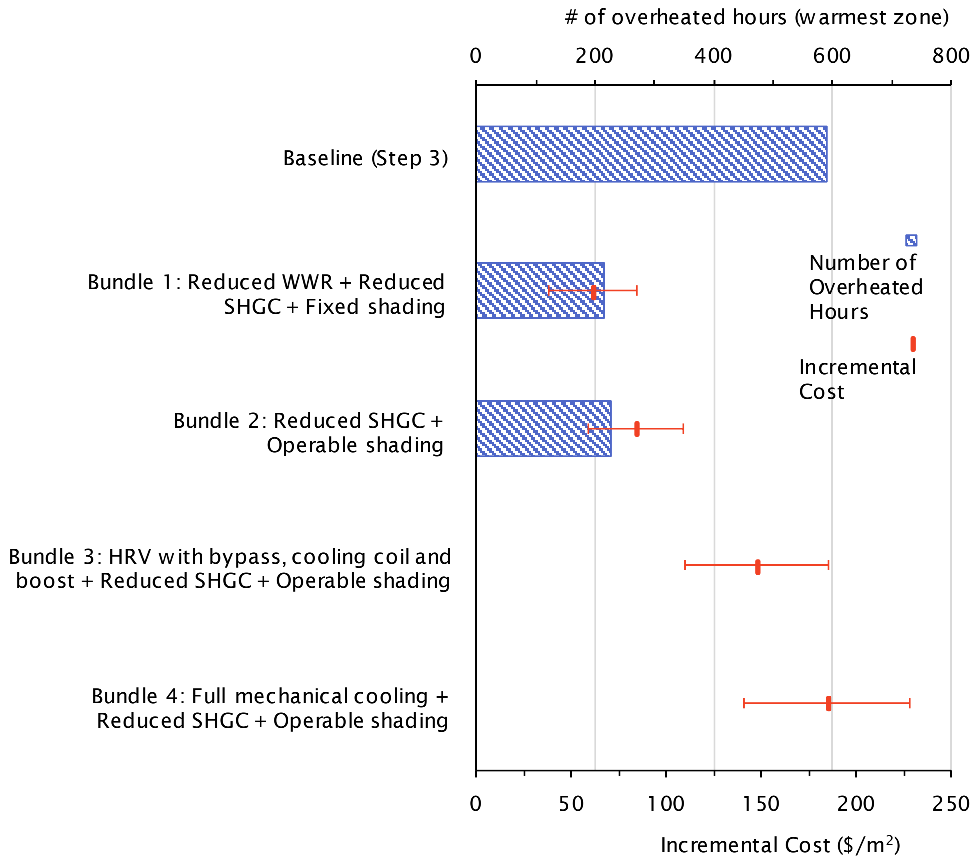

Figure D.1 Incremental cost ($/m²) for the Step 3 bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

TABLE D.5 INCREMENTAL COST FOR THE STEP 3 LOW RISE NEW BUILDING BUNDLES			
	Low	Mean	High
Bundle 1 ($/m²)	38	62	85
Bundle 2 ($/m²)	60	85	108
Bundle 3 ($/m²)	111	149	185
Bundle 4 ($/m²)	138	181	223

The incremental costs of Bundles 1 through 3 are unchanged compared to the hydronic archetype since the measures are independent of the heating system.

The full mechanical cooling measure included in Bundle 4 includes installation of air source heat pumps that provide both heating and cooling. Recall that the estimated incremental capital cost of switching the mechanical system from hydronic in-floor radiant heating to in-suite heat pumps was negligible. This additional analysis shows that the incremental capital cost of installing heat pumps compared to an electric baseboard baseline is significant, at approximately $140-220/m².

Figure D.2 shows the annual energy cost ($/m²) for the Step 3 baseline and bundles. Table D.6 summarizes the annual energy cost, and energy cost savings compared to the baseline for both the electric baseboard and hydronic archetype.

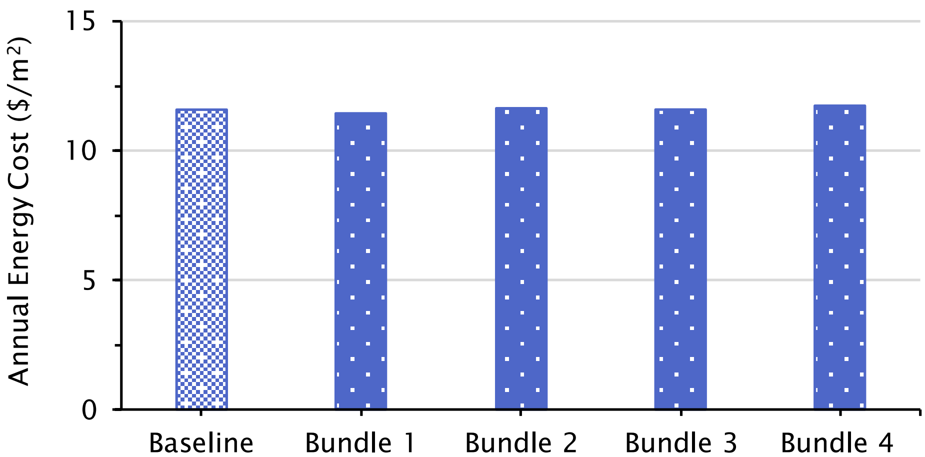

Figure D.2 Annual energy cost ($/m²) for the Step 3 baseline and bundles.

TABLE D.6 ANNUAL ENERGY COST AND COST SAVINGS COMPARED TO THE STEP 3 LOW RISE NEW BUILDING BASELINE					
	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
Electric baseboard archetype					
Annual energy cost ($/m²)	11.6	11.5	11.7	11.6	11.8
Energy Cost Savings (%)	-	1%	-1%	0%	-1%
Hydronic archetype (district energy connection)					
Annual energy cost ($/m²)	9.9	9.9	9.9	10.4	11.8
Energy Cost Savings (%)	-	0%	0%	-5%	-19%

The annual energy cost of the electric baseboard baseline is slightly higher than the hydronic archetype, due to the higher utility rate for electricity compared to district energy. The increase in annual energy cost for Bundle 4, from introducing full mechanical cooling, is higher for the in-floor radiant heating archetype than the electric baseboard archetype because the upgrade results in a fuel-switch from district energy to electricity for space heating.

The additional energy cost associated with introducing cooling in Bundle 3 and Bundle 4 for the electric baseboard archetype is similar to the reduction in energy cost due to reduced heating demand associated with the increased HRV efficiency for Bundle 3, and to increased heating system efficiency for Bundle 4. Both bundles (Bundle 3 and 4) therefore show a significant improvement in thermal comfort compared to the baseline without resulting in significant increase in total energy use or energy cost.

The energy cost associated with space heating is lower for the hydronic archetype than the electric baseboard archetype. Therefore, there is a smaller reduction in heating energy cost from improving the HRV efficiency for the hydronic archetype Bundle 3, and the cost associated with adding cooling has a greater impact on the total energy cost compared to the electric baseboard archetype.

Step 4

Recall that to meet the BC ESC Step 4 targets, the overall thermal performance of the enclosure was improved by upgrading the windows, wall and roof, and the minimum efficiency HRVs were upgraded to high efficiency HRVs with bypass. Table D.7 summarizes the adjustments that were made to the Step 3 low rise new building baseline to meet Step 4.

TABLE D.7	ADJUSTMENTS MADE TO MEET STEP 4 OF THE BC ESC FOR THE LOW RISE NEW BUILDING ARCHETYPES
	Description
Step 4	→ Improved window performance to USI-0.8 (U-0.14), SHGC-0.28 → Improved wall thermal performance to R_{eff}-27 → Improved roof thermal performance to R_{eff}-40 → Upgraded HRVs to 85% efficient with bypass

Energy and Emission Analysis

The bundles described in Table D.2 were modelled for the Step 4 archetype. Table D.8 summarizes the energy and GHG results for the passive bundles for the Step 4 low rise new building archetype based on the RCP-8.5 2050s climate file.

TABLE D.8 PASSIVE BUNDLE RESULTS FOR LOW RISE NEW BUILDING STEP 4 BASED ON RCP-8.5 2050S CLIMATE FILE

	Baseline	Bundle 1	Bundle 2
TEUI (kWh/m²a)	95	95	95
TEDI (kWh/m²a)	11	11	11
Peak heating demand[1] (W/m²)	12	11	12
GHGI[2] (kgCO_2e/m²a)	3	3	3

[1]Peak heating demand on grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

Table D.9 summarizes the results for the active bundles for the Step 4 low rise new building. For comparison, the results for the individual active measures are included, i.e. the bundles without passive measures. Red font color indicates that the Step 4 target has been exceeded.

TABLE D.9 COMBINED BUNDLE RESULTS FOR LOW RISE NEW BUILDING STEP 4 BASED ON RCP-8.5 2050S CLIMATE FILE					
	Baseline (Step 4)	HRV with bypass, cooling coil, and boost as needed		Full mechanical cooling	
		Without passive measures	**With** passive measures (Bundle 3)	**Without** passive measures	**With** passive measures (Bundle 4)
TEUI (kWh/m²a)	95	99	98	105	99
TEDI (kWh/m²a)	11	11	11	11	11
CEDI (kWh/m²a)	n/a	9	8	15	10
TEDI + CEDI (kWh/m²a)	n/a	20	19	26	21
Peak heating demand[1] (W/m²)	12	12	12	5	5
Peak cooling demand[1] (W/m²)	n/a	10	7	8	4
Peak operative temperature (°C)	34	30	28	27	27
GHGI[2] ($kgCO_2e/m^2a$)	3	3	3	3	3

[1]Peak heating/cooling demand on grid (accounts for system efficiency), see Table 2.5 for full description.
[2]The GHGI is calculated with the emission factor for the future UBC district energy system that is planned to consist of 60% renewable energy by 2024.

Similar to the Step 3 archetype, TEUI and peak heating demand is slightly lower for the Step 4 electric baseboard archetype compared to the Step 4 hydronic archetype due to a higher system efficiency. The GHGI is also slightly lower for the electric baseboard archetype compared to the hydronic, as a result of the lower emission factor for electricity compared to the UBC district energy system.

Costing Analysis

This section summarizes the costing analysis of the Step 4 low rise new building bundles, including the incremental capital cost and annual energy cost.

Figure D.3 shows the incremental cost at the building level for the Step 4 bundles together with the number of overheated hours based on the RCP-8.5 2050s climate file. The error bars illustrate the high and low bundle cost ranges. The incremental bundle costs per floor area ($/m²) are summarized in Table D.10.

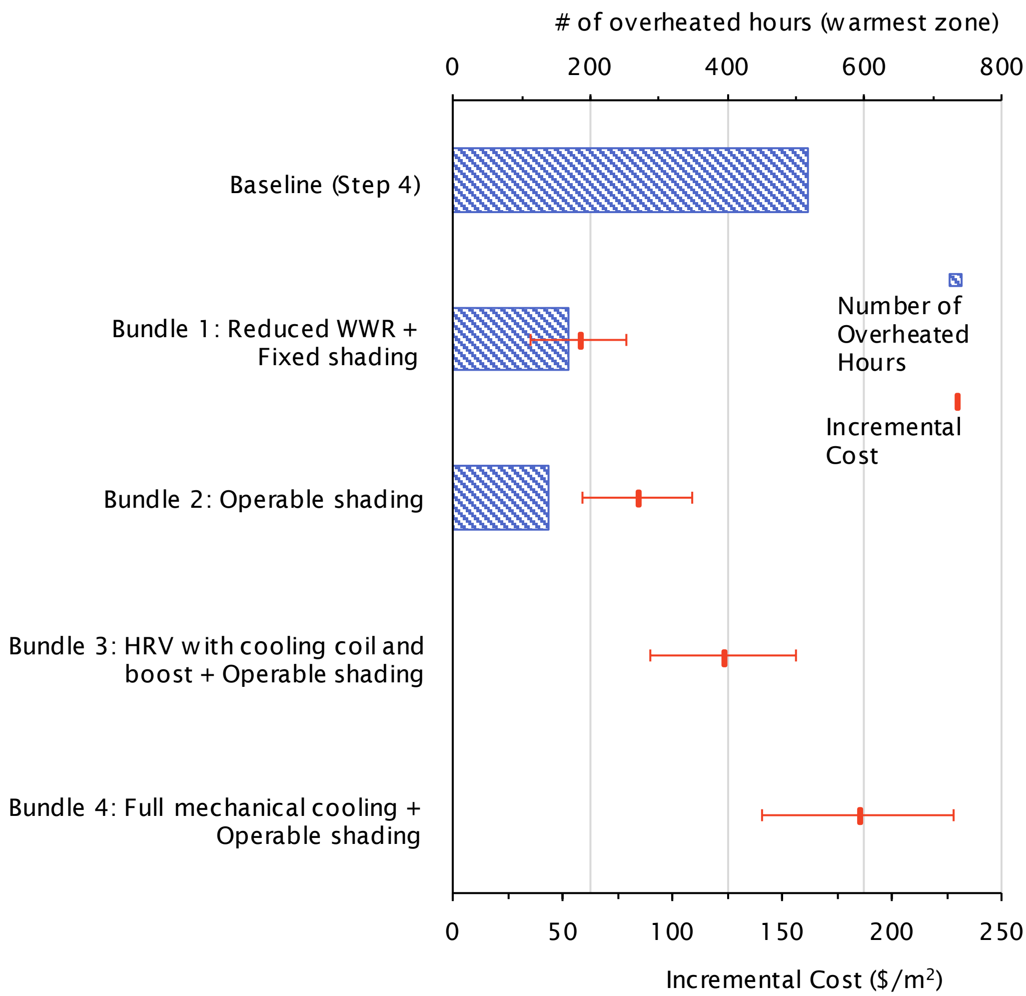

Figure D.3 Incremental cost ($/m²) for the Step 4 bundles shown together with the number of overheated hours based on RCP-8.5 2050s climate file. The error bars show the high and low incremental bundle cost.

TABLE D.10	INCREMENTAL COST FOR THE STEP 4 LOW RISE NEW BUILDING		
	Low	Mean	High
Bundle 1 ($/m²)	36	57	79
Bundle 2 ($/m²)	60	85	108
Bundle 3 ($/m²)	89	123	155
Bundle 4 ($/m²)	138	181	223

Similar to the Step 3 archetype, the incremental costs for Bundles 1 through 3 are unchanged compared to the hydronic archetype since the measures are independent of the heating system. The incremental capital cost of installing heat pumps compared to an electric baseboard baseline is the same as for the Step 3 case, at approximately $140-220/m². This is unchanged because it was assumed that the sizing/capacity of the installed system would be similar to the Step 3 archetype, regardless of the improved enclosure.

Figure D.4 shows the annual energy cost ($/m²) for the Step 4 baseline and bundles. Table D.11 summarizes the annual energy cost, and energy cost savings compared to the baseline for both the electric baseboard and hydronic archetype.

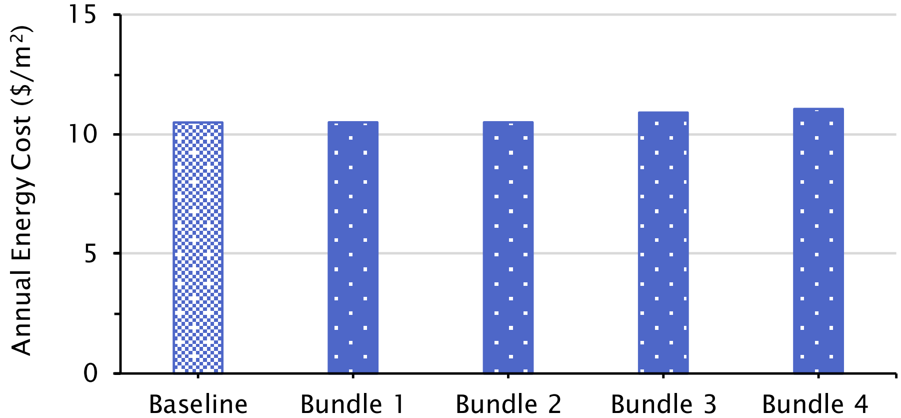

Figure D.4 Annual energy cost ($/m²) for the Step 4 baseline and bundles.

TABLE D.11 ANNUAL ENERGY COST AND COST SAVINGS COMPARED TO THE STEP 4 LOW RISE NEW BUILDING BASELINE					
	Baseline	Bundle 1	Bundle 2	Bundle 3	Bundle 4
Electric baseboard archetype					
Annual energy cost ($/m²)	10.5	10.5	10.5	10.9	11.1
Energy Cost Savings (%)	-	0%	0%	-4%	-6%
Hydronic archetype (district energy connection)					
Annual energy cost ($/m²)	9.5	9.5	9.5	9.9	11.1
Energy Cost Savings (%)	-	0%	0%	-4%	-16%

The Step 4 baseline archetype includes a high efficiency HRV, and since there is no resulting increase in HRV efficiency for the Step 4 partial cooling bundle (Bundle 3), there are no energy cost savings due to reduced heating demand. The increase in annual energy cost for Bundle 3, as a result of additional cooling, is the same for the electric baseboard archetype and the hydronic baseboard archetype.

The increase in annual energy cost as a result of installing air-source heat pumps for heating and cooling (Bundle 4) is lower for the electric baseboard archetype compared to the hydronic archetype. Even though the air source heat pump has a higher heating efficiency than the baseline, this upgrade results in a fuel switch for space heating for the hydronic archetype, and therefore an increase in heating energy cost along with the addition of cooling energy cost. Upgrading from electric baseboards to air-source heat pumps reduces the cost associated with heating, and the overall increase is lower compared to the hydronic archetype. Recall, however, that Bundle 4 also includes operable shading. If this was not included, the increase in operating energy cost (and consumption) would be even higher.

Key Findings

The key findings below are specific to the additional analysis. Additional key findings are provided in Section 3.1.3 of the main report.

→ Compared to the original low rise new building archetype with district energy connection for space heating, the total energy use intensity (TEUI) and peak heating demand results are slightly lower for the Step 3 and Step 4 baselines and bundles with electric baseboards. This is because the electric baseboards have a slightly higher modelled efficiency than the district energy connection[2].

→ The thermal energy demand intensity (TEDI) represents the heating energy demand for space conditioning and conditioning of ventilation air, and does not include the system efficiency. Therefore, TEDI is unchanged compared to the original low rise new building archetype.

→ Since the space heating is assumed to be all-electric in this analysis, the GHGI is slightly lower compared to the hydronic low rise new building archetype, due to the lower emission factor for electricity compared to the UBC district energy.

→ The CAMM Bundle with the highest associated incremental cost is shown to be the full mechanical cooling bundle (Bundle 4), followed by the partial cooling bundle (Bundle 3), for both the Step 3 and Step 4 archetypes.

→ For both the Step 3 and Step 4 archetype, adding partial or full mechanical cooling *in combination with passive measures* significantly increases the thermal comfort when modelled with the RCP-8.5 2050s climate scenario, with no or minimal impact to GHG emissions, total energy use, or the operating energy cost of the building.

→ The increase in annual energy cost for Bundle 4, from introducing full mechanical cooling, is lower for the electrically heated baseline than the hydronic baseline because it does not include a fuel switch from district energy to electricity. Further, the inclusion of passive measures, plus more efficient heating via the heat pumps, effectively neutralizes the increased operating energy cost associated with mechanical cooling.

[2] The efficiency of the district energy plant is not accounted for in TEUI or peak heating demand, however, the losses across the heat exchanger are accounted for and therefore the efficiency is lower for the district energy connection compared to direct electricity.