Technical analysis of New Zealand Building Code energy efficiency clause H1 settings for residential buildings

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Reference

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Glossary

Benefit-Cost Ratio (BCR) - the ratio of the net cumulative benefits to the net cumulative costs.

Calculation method – part of clause H1 that uses equations and allows a building to have different combinations of insulation as long as the overall thermal performance is comparable to or better than the MBIE reference building, which is insulated in accordance with the schedule method. Using the calculation method allows some flexibility between elements, so higher R-values than the schedule method tables can be used. In using the calculation method, the minimum R-value for a floor, wall or roof building element should be 50% of the schedule method R-value for that building element. For this method, there is no minimum for doors and windows. However, when using the calculation method, the window area of the building can be no greater than 40% of the total wall area.

MBIE - Ministry of Business, Innovation and Employment. The ministry responsible for the regulation of buildings.

Modelling method – part of clause H1 that uses building simulation to assess energy performance of a proposed building design, which is then compared to the energy use of a reference building that is calculated with the same method. The modelling assesses a number of factors such as heating and cooling loads. The reference building is the same shape, dimensions and orientation as the proposed building, with building elements based on the minimum R-values in the tables as outlined the schedule method. Compliance is proven when the calculated annual space heating and cooling load of the proposed building does not exceed that of the reference building

Net Present Value (NPV) - the value of all future cash flows (positive and negative) over the analysis period discounted to the present value.

Schedule method – part of clause H1 that uses tables of minimum construction R-values for different building elements. A building is said to comply with this method if its thermal envelope components – roof, walls, windows, doors, skylights and floor – are insulated to meet or exceed R-values from the tables. The R-values vary depending on the climate zone a building is in. However, the limitation of this compliance pathway is that the window area of the building can be no greater than 30% of the total wall area.

Contents

Figures

Tables

Executive summary

BRANZ was commissioned by the Ministry of Business, Innovation and Employment (MBIE) to undertake a technical analysis of the changes to the thermal envelope settings in Acceptable Solution H1/AS1 and Verification Method H1/VM1 (both 5th edition amendment 1). These documents apply to all housing, plus other buildings up to 300 m², and are commonly used for demonstrating compliance with New Zealand Building Code clause H1 *Energy efficiency*.

The aim of this study was to test and compare the cost-effectiveness of the current settings and compliance methods and to investigate if recent increases in insulation requirements may unintentionally cause new homes to overheat or suffer internal moisture problems.

The analysis covered four building typologies: single-storey stand-alone, double-storey stand-alone, medium-density and an apartment across the six H1 climate zones in New Zealand.

Thermal modelling with EnergyPlus examined the year-round heating and cooling energy use of the four typical sample buildings and compared their performance when equipped with different insulation configurations. These insulation levels were initially chosen to represent the lowest upfront cost constructions to comply with the current H1 schedule, calculation and modelling methods.

A cost-benefit analysis was undertaken, informed by the thermal modelling results and independently sourced building cost estimates from quantity surveyors (separately procured by MBIE).

Further thermal modelling assessed overheating risk by examining simulated indoor temperatures in the sample model buildings during hot summer weather for the six climate zones, comparing different insulation configurations and a range of possible ventilation and shading assumptions.

Hygrothermal modelling evaluated potential moisture risks in external walls, roofs and roof spaces.

The research does not provide policy advice but aims to inform MBIE's decision making on potential regulatory changes.

Compliance methods and achieving the lowest upfront cost

- Compared to the H1 5th edition schedule method, the flexibility of the calculation and modelling methods enable compliance with less insulation and therefore cheaper upfront build costs at the expense of only modestly higher annual heating and cooling energy costs. These results are outlined in Table 14 of the report.

Table 14: Upfront cost saving

Upfront cost saving compared to H1 5th edition schedule method												
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	$7,057	$8,184	$6,738	$7,488	$6,925	$7,581	$10,282	$10,933	$10,282	$13,051	$12,801	$18,858
H1 5th ed calculation	$4,297	$4,329	$3,950	$4,108	$4,012	$4,208	$3,898	$4,831	$3,890	$6,152	$3,712	$8,907
H1 5th ed modelling	$9,038	$9,815	$7,036	$7,218	$4,021	$4,337	$3,890	$3,960	$2,318	$4,966	$3,712	$8,907
Double Storey House												
H1 4th ed schedule	$6,246	$9,111	$5,993	$8,469	$6,236	$8,582	$8,523	$9,830	$8,416	$12,371	$9,112	$15,479
H1 5th ed calculation	$7,203	$7,968	$6,935	$7,428	$7,059	$7,492	$7,783	$9,005	$5,748	$6,441	$5,914	$9,565
H1 5th ed modelling	$10,773	$12,213	$9,981	$11,768	$9,090	$10,709	$10,072	$10,905	$9,965	$13,396	$9,204	$15,017
Medium-Density Dwelling (2) (3)												
H1 4th ed schedule	$35,452		$32,408		$33,006		$43,092		$40,041		$44,691	
H1 5th ed calculation	$37,277		$34,808		$35,290		$25,986		$21,934		$25,494	
H1 5th ed modelling	$47,231		$43,909		$38,623		$41,813		$39,141		$26,681	
(1) Based on pricing from two quantity surveyors												
(2) Only one QS gave us cost estimates for timber floors in MDH												
(3) Note that the results for the medium-density dwelling is across 8 dwelling units												

- If minimising upfront cost is a key driver for the selection of insulation levels, our analysis suggests it is more economic to use the H1 5th edition calculation or modelling methods rather than return to the H1/AS1 4th edition schedule method to determine insulation levels.
- The H1/AS1 5th edition calculation method is the most economic method for demonstrating compliance for most housing typologies and H1 climate zones. For our sample buildings, the calculation method requires slightly higher insulation levels than the modelling method. While the calculation method has a slightly higher upfront cost, additional compared to the current schedule method, longer-term operational energy costs are lower compared to those determined by the modelling method as can be seen in Tables 15–17 of the report.

Table 15: Estimated additional annual household energy costs – calculation and modelling method – single-storey house

Climate	Additional energy use calculation method (KWh/a)	Cost calculation method ($/a)	Additional energy use modelling method (KWh/a)	Cost modelling method ($/a)
Zone 1	281	$53 - $66	634	$120 - $149
Zone 2	444	$100 - $112	514	$116 - $129
Zone 3	453	$96 - $112	292	$62 -$72
Zone 4	554	$133 - $146	351	$84 - $92
Zone 5	699	$138 - $160	219	$43 - $50
Zone 6	606	$166 - $181	98	$27 - $29

Table 16: Estimated additional annual household energy costs – calculation and modelling method – double-storey house

Climate	Additional energy use calculation method (KWh/a)	Cost calculation method ($/a)	Additional energy use modelling method (KWh/a)	Cost modelling method ($/a)
Zone 1	412	$78 - $97	909	$172 - $214
Zone 2	637	$144 - $160	1398	$316 - $351
Zone 3	616	$130 - $152	918	$193 - $227
Zone 4	840	$202 - $221	1114	$268 - $293
Zone 5	676	$134 - $155	1302	$257 - $298
Zone 6	791	$216 - $236	1173	$321 - $350

Table 17: Estimated additional annual household energy costs – calculation and modelling method – medium-density dwelling

Climate	Additional energy use calculation method (KWh/a)	Cost calculation method ($/a)	Additional energy use modelling method (KWh/a)	Cost modelling method ($/a)
Zone 1	1938	$366 - $457	2979	$562 - $702
Zone 2	2041	$461 - $513	4397	$993 - $1,105
Zone 3	2253	$475 - $556	1412	$297 - $348
Zone 4	3473	$835 - $914	3473	$835 - $914
Zone 5	3327	$658 - $761	2223	$439 - $508
Zone 6	4299	$1,176 - $1,282	3993	$1,092 - $1,191

Economics of changing the H1 R-value settings:

- Our analysis suggests that the current H1 5th edition R-value settings do not need changing. The highest ratio of benefits to costs was obtained for constructions that comply with the current H1 5th edition R-value settings. Refer to Table 19 in the report for the benefit-cost ratios.

Table 19: Benefit-cost ratios

Benefit-Cost Ratio compared to H1 5th edition schedule method												
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	1.63	2.86	0.94	1.41	0.97	1.51	1.12	1.58	1.15	2.05	0.92	1.80
H1 5th ed calculation	2.81	4.29	1.53	2.15	1.57	2.34	1.11	1.83	1.62	3.59	5.45	17.30
H1 5th ed modelling	2.61	4.29	2.35	3.26	2.47	3.79	1.90	2.57	1.35	4.05	5.45	17.30
Double Storey House												
H1 4th ed schedule	1.49	3.29	0.87	1.66	0.96	1.88	0.95	1.46	0.94	1.94	0.64	1.43
H1 5th ed calculation	4.06	6.81	2.38	3.44	2.51	3.79	1.76	2.70	4.18	6.57	2.96	6.34
H1 5th ed modelling	2.29	3.94	1.30	2.07	1.73	2.89	1.48	2.12	1.44	2.72	1.10	2.38
Medium-Density Density (2)												
H1 4th ed schedule	2.20	3.33	1.25	1.68	1.29	1.84	1.29	1.71	1.18	1.65	0.80	1.06
H1 5th ed calculation	6.82	10.33	3.88	5.24	3.82	5.43	2.12	2.81	1.68	2.35	1.22	1.61
H1 5th ed modelling	2.94	4.46	1.68	2.27	3.33	4.74	2.04	2.71	2.06	2.89	1.17	1.55
(1) Based on assumptions of the upfront cost differences, electricity tariff type (low/standard), and real inflation in electricity prices (0% or 1.2% p.a.)												
(2) Note that the results for the medium-density dwelling is across 8 dwelling units												

- For some buildings, the current modelling method already enables reducing insulation to less than what was commonly used under the previous H1 4th edition.
- There is no single simple answer to what constitutes most cost-effective insulation settings. This is mainly because the settings are critically dependent upon house design. They vary due to uncertainty in the economic analysis, variations in material costs, uncertainties in energy use estimates and dependencies on modelling assumptions.

Overheating risk: effect of the H1/AS1 5th edition insulation requirements

- This work has shown that reducing minimum R-values back to the H1 4th edition could contribute to greater overheating.
- The Building Code does not currently aim to manage overheating in buildings, allowing buildings to be designed so they are likely to overheat irrespective of insulation levels.
- Ventilation, shading and window size are significant risk factors. A poorly ventilated and airtight building may overheat significantly, and this could be exacerbated by high insulation levels.
- The effects of the H1 5th edition insulation changes on overheating are variable. Different effects may be seen in different houses, rooms and climate zones. Overheating is most likely to occur during daytime, where the most common result was a reduction in overheating risk from the increased insulation in the H1 5th edition. In contrast, night-time overheating risk was increased by higher insulation levels.
- Increased roof, wall and glazing R-values typically reduce daytime overheating risk by reducing solar gains
- Increased slab insulation may increase overheating risk by reducing the cooling thermal mass effect of the ground.
- Managing overheating risk properly would require the Building Code to address overheating directly by requiring new homes to be designed to minimise overheating risk.

Moisture risks: effect of the H1 insulation requirements

- While higher insulation levels can change the risk of moisture accumulation in walls and roofs, the values tested in this report do not suggest that the H1 5th edition insulation changes result in increased internal moisture risks.
- The key factors in terms of moisture risk were found to be the colour of the roof and wall claddings, indoor moisture loads and orientation of the construction.

Window to wall ratio (WWR) in new housing

- The average WWR of our sample of new detached homes was 22%, which is significantly lower than the 30% WWR assumed for the MBIE reference building in the H1 calculation and modelling methods.
- Only around 10% of the sample had WWRs above 30%, which is the maximum permitted for using the H1/AS1 schedule method.
- Only 1.4% of the sample had WWRs of 40% or higher, which is the maximum permitted for using the H1/AS1 calculation method.

Thermal benefit of thermal breaks in window joinery

- Thermal breaks in aluminium-based window frames improve the thermal performance of these windows, although they only achieve about 75% of the design thermal performance (R-value) when they are installed in accordance with E2/AS1 Figure 116, where the outside of the window frame aligns with the outside of the wall cladding. This is still better thermal performance than (cold) aluminium windows without thermal breaks.
- The thermal performance of thermally broken aluminium windows can be further improved by positioning them further inwards in the wall construction to prevent cold air in the cladding cavity bypassing the thermal break. However, such window installation can pose weathertightness issues that need to be carefully managed.

Observed challenges with the H1 compliance methods

The report outlines several challenges with the current H1 compliance methods:

- **Calculation versus modelling method:** The results from the calculation and modelling methods do not necessarily agree on whether a construction will comply. With modern windows, compliance through the modelling method largely revolves around cooling energy use and not heat loss, the latter being the sole focus of the calculation method.
- **Concrete slab R-values:** It may be difficult for small slabs in multi-storey houses to achieve R-values that comply with the schedule method or the 50% rule in the calculation method (H1/AS1 2.1.3.8).
- **Compliance issues for apartments:** The case study apartment building had very high glazing areas that could not comply with the current glazing area limits of the H1 calculation and schedule methods. Despite this, its modelled energy use was not significantly different from the other houses that did comply. This is a limitation in how H1/VM1 works and highlights the need for adjustment to the modelling method.

The report has outlined that, while the current H1/AS1 5th edition standards reduce space-conditioning energy use, there are several issues to address:

- Management of overheating risk is not directly addressed by the New Zealand Building Code, and the modelling method in H1/VM1 is not designed to assess overheating.
- Within the modelling method for H1/VM1, there are circumstances where it is difficult to apply the reference model windows due to doors and limited wall area, as it can make it difficult to adjust the window area for the reference model exactly as prescribed by H1/VM1 D.2.2.2.

Key limitations

The buildings used in the simulations are representations of their respective typologies. There is of course large variation in the actual construction. It is important to note that thermal performance modelling is a simplification. Its strength lies as a comparative assessment rather than predicting actual energy use.

When developing the highest net present value (NPV) construction – the value of all future cash flows (positive and negative) over the analysis period discounted to the present value – it should be noted there is a high degree of uncertainty. Determining the NPV or cost-effectiveness of different constructions may significantly overlap. We note that different options could be selected for different houses, different suppliers and different modelling assumptions. Therefore, the highest NPV constructions should be read more as examples that illustrate tendencies rather than assuming they are universal in all situations.

Future updates to this report

BRANZ will provide MBIE with an updated report in December 2024 that will also outline the following:

- Whole-of-life operational and embodied carbon impacts of the H1/AS1 settings as outlined in this report.
- The merits and impacts of changing these parameters of the H1/VM1 modelling:
    - Reducing the natural ventilation setpoint from currently 24°C to 22°C or 23°C (refer H1/VM1 D.3.1.1).
    - Changing the assumed internal gains from occupant and plug loads for housing in H1/VM1 D.5.1.
    - Removing the ability of modelling certain exterior shading differently between the reference and proposed buildings (H1/VM1 D.1.11.1).
- The merits and impacts of excluding multi-unit dwellings with three or more dwellings (townhouses, walk-ups or apartment buildings) from the scope of the schedule and calculation methods.
- The estimated additional professional fees for using the modelling method and to what extent these would be offset by reduced upfront construction costs and/or reduced ongoing operational costs.

This report provides valuable insights into the trade-offs between energy efficiency, cost and comfort in residential buildings and recognises the differences between the current H1 5th edition and the H1 4th edition of the H1 *Energy efficiency* standards. The research highlights that the current H1 5th edition settings are effective. Any potential changes to H1/AS1 should give careful consideration to unintended consequences such as overheating and moisture risks.

1. Introduction

1.1 Purpose of report

The Ministry of Business, Innovation and Employment (MBIE) commissioned BRANZ to undertake a detailed and technical analysis of thermal envelope (R-value) options for new housing compared to the current minimum settings for NZBC clause H1 *Energy efficiency* Acceptable Solution H1/AS1 and Verification Method H1/VM1 5th edition amendment 1 for housing and small buildings.

This technical study is limited to three key aspects: thermal and financial implications as well as internal moisture risks. It provides a detailed and accurate picture of the costs and benefits of the current thermal envelope requirements under H1 5th edition amendment 1 compared to the current minimum settings. Broader health and social benefits have not been factored into the cost-benefit calculations.

1.2 Background

H1 *Energy efficiency* was introduced in 1992 as part of Building Regulations. Since 1992, there have been several editions of the H1 acceptable solutions and verification methods, which include compliance pathways for Building Code clause H1. The most recent step change was transitioning from the 2008 H1/AS1 and VM1 4th edition to H1/AS1 and H1/VM1 5th edition in 2021. Some key changes to the H1 5th edition compared to the 4th edition included:

- limiting H1/AS1 to cover only housing and buildings less than 300 m²
- excluding buildings with curtain walling from H1/AS1
- revised thermal resistance and construction R-values for building elements
- significant uplift in the R-value requirements for windows
- updating the climate zone map from three zones to six zones
- adding tables with construction R-values of selected slab-on-ground floor scenarios.

The current version H1/AS1 and H1/VM1 5th edition amendment 1 was effective transitionally across several dates from 4 August 2022. In this report, we refer to this update as H1 5th edition, unless specifically addressing H1/AS1 and H1/VM1

There are three primary methods to demonstrate buildings meet H1 regulations:

- The **schedule method** uses tables of minimum construction R-values for different building elements. A building is said to comply with this method if its thermal envelope components – roof, walls, windows, doors, skylights and floor – are insulated to meet or exceed R-values from the tables. The R-values vary depending on the climate zone a building is in. However, the limitation of this compliance pathway is that the window area of the building can be no greater than 30% of the total wall area.
- The **calculation method** uses equations and allows a building to have different combinations of insulation as long as the overall thermal performance is comparable to or better than the MBIE reference building, which is insulated in accordance with the schedule method. Using the calculation method allows some flexibility between elements, so lower R-values than the schedule method tables can be used. In using the calculation method, the minimum R-value for a floor, wall or roof building element should be 50% of the schedule method R-value for that building element. For this method, there is no minimum for doors and windows. However, when using the calculation method, the window area of the building can be no greater than 40% of the total wall area.
- The **modelling method** uses building simulation to assess energy performance of a proposed building design, which is then compared to the energy use of a reference building that is

calculated with the same method. The modelling assesses a number of factors such as heating and cooling loads. The reference building is the same shape, dimensions and orientation as the proposed building, with building elements based on the minimum R-values in the tables from the schedule method. Compliance is proven when the calculated annual space heating and cooling load of the proposed building does not exceed that of the reference building (Burn, 2024).

In 2020, MBIE commissioned BRANZ to undertake a technical study to support the policy review of increasing residential insulation requirements of NZBC clause H1 *Energy efficiency* Acceptable Solution H1/AS1 for housing and small buildings. This research was published as *Thermal, financial and carbon review of NZBC energy efficiency clause H1/AS1 thermal envelope requirements for residential and small buildings*, which we will refer to as the 2020 BRANZ study on H1 (Jaques et al., 2020). The aim of the BRANZ 2020 study on H1 was to provide the information required for MBIE to propose and consult on new insulation requirements for each new climate zone that will apply to housing. The 2020 BRANZ study on H1 used H1/AS1 4th edition amendment 4.

The 2020 BRANZ study on H1 used four representative dwelling typologies: single-storey stand-alone houses, double-storey stand-alone houses, townhouses and mid-rise apartments. Three key aspects were examined in some detail for each dwelling typology envelope upgrade: year-round passive and active thermal performance, a financial analysis and lifetime carbon emission quantification. The assessment was carried out at the individual building level for the next 50 years (i.e. to 2070). An accurate picture of the thermal, economic and environmental costs and benefits of each upgrade compared to the current minimum NZBC settings was provided.

Within the 2020 BRANZ study on H1, the following thermally related aspects were out of scope:

- The effects of climate change in terms of influencing space heating and cooling loads.
- The impact of thermal bridging at elemental wall/floor/ceiling junction details and wall corners.
- The implications for interstitial condensation within building elements for the most extreme constructions proposed.
- Reduction in peak energy loading and the resulting infrastructure savings.

While having similar aspects such as examining H1 in different contexts, this 2024 BRANZ study on H1 is a different report to the 2020 report and should not be compared as it examines the impact of changing the current H1 5th edition from the previous version of H1 4th edition amendment 4. This report also includes other issues that were not included as part of the 2020 BRANZ study on H1, such as overheating risk and internal moisture risk.

1.3 Research questions

This report undertakes a detailed and technical analysis of H1 5th edition amendment 1 for new housing. These are the key questions that MBIE sought to understand:

1. What are the estimated impacts of changing thermal envelope settings (R-values), compared with the current minimum settings of H1/AS1 5th edition amendment 1 for new housing? Complete this analysis for a range of R-value options …, four sample buildings, and the six H1/AS1 climate zones. Including:
    a. annual space heating and cooling useful energy demand impacts (kWh/(m²a) and kWh/a)
    b. annual space heating and cooling delivered energy demand impacts (kWh/(m²a) and kWh/a) – ie considering the efficiency of assumed heating and cooling equipment
    c. peak space heating and cooling load impacts (kWp)
    d. changes in overheating risk
    e. estimated changes to annual household energy costs for space heating and cooling ($/a)

   f. cost benefit analysis on a per-dwelling basis, including marginal upfront costs, benefit-cost ratios and net-present values (this will be informed by elemental upfront cost estimates which MBIE procures separately from quantity surveyors)
2. For each of the four sample buildings and for the six climate zones, what upfront cost reductions are achievable when using the H1 calculation and modelling methods, compared to the schedule method under current H1/AS1 and H1/VM1 settings?
3. For each of the four sample buildings and for the six climate zones, what are the most cost-effective elemental R-values for roof, walls, windows and floor? Do these combinations comply with the current schedule, calculation and/or modelling methods?
   a. If yes: What is the maximum glazing area to wall area ratio for these combinations to comply with the current calculation and/or modelling methods?
   b. If no: What adjustments would be needed to the reference building R-values so the four buildings comply with a) the calculation method and b) the modelling method?
4. To what extent has the 2021 H1 update increased the overheating risk in new housing? Is the change to insulation and glazing a dominant driver for overheating risk, and if so, under what conditions and climate zones?
5. To what extent has the 2021 H1 update increased internal moisture risks in new housing? Is the increased insulation a dominant driver for internal moisture risk, and if so, under what conditions and climate zones?
6. To what extent has the 2021 H1 update increased the risk of moisture damage in roofs and roof spaces? What is the estimated impact of the increased ceiling insulation on roof space temperatures and drying potential? How does this impact compare to other factors that determine roof space moisture risks and drying potential?
7. What is the estimated distribution of glazing area to wall area ratios in new housing, and how does this differ between different new housing typologies (eg stand-alone houses, medium-density townhouses, and apartment buildings)?
8. To what extent is the thermal benefit of thermal breaks in aluminium window joinery realised when windows are installed as per NZBC E2/AS1 (window installed on the outside of external walls with the thermal break protruding into a drained cavity), versus when windows are installed in a recessed position in external walls?

1.4 Structure of this report

Executive summary provides a summary of the key research results and highlights regulatory challenges for MBIE to consider in any changes to the Acceptable Solution and Verification Method documents for clause H1 *Energy efficiency*.

Chapter 1 outlines the background and research questions that this report answers.

Chapter 2 outlines the key approaches used in this analysis: thermal modelling and simulation, cost-benefit analysis and hygrothermal analysis.

Chapter 3 outlines the research to address the research questions organised according to key themes:

- Impacts of changing thermal envelope settings (R-values) for new housing
- Most cost-effective constructions
- Effect of the 2021 H1 update on overheating risk
- Internal moisture risk
- Roof moisture risk
- Window/wall ratios in new housing
- Thermal benefit of thermal breaks in window joinery.

2. Methodology

2.1 Representative model building descriptions

Four representative model buildings were chosen, one for each typology: detached single-storey, detached double-storey, townhouse and apartment. The four selected representative buildings were not designed to be 'designed for the sun', reflecting the current new-build approach. A dwelling that is well designed for the sun will respond to solar access in its window sizing, placement and shading and therefore perform thermally quite differently to the representative dwellings chosen.

Three-dimensional schematics of the representative models are shown in Figure 1 to Figure 4.

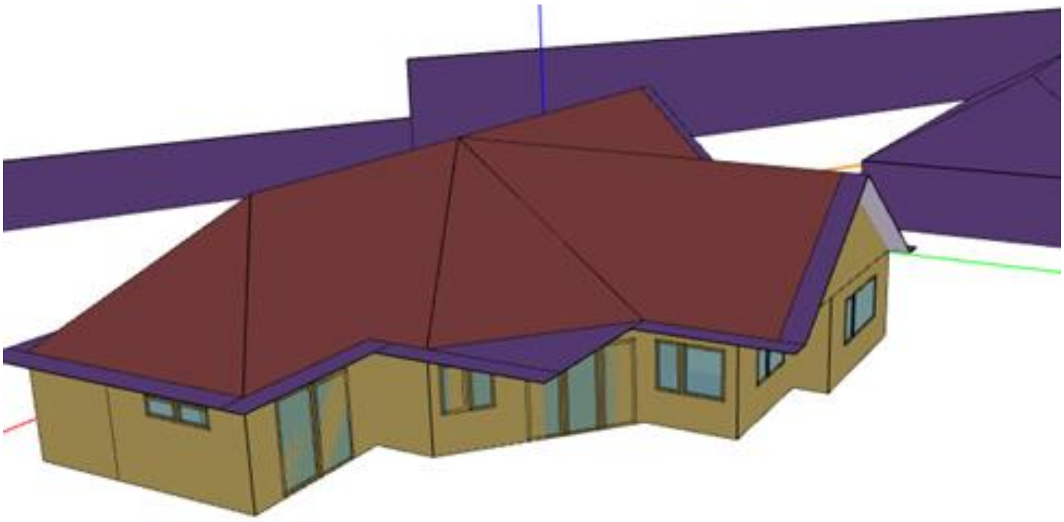


Figure 1: Single-storey stand-alone representative building schematic.

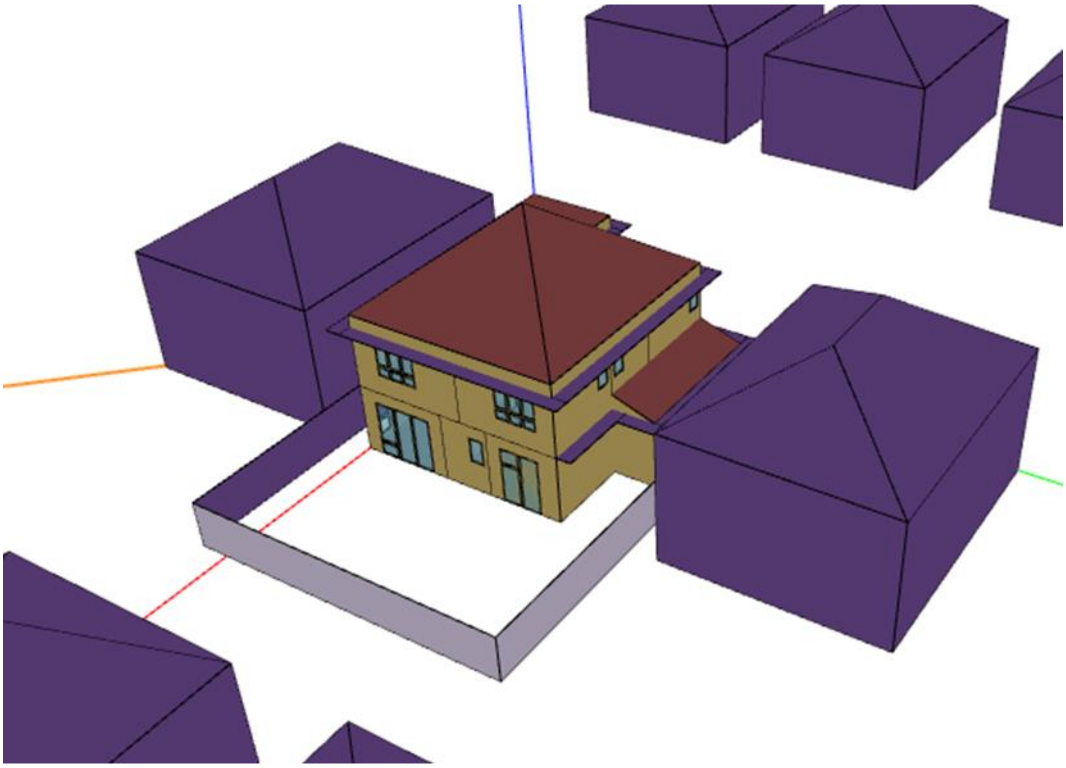


Figure 2: Double-storey stand-alone representative building schematic.

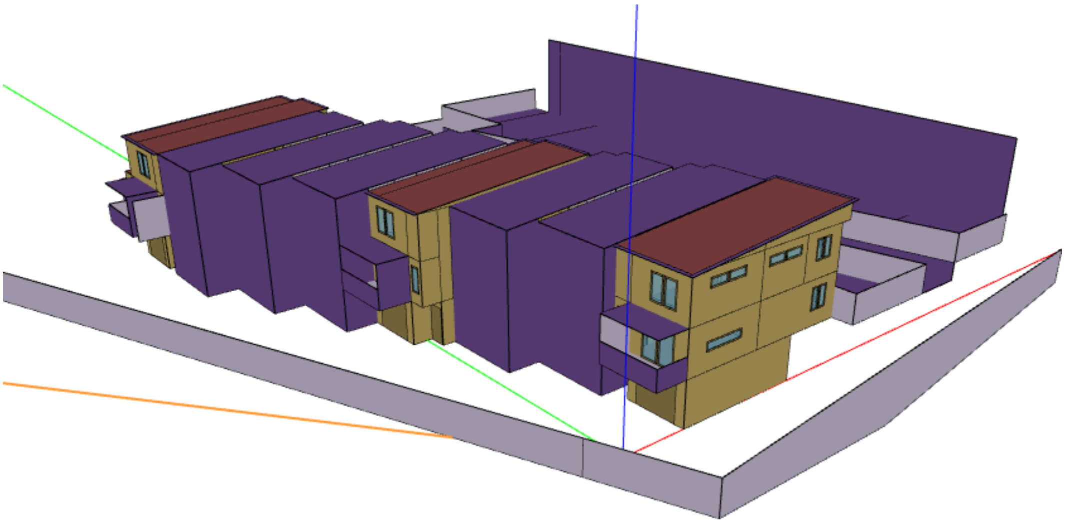


Figure 3: Medium-density (townhouse) representative building schematic.

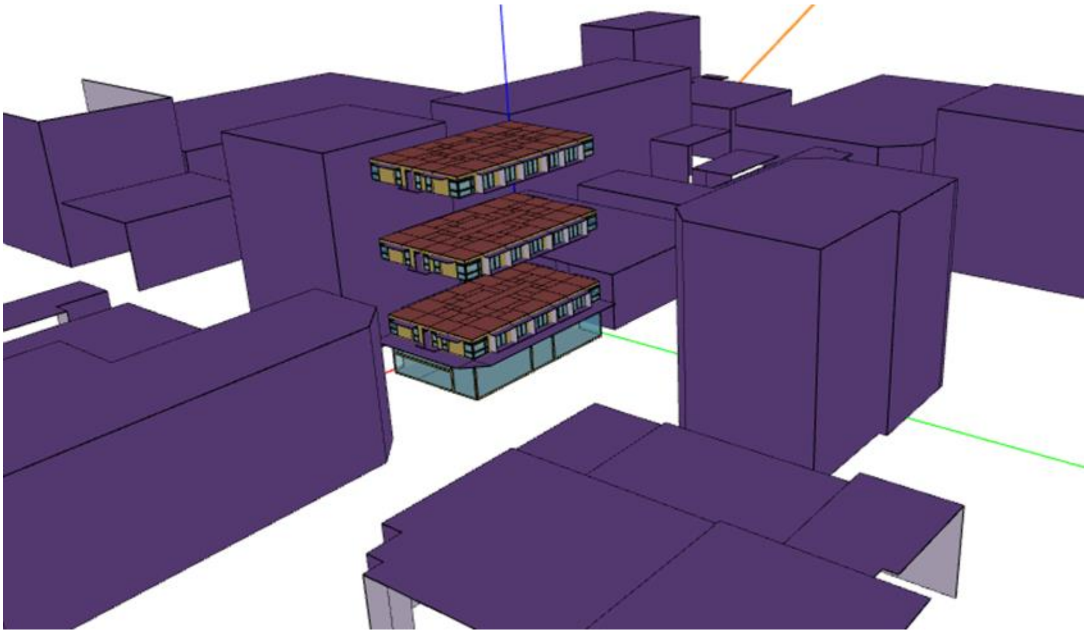


Figure 4: Apartment representative building schematic (with office on ground floor).

2.1.1 Details of representative model buildings

- The single-storey house has four bedrooms, a double garage, a pitched roof and 156 m² of conditioned floor area (internal zones that are temperature modified to be within a predetermined comfort range). It has a window to wall area ratio (WWR) of 20%.
- The double-storey house has four bedrooms, a double garage, a pitched roof and 151 m² of conditioned floor area. It has a WWR of 17%.
- The medium-density development comprises eight units with two bedrooms per unit for a total conditioned floor area of 695 m². It has a WWR of 16% and garages on the ground floor.
- The nine-level apartment building has an apartment floor area of 3,123 m² (3,604 m² conditioned floor area including corridors) made up of 108 units, with offices on the ground floor, a flat roof and a WWR of 47%.

The make-up of the roofs, walls, floors and windows are outlined in detail in section 2.2.2.

2.2 Thermal modelling and simulation methodology

As with any process that tries to model reality, thermal performance simulation is a simplification. Where its strength lies is in comparative assessment rather than predicting actual energy use. This needs to be kept in mind when reading this document.

The following thermally related aspects were out of scope for this study:

- The effects of future climate change in terms of influencing space heating and cooling loads.
- The impact of thermal bridging at elemental wall/floor/ceiling junction details and wall corners.
- Reduction in peak energy loading and the resulting infrastructure savings.
- Harder-to-quantify implications of having a more comfortable house year round (better physiological health, lower health costs, lower mental stress).

Thermal modelling was conducted exclusively using EnergyPlus (version 22.1.0)[1] and the new TMY3 weather files produced by NIWA for MBIE. These files are designed to represent modern typical conditions, updated for the effects of climate change.

2.2.1 Assumptions

The models were run using the following assumptions:

- The model is heated to 18°C and cooled to 25°C (operative temperature). All zones inside the thermal envelope were conditioned 24/7 following H1/VM1.
- MBIE requested both baseline energy use figures using ideal loads (COP = 1, used to assess H1 compliance) and figures assuming a heat pump in the living room with electric resistive heating in other zones. Previously, we have assumed a COP of 2 based on old BRANZ studies of heat pumps (Burrough et al., 2015). However, discussions with EECA have suggested that a COP of 3.75 better reflects common modern systems. This heat pump COP was also applied to the cooling loads in the non-living zones on the grounds that if they had cooling, they would have a heat pump.[2]
- Internal gains were based on H1/VM1 defaults and adjusted following discussions with MBIE:
  - Equipment gain was reduced from 24.5 W/m^2 to 13.5 W/m^2 following suggested adjustments by MBIE to reflect energy efficiency improvements observed by EECA over the past decades and better align with the average electricity use of a modern household.
  - Occupant sensible gains were assumed at 75 W/person, reduced by 30% from 11pm to 7am to reflect lower metabolic rates while sleeping, following CIBSE TM59 (Chartered Institution of Building Services Engineers, 2013) and Addendum G to ANSI/ASHRAE Standard 55 *Thermal environmental conditions for human occupancy*.
  - Houses were assumed to be fully occupied, with occupancy equal to number of bedrooms plus one. In the case of the apartments, this was two people in each full apartment and one person in a studio. Occupants were divided up over living zones during the day according to relative floor area and to the bedrooms overnight. Intermittently occupied zones such a corridors and bathrooms were assumed to have no significant occupant loads.
  - Hot water cylinders were modelled as providing a 100 W load in the zone they exist in following H1/VM1.
- A baseline infiltration/ventilation rate of 0.5 air changes per hour (ACH) was assumed following H1/VM1. Roof spaces were assumed to be 3 ACH based on average BRANZ measurements (McNeil & Rupp, 2018).

[1] https://energyplus.net

[2] In reality, of course, many New Zealand houses simply wouldn't have cooling in those zones and would overheat if they could not control temperatures by opening windows. How to best assign cost to high temperatures is not a question with a simple answer, and valuing them based on the energy needed by a hypothetical heat pump to cool them is only one option.

- Natural ventilation was assumed to be provided at 22°C. This was deliberately lowered from the H1/VM1 24°C setpoint at the request of MBIE due to concerns that the 24°C setpoint was giving natural ventilation too little room to control temperatures before cooling was applied and inflating cooling loads. This significantly lowers cooling and focuses the models more on differences in heating use, which aligns with the focus of H1 on insulation and heat loss. Ventilation was turned off at 25°C or when the outdoor temperature was above the indoor temperature in order to avoid potential conflicts with cooling.
- Maximum ventilation rates were assumed to be 30 ACH in the main living spaces with good cross-ventilation potential and openable outside doors and 10 ACH in other rooms. Due to the design of the apartment building, there is much less capacity for cross-ventilation between different rooms, and ventilation rates may be lower. A maximum of 15 ACH was assumed in living spaces with openable balcony doors and 5 ACH in rooms with only small openable windows. These assumptions were based on estimates of high-end ventilation rates that were readily reached in more complicated airflow network models when the windows were opened.
- Some interzonal air mixing through doors and openings was applied using Zone Cross Mixing objects, assuming 0.1 m/s base air movement[3] through openings. Doors were assumed to be opened when temperatures were over 22°C, raising the air movement by 0.3 m/s to reflect cross-ventilation through zones.
- Ground modelling was done using the Kiva model. Note that the GroundDomain model would produce different results. Soil conductivity = 2.0 W/(m.K) and volumetric heat capacity = 2.0×10^6 J/(m^3K) following H1/VM1.
- Curtains and furniture are not included in the model.
- Surrounding site shading was modelled based on the environments of the case study buildings.
- The solar distribution algorithm used was FullExteriorWithReflections, and the shadow calculation algorithm was the default PolygonClipping.
- Constructions were modelled accounting for the thermal mass of insulation and timber framing using the Combined Thermal Properties method. To account for the mass of both the timber and insulation in a bridged layer, the mass properties were averaged. External walls were assumed to have a framing ratio of 24% by request of MBIE to be consistent with previous analysis. Internal walls were assumed to be 22%.
- Glazing was modelled using EnergyPlus's detailed window construction inputs in LBNL Window 7. Frame widths were set based on estimates of average frame width in a typical house (aluminium: 23%, thermally broken: 27%). Window frames were modelled by manually adding opaque sub-surfaces around the windows with the appropriate U-values. This is because testing has found that EnergyPlus's FrameAndDivider is not accounting for ~75% of the heat transfer through it due to not accounting for radiative exchange.[4] In order to capture the high U-values of aluminium frames, their surface areas were increased to produce the correct overall heat loss. (Windows are modelled as flat planes – shading effects from window geometry are not accounted for.)
- Testing has indicated that surface reflectances other than the roof – particularly internal reflectances – can have significant impacts on performance. Internal surface reflectances were assumed to be 70% on the ceiling, 50% on the walls and 30% on the floor following clause G7 *Natural light*. External walls, roof reflectances and eaves were assumed to be 50%. Window frames were assumed to be white at 80% reflectance, which minimises their sensitivity to solar gains to focus on differences in heat losses. Surface finishes are obviously highly uncertain and can change based on the whim of the occupants. However, they do also affect thermal performance. Window frames in particular can be sensitive due to their relatively high U-values and the fact that both black and white are common window frame colours.
- Floors were assumed to be carpeted, with linoleum in wet areas (kitchen and bathrooms).

[3] 0.1 m/s is a typical value assumed for still air (Chartered Institution of Building Services Engineers, 2006).
[4] https://github.com/NREL/EnergyPlus/issues/10445

2.2.2 Construction scenarios

MBIE asked BRANZ to analyse a number of different house constructions taken from the BRANZ *House Insulation Guide* for their potential use in achieving Code compliance, which are:

- four timber-framed walls
- 10 pitched roofs
- seven timber floors
- 10 concrete slabs
- four windows.

We note that skillion roof constructions, while costed, were not modelled as none of the houses had a skillion roof. These constructions were the only ones used to produce the various solution sets used to achieve Code compliance under either the schedule, calculation or modelling methods (with occasional surface material adjustments to match specific houses).

2.2.2.1 Roof

The roof construction is based on a typical pitched roof with trusses at 900 mm centres and 90 mm bottom chords providing thermal bridging (5% framing). Construction R-values were taken from the *House Insulation Guide*, assuming that the batts would cover the chords once they were at least twice as deep (180+ mm). Additionally, insulation was assumed to be compressed at the edges of the roof, and this was accounted for using the estimator and correction in the *House Insulation Guide* as appropriate (Table 1).

- The single-storey and double-storey houses had slopes of 25° with roof slope area to perimeter (A/P) ratios of 3.7 and 2.2 respectively.
- The medium-density house has a low-slope roof (5°) using steel beams running crossways and a dropped ceiling. This construction would make it difficult to fit thicker insulation into the ~2 m perimeter area at the low end of the roof, and the steel sections would produce significant thermal bridging and potential moisture risks. For simplicity and consistency, we modelled it as instead having a low-slope truss roof for the purposes of testing how well these constructions work from an H1 perspective. With a raised heel, the low-slope truss should have no need to compress the insulation at the edge and so no correction was applied.
- The apartment building departs from this set-up slightly as it uses a suspended ceiling system with the insulation layered over the ceiling grid rather than a truss system. R-values were calculated excluding the bridging from the trusses.

Table 1: Ceiling insulation and roof construction R-values for different houses

Insulation	1 R3.0 batts 160mm	2 R3.3 batts 155mm	3 R3.4 batts 110mm	4 R3.6 batts 180mm	5 R4.0 batts 195mm	6 R4.5 batts 210mm	7 R5.0 batts 225mm	8 R6.0 batts 245mm	9 R7.0 batts 275mm	10 R8.0 batts 330mm
Single storey	R2.91	R3.21	R3.39	R3.58	R3.96	R4.42	R4.90	R5.84	R6.78	R7.69
Two storey	R2.89	R3.18	R3.39	R3.54	R3.91	R4.35	R4.81	R5.71	R6.63	R7.44
Medium density	R2.95	R3.24	R3.39	R3.64	R4.04	R4.54	R5.04	R6.04	R7.07	R7.81
Apartment	R3.31	R3.61	R3.71	R3.91	R4.31	R4.81	R5.31	R6.31	R7.31	R8.31

2.2.2.2 Walls

Walls are timber-framed with timber weatherboards on a ventilated cavity. Frame ratio is assumed to be 24%. Options include two basic 90 mm walls to meet 4th and 5th edition H1 requirements and two more heavily insulated 140 mm options (Table 2). Note that, in the 5th edition of the *House Insulation Guide*, R2.2 batts achieved a construction R-value of R1.9 and were used for compliance. Slight changes to calculations in the 6th edition have made that no longer the case.

Table 2: Wall insulation and construction R-value

Insulation	1 R2.5 batts, 90mm stud	2 R2.8 batts, 90mm stud	3 R4.0 batts, 140mm stud	4 R4.4 batts, 140mm stud
Construction R-value	R1.91	R2.0	R2.82	R2.93

2.2.2.3 Floors

While the primary floor type in the models is concrete slab, there are still some elements where insulated timber floors are present. The medium-density house has some small cantilevered sections, and the double-storey house has the floor over the garage. Additionally, as we have placed the garage outside the thermal envelope following recommended practice in H1, the living room floor over the garage in the medium-density house needs to be insulated as well.

The timber floors were calculated with 140 mm joists at 450 centres and ~11% framing, and the bottom of the joists was lined. These R-values do not include floor coverings as per H1. For floors over the garage, we have assumed internal surface coefficients rather than external.

For the suspended concrete floor over the garage in the medium-density house, it was assumed that the same batts as the timber floor sections would be used but without bridging from timber framing. Note that the values for the medium-density house here are the average across the house – the different floor sections have varying construction R-values and the insulation selected for compliance was chosen based on the lowest R-value floor section (Table 3).

Table 3: Suspended floor insulation and average construction R-value

Insulation	1 R1.5 batts	2 R1.8 batts	3 R2.0 batts	4 R2.6 batts	5 R2.8 batts	6 R3.0 batts	7 R3.2 batts
Two storey	R1.83	R2.04	R2.19	R2.80	R2.91	R3.10	R3.34
Medium density	R1.95	R2.24	R2.43	R3.03	R3.22	R3.42	R3.62

2.2.2.4 Slabs

Ten concrete slab options with varying combinations of edge and underslab insulation were modelled. It should be noted that there have been a number of changes to slab R-value calculations since the previous analysis and update to H1 – in particular, the addition of a correction factor in the *House Insulation Guide* reducing the effect of edge insulation in order to account for the (typical) lack of a thermal break between the house and garage. Slab A/P ratios and the fraction of the perimeter that was along the garage wall were calculated from the models as shown in Table 4.

Table 4: Slab A/P ratios and garage perimeter fraction

Building	A/P ratio	Fraction of perimeter length abutting garage
Single storey	2.4	18%
Two storey	1.6	26%
Medium density	1	45%

Note here how the garage uses up a large proportion of the ground floor of the double-storey house and the A/P ratio of the slab within the thermal envelope is on the edge of what the *House Insulation Guide* and tables in H1/AS1 support at 1.6.

In the medium-density development, the house is on a slope, and the ground floor consists of both part of the first-floor living room and the bottom of the stairs going down to the garage. Placing the garage outside the thermal envelope makes the A/P ratio very low and the fraction of the perimeter that has no edge insulation due to the garage is very high, making it very difficult to achieve acceptable R-values. R-values for an A/P ratio of 1.0 were estimated by extrapolating backwards from A/P = 1.6 based on the difference between an A/P ratio of 1.6 and 2.2.

Table 5: Slab constructions and R-values

Insulation	1 No insulation	2 R1.0 edge insulation	3 R1.2 underslab insulation	4 R2.4 underslab insulation	5 R1.2 underslab + edge insulation	6 R2.4 underslab + edge insulation	7 40mm R1.0 slab topper insulation	8 Raft slab	9 Raft + R1.0 edge insulation
Single storey	R0.94	R1.15	R1.4	R1.65	R1.72	R2.06	R2.99	R1.24	R1.47
Two storey	R0.71	R0.86	R1.1	R1.29	R1.35	R1.6	R2.35	R0.97	R1.14
Medium density	R0.54	R0.63	R0.87	R1.02	R1.04	R1.22	R1.77	R0.77	R0.87

2.2.2.5 Windows

Four window options were tested ranging from basic clear aluminium-framed double glazing used under H1/AS1 4th edition to low-E thermally broken double glazing achieving H1/AS1 5th edition R-values (Table 6).

Table 6: Modelled window details[5]

Nominal R-value	Glass	Frame	Spacer	Spacer psi	Ucog EN673	Uframe	Frame fraction	SHGC glass
0.26	Clear_glass_4mm, Air_12mm, Clear_glass_4mm	Aluminium	Aluminium	0.023	2.9	7	23%	0.792
0.37	Clear_glass_4mm, ArgonAir_16mm, PlanithermUltraNII_glass_4mm	Aluminium	Thermally improved	0.051	1.1	7	23%	0.602
0.46	Clear_glass_4mm, ArgonAir_12mm, PlanithermUltraNII_glass_4mm	Thermally Broken	Thermally improved	0.041	1.3	4	27%	0.601
0.5	Clear_glass_4mm, ArgonAir_16mm, PlanithermUltraNII_glass_4mm	Thermally Broken	Thermally improved	0.041	1.1	4	27%	0.602

Ucog was calculated using the WGANZ glazing calculator,[6] from which we selected Planitherm Ultra N II glass (ID#20851 in Window 7) as an example of low-E glazing used in New Zealand that achieved the required R-values. From there, the windows were defined following Table E.1.1.1 in H1/AS1 to reflect typical practice. Frame and spacer properties were set to match – aluminium frames assumed U7.9, thermally broken frames assumed U4.0. Spacer psi values are WEERS defaults for New Zealand. Assumed frame fractions of 23% and 27% are based on estimates of average window frame ratios in a typical house. Ucog 1.1 and Ucog 1.3 IGUs were produced using the same glass, simply varying the thickness of the air gap. Argon fills were assumed to be a 90:10 argon:air mix.

It should be noted here that the WGANZ calculator estimates clear double glazing to have Ucog = 2.9 W/m².K, which does not match the value given in H1/AS1 (Ucog = 2.63). Using these figures, the clear aluminium double glazing in these models ends up with an R-value slightly below the R0.26 it is nominally supposed to have. This change in the nominal R-value is a result of changes to calculation approaches rather than a change in window performance per se, and so we have not changed how we model the windows. Ideally the line for clear double glazing in Table E.1.1.1 would be updated to reflect current practice.

It should be noted here that these are just examples of windows chosen to match the options requested by MBIE from Table E.1.1.1 – actual window performance will vary depending on the specifics of the window suite, glass selection and window areas and dimensions.

2.2.2.6 Exclusions

Several elements in the models that were not part of the core constructions being compared above have been excluded from the analysis. This includes:

- the retaining walls at the back of the stairs in the medium-density house
- the inter-tenancy walls between dwellings in the medium-density house
- the floor of the apartment building over the offices below.

[5] The SHGC of the glass was calculated in Window 7 using CEN conditions and is reported for informational purposes – as the detailed window construction method was used in EnergyPlus, it was not input into the model.

[6] https://www.wganz.org.nz/igu-thermal-calculator/

These are all in the energy models, but their constructions have not been varied and they have not been costed. The medium-density house includes retaining walls around the back of the garage and ground floor. This is a different construction to the basic external wall construction being focused on and has not been costed. With the removal of the garage from the thermal envelope, only a small area of retaining wall at the back of the stairwell is even part of the external envelope, comprising less than 2% of the external wall area. Moreover, the recommended approach using Kiva in EnergyPlus to model such foundation walls between an upper and lower zone (as the living zone is above the retaining wall) is to simply approximate it as adiabatic. This means there would be no heat loss through it in the model. In this light, it was felt simplest to simply assign the retaining wall a constant construction and ignore it in the analysis. The retaining walls behind the stairs were estimated to have an A/P ratio of ~0.6, giving a very rough base R-value of 0.4 for a similar concrete slab. To this, we simply added 70 mm R2.2 batts strapped and lined (frame ratio of 11%) to produce a crude nominal R-value of R2.1, which was applied to all models.

Similarly, the inter-tenancy walls between the dwellings were left as described in the consent documentation – concrete panels with foam insulation on both sides. Again, this is a very different construction to the external timber walls being focused on and has not been costed. It would be difficult to apply those walls to the inter-tenancy wall, which has very different requirements. It would not make a lot of sense, for example, to add the external wall insulation twice on both sides of the inter-tenancy wall purely for the sake of varying it. As the documented inter-tenancy wall construction R-value was well over minimum schedule method requirements anyway (R2.4), it was left constant across all models and ignored in the analysis.

The apartment building floor is over conditioned offices and so does not experience meaningful heat loss in the model. In that light, floor constructions for the apartment were not costed and the floor was ignored in analysis. The floor was simply assigned R1.8 acoustic batts as in the documentation, and this was not varied between models.

2.2.3 Code-compliant construction sets

MBIE asked BRANZ to model four different combinations of constructions that achieved compliance under:

- H1/AS1 4th edition schedule method R-values
- H1/AS1 5th edition (current) schedule method R-values
- the lowest-cost combination of constructions that achieves compliance using the calculation method (H1/AS1)
- the lowest-cost combination of constructions that achieves compliance using the modelling method (H1/VM1).

These were put together based on the constructions outlined previously, taking the closest construction that would achieve a given R-value for that house. This could vary. For example, the lower A/P ratio of the double-storey house meant that, after the correction for roof insulation compression at the edge was applied, it narrowly failed to achieve R2.9 (H1/AS1 4th edition schedule method) with R3.0 batts and had to use R3.3 instead.

Slab constructions in particular varied significantly compared to the BRANZ 2020 study on H1 due to differences between houses and changes in calculation methods. Key changes include:

- the increase in assumed soil conductivity from 1.2 to 2.0 W/m.K
- the addition of a correction factor for the effect of not having edge insulation between the house and garage in the BRANZ *House Insulation Guide*
- the removal of the assumption that an uninsulated slab is R1.3 regardless of A/P ratio.

With the garage outside the thermal envelope and the edge between it and the house counted as exposed perimeter, the A/P ratio of the slab would be quite low. This is particularly the case for the multi-storey houses here – the double-storey house has a ratio of 1.6 and the medium-density development has a ratio of ~1.0. This is due to the bottom of the stairwell next to the garage on the ground floor – a small narrow area with most of its perimeter exposed to the adjacent garage(s). This can make achieving schedule method R-values very difficult – and indeed the double-storey house cannot reach the zone 6 requirement of R1.7 with standard underslab and edge insulation. One would need to either fully insulate the foundations as well (requiring specific engineering design) or use slab topper insulation. The same is true to a greater degree with the medium-density house, which requires foundation insulation or slab topper insulation to even achieve R1.3.

While slab topper insulation achieves very high nominal R-values in static heat loss calculations, its performance in dynamic energy simulations tends to be worse due to it preventing the house from making use of the thermal mass of the concrete slab. Being pushed into using it to comply with the schedule method in cases like this is not necessarily ideal from a performance standpoint.

To identify the lowest-cost construction sets that would comply using the calculation method, we calculated the heat loss of every combination of the given constructions. We then selected the lowest upfront cost option that had a lower heat loss than the reference in each climate zone. Options that would fall below 50% of the minimum R-value (H1/AS1 2.1.3.8) were also excluded – if they were not, the cheapest option for zones 1–3 for the double-storey house and zone 1 for the medium-density house would use R3.0 roof batts. The same process was carried out for the modelling method using an iterative process:

- The difference between the reference model (with 30% WWR) and the baseline (the actual design with various Code-compliant insulation levels) was calculated. This produced an allowance for how much we could increase the energy use by adjusting insulation levels. For example, the baseline might use 1,000 kWh less energy than the reference model, which means we can increase energy use by up to 1,000 kWh and still comply.
- The effect of each individual construction was estimated by comparing it to the baseline model. These effects were then added together to see what combinations would add up to produce an effect less than the difference between the baseline and reference. Continuing the above example, if reducing the wall, roof, slab and window insulation increased the baseline energy use by 800 kWh, we would expect this to comply as the reference was 1,000 kWh above the baseline.
- From there, the lowest-cost combination that complied was selected. The complete combination was then simulated to check that it did in fact use less energy than the reference. If it did not, the next-cheapest combination was selected.

Note that the raft slabs were excluded from the set of possible constructions due to lack of cost data to compare them against the regular slabs. We note here that the modelling method compliant construction sets would not necessarily comply when using the calculation method. The uninsulated slab options for the double-storey and medium-density houses for example would fail the 50% rule as would the use of R3.0 roof batts in zones 1 and 2. That being said, even ignoring that restriction models that comply using the modelling method do not necessarily comply using the calculation method and vice versa.

When checking compliance following H1/VM1, we chose to use the reference model including the eaves. H1/VM1 allows the option of removing eaves and other external shading from the reference model (D.1.11.1), which would increase cooling loads and make achieving compliance easier.

The constructions used for the sets are outlined in Table 7 to Table 11.

Table 7: Single-storey house construction sets for different climates

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	H1 4th ed schedule	R2.5 batts	R3.0 batts	.	R1.2 underslab	Aluminium double glazing
Zone 2 - Napier	H1 4th ed schedule	R2.5 batts	R3.0 batts	.	R1.2 underslab	Aluminium double glazing
Zone 3 - Wellington	H1 4th ed schedule	R2.5 batts	R3.0 batts	.	R1.2 underslab	Aluminium double glazing
Zone 4 - Taupo	H1 4th ed schedule	R2.8 batts	R3.6 batts	.	R1.2 underslab	Aluminium double glazing
Zone 5 - Christchurch	H1 4th ed schedule	R2.8 batts	R3.6 batts	.	R1.2 underslab	Aluminium double glazing
Zone 6 - Queenstown	H1 4th ed schedule	R2.8 batts	R3.6 batts	.	R1.2 underslab	Aluminium double glazing
Zone 1 - Auckland	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	R2.4 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 2 - Napier	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	R2.4 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 3 - Wellington	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	R2.4 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 4 - Taupo	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	R2.4 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 5 - Christchurch	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	R2.4 underslab	Thermally broken low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	R1.2 underslab + edge	Thermally broken low-E3 argon double glazing Ucog 1.1
Zone 1 - Auckland	H1 5th ed calculation	R2.8 batts	R4.0 batts	.	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 2 - Napier	H1 5th ed calculation	R2.8 batts	R4.0 batts	.	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 3 - Wellington	H1 5th ed calculation	R2.8 batts	R4.0 batts	.	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 4 - Taupo	H1 5th ed calculation	R2.8 batts	R3.6 batts	.	R2.4 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 5 - Christchurch	H1 5th ed calculation	R4.0 batts	R3.6 batts	.	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	H1 5th ed calculation	R4.0 batts	R3.6 batts	.	R2.4 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 1 - Auckland	H1 5th ed modelling	R2.8 batts	R3.0 batts	.	Uninsulated	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 2 - Napier	H1 5th ed modelling	R2.8 batts	R7.0 batts	.	Uninsulated	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 3 - Wellington	H1 5th ed modelling	R2.8 batts	R7.0 batts	.	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 4 - Taupo	H1 5th ed modelling	R4.0 batts	R3.6 batts	.	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	H1 5th ed modelling	R2.8 batts	R7.0 batts	.	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	H1 5th ed modelling	R4.0 batts	R3.6 batts	.	R2.4 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3

Table 8: Double-storey house construction sets for different climates

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	H1 4th ed schedule	R2.5 batts	R3.3 batts	R1.5 batts	R1.2 underslab + edge	Aluminium double glazing
Zone 2 - Napier	H1 4th ed schedule	R2.5 batts	R3.3 batts	R1.5 batts	R1.2 underslab + edge	Aluminium double glazing
Zone 3 - Wellington	H1 4th ed schedule	R2.5 batts	R3.3 batts	R1.5 batts	R1.2 underslab + edge	Aluminium double glazing
Zone 4 - Taupo	H1 4th ed schedule	R2.8 batts	R3.6 batts	R1.5 batts	R1.2 underslab + edge	Aluminium double glazing
Zone 5 - Christchurch	H1 4th ed schedule	R2.8 batts	R3.6 batts	R1.5 batts	R1.2 underslab + edge	Aluminium double glazing
Zone 6 - Queenstown	H1 4th ed schedule	R2.8 batts	R3.6 batts	R1.5 batts	R1.2 underslab + edge	Aluminium double glazing
Zone 1 - Auckland	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R2.6 batts	R2.4 underslab + edge	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 2 - Napier	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R2.6 batts	R2.4 underslab + edge	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 3 - Wellington	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R2.6 batts	R2.4 underslab + edge	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 4 - Taupo	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R2.6 batts	R2.4 underslab + edge	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 5 - Christchurch	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R3.0 batts	R2.4 underslab + edge	Thermally broken low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R3.0 batts	40mm R1.0 slab topper[1]	Thermally broken low-E3 argon double glazing Ucog 1.1
Zone 1 - Auckland	H1 5th ed calculation	R2.8 batts	R3.6 batts	R2.8 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 2 - Napier	H1 5th ed calculation	R2.8 batts	R3.6 batts	R2.8 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 3 - Wellington	H1 5th ed calculation	R2.8 batts	R3.6 batts	R2.8 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 4 - Taupo	H1 5th ed calculation	R2.8 batts	R3.6 batts	R2.8 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	H1 5th ed calculation	R4.0 batts	R3.6 batts	R2.8 batts	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	H1 5th ed calculation	R4.0 batts	R3.6 batts	R2.8 batts	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 1 - Auckland	H1 5th ed modelling	R2.8 batts	R3.0 batts	R1.5 batts	Uninsulated	Aluminium double glazing
Zone 2 - Napier	H1 5th ed modelling	R2.8 batts	R3.0 batts	R1.5 batts	Uninsulated	Aluminium double glazing
Zone 3 - Wellington	H1 5th ed modelling	R2.8 batts	R7.0 batts	R1.5 batts	Uninsulated	Aluminium double glazing
Zone 4 - Taupo	H1 5th ed modelling	R2.8 batts	R3.6 batts	R1.5 batts	Uninsulated	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	H1 5th ed modelling	R2.8 batts	R3.6 batts	R1.5 batts	Uninsulated	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	H1 5th ed modelling	R2.8 batts	R3.6 batts	R2.8 batts	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1

[1] Replaced with a slab with R1.0 edge and foundation insulation and R1.2 underslab insulation in the reference model for checking compliance with the modelling method.

Table 9: Medium-density house construction sets for different climates[7]

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	H1 4th ed schedule	R2.5 batts	R3.0 batts	R1.5 batts	40mm R1.0 slab topper	Aluminium double glazing
Zone 2 - Napier	H1 4th ed schedule	R2.5 batts	R3.0 batts	R1.5 batts	40mm R1.0 slab topper	Aluminium double glazing
Zone 3 - Wellington	H1 4th ed schedule	R2.5 batts	R3.0 batts	R1.5 batts	40mm R1.0 slab topper	Aluminium double glazing
Zone 4 - Taupo	H1 4th ed schedule	R2.8 batts	R3.6 batts	R1.5 batts	40mm R1.0 slab topper	Aluminium double glazing
Zone 5 - Christchurch	H1 4th ed schedule	R2.8 batts	R3.6 batts	R1.5 batts	40mm R1.0 slab topper	Aluminium double glazing
Zone 6 - Queenstown	H1 4th ed schedule	R2.8 batts	R3.6 batts	R1.5 batts	40mm R1.0 slab topper	Aluminium double glazing
Zone 1 - Auckland	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R2.6 batts	40mm R1.0 slab topper	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 2 - Napier	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R2.6 batts	40mm R1.0 slab topper	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 3 - Wellington	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R2.6 batts	40mm R1.0 slab topper	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 4 - Taupo	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R3.0 batts	40mm R1.0 slab topper	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 5 - Christchurch	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R3.2 batts	40mm R1.0 slab topper	Thermally broken low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	H1 5th ed. schedule	R2.8 batts	R7.0 batts	R3.2 batts	40mm R1.0 slab topper	Thermally broken low-E3 argon double glazing Ucog 1.1
Zone 1 - Auckland	H1 5th ed calculation	R2.8 batts	R4.0 batts	R3.2 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 2 - Napier	H1 5th ed calculation	R2.8 batts	R4.0 batts	R3.2 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 3 - Wellington	H1 5th ed calculation	R2.8 batts	R4.0 batts	R3.2 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 4 - Taupo	H1 5th ed calculation	R2.8 batts	R3.6 batts	R2.8 batts	R1.2 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 5 - Christchurch	H1 5th ed calculation	R2.8 batts	R3.6 batts	R2.8 batts	R2.4 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 6 - Queenstown	H1 5th ed calculation	R2.8 batts	R3.6 batts	R3.2 batts	R2.4 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 1 - Auckland	H1 5th ed modelling	R2.8 batts	R3.0 batts	R1.5 batts	Uninsulated	Aluminium double glazing
Zone 2 - Napier	H1 5th ed modelling	R2.8 batts	R3.0 batts	R1.5 batts	Uninsulated	Aluminium double glazing
Zone 3 - Wellington	H1 5th ed modelling	R2.8 batts	R4.0 batts	R2.8 batts	Uninsulated	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 4 - Taupo	H1 5th ed modelling	R2.8 batts	R3.6 batts	R1.5 batts	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	H1 5th ed modelling	R2.8 batts	R3.6 batts	R2.8 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	H1 5th ed modelling	R2.8 batts	R3.6 batts	R3.0 batts	R1.2 underslab	Thermally broken low-E3 argon double glazing Ucog 1.3

[7] Note that the floor batts were selected to ensure that the lowest R-value floor construction achieved the schedule method minimum.

Table 10: Apartment building construction sets for different climates

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	H1 4th ed schedule	R2.5 batts	R3.0 batts	.	.	Aluminium double glazing
Zone 2 - Napier	H1 4th ed schedule	R2.5 batts	R3.0 batts	.	.	Aluminium double glazing
Zone 3 - Wellington	H1 4th ed schedule	R2.5 batts	R3.0 batts	.	.	Aluminium double glazing
Zone 4 - Taupo	H1 4th ed schedule	R2.8 batts	R3.0 batts	.	.	Aluminium double glazing
Zone 5 - Christchurch	H1 4th ed schedule	R2.8 batts	R3.0 batts	.	.	Aluminium double glazing
Zone 6 - Queenstown	H1 4th ed schedule	R2.8 batts	R3.0 batts	.	.	Aluminium double glazing
Zone 1 - Auckland	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	.	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 2 - Napier	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	.	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 3 - Wellington	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	.	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 4 - Taupo	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	.	Thermally broken low-E3 argon double glazing Ucog 1.3
Zone 5 - Christchurch	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	.	Thermally broken low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	H1 5th ed. schedule	R2.8 batts	R7.0 batts	.	.	Thermally broken low-E3 argon double glazing Ucog 1.1

Table 11: Revised apartment building construction sets for different climates[8]

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	H1 5th ed calculation	R4.4 batts	R8.0 batts	.	.	uPVC low-E3 argon double glazing Ucog 1.3
Zone 2 - Napier	H1 5th ed calculation	R4.4 batts	R8.0 batts	.	.	uPVC low-E3 argon double glazing Ucog 1.3
Zone 3 - Wellington	H1 5th ed calculation	R4.4 batts	R8.0 batts	.	.	uPVC low-E3 argon double glazing Ucog 1.3
Zone 4 - Taupo	H1 5th ed calculation	R4.4 batts	R8.0 batts	.	.	uPVC low-E3 argon double glazing Ucog 1.3
Zone 5 - Christchurch	H1 5th ed calculation	R4.4 batts	R8.0 batts	.	.	uPVC low-E3 argon double glazing Ucog 1.3
Zone 6 - Queenstown	H1 5th ed calculation	R4.4 batts	R8.0 batts	.	.	uPVC low-E3 argon double glazing Ucog 1.3
Zone 1 - Auckland	H1 5th ed modelling	R4.4 batts	R8.0 batts	.	.	uPVC low SHGC argon double glazing Ucog 1.2
Zone 2 - Napier	H1 5th ed modelling	R4.4 batts	R8.0 batts	.	.	uPVC low SHGC argon double glazing Ucog 1.2
Zone 3 - Wellington	H1 5th ed modelling	R4.4 batts	R8.0 batts	.	.	uPVC low-E3 argon double glazing Ucog 1.3
Zone 4 - Taupo	H1 5th ed modelling	R4.4 batts	R8.0 batts	.	.	uPVC low-E3 argon double glazing Ucog 1.3
Zone 5 - Christchurch	H1 5th ed modelling	R4.4 batts	R8.0 batts	.	.	uPVC low-E3 argon double glazing Ucog 1.3
Zone 6 - Queenstown	H1 5th ed modelling	R4.4 batts	R8.0 batts	.	.	uPVC low-E3 argon double glazing Ucog 1.3

[8] Note that the apartment building could not comply using any of the available construction options. The windows had to be improved further.

Additionally, to check compliance with the modelling method, a reference model had to be created. This is in general just the H1/AS1 5th edition schedule method model but with a 30% WWR. Two challenges with applying the modelling method were identified during this process:

Setting the WWR to 30%

- H1/VM1 allows two paths to adjust the WWR – adjusting the size of every window by the same proportion or applying a 30% WWR evenly across the entire model.[9] Both of these run into potential problems with walls not having enough room. For proportional adjustment, some walls may not have enough surface area to increase the windows on them by, say, 70%. For even distribution, the problem was that the walls with the front door on them would not have enough room to also cover 30% of the wall in glass.
- The problem with proportional adjustment may be addressed by adjusting windows to their available limit and increasing the area of the remaining windows to compensate for those that cannot be increased all the way. For example, if the goal is to increase every window by 70% to achieve 30% WWR and some windows can only be increased by 50%, you might increase the others by 80% to get the correct overall total. The issue is that technically this no longer meets the H1/VM1 specifications, which demands all the windows be adjusted by the same proportion.
- A simple solution for the even distribution problem is not adding a window to the front door wall if there is not room and increasing the area on the other walls to reach 30% WWR overall. Again, the problem is that you are technically no longer applying an even distribution of windows.

Defining the concrete slab construction while keeping thermal mass consistent

- Under H1/VM1, the thermal mass of the floor should be the same between both the design and reference models (D.1.2.4). You should not compare a timber floor to a slab floor for example (D.1.2.3). The problem here was that, due to low A/P ratios and the garage edge correction, some of the models could only achieve the needed nominal R-values using slab topper insulation. Putting insulation on top of a slab significantly reduces its ability to apply the benefits of the slab's thermal mass.[10] The argument can be made that this means it should not be used in the reference model to be compared against normal slabs because it has less thermal mass. The problem here was that, with the given constructions, we did not have any other way to meet the needed R-values in this context. This is especially a problem for the medium-density house.

Following discussion, it was agreed with MBIE that we would do the following:

- WWRs would be adjusted using the proportional method, limiting windows to the available wall area as needed. A script was run to iteratively adjust the window areas, increasing them up to 90% of the available wall area and then further adjusting the areas of the remaining windows to ensure the total area would meet 30% WWR.
- In the case of the double-storey house, it was found that the required R1.7 slab R-value in zone 6 could be achieved by a slab with R1.2 underslab insulation and both edge and foundation insulation. As the reference model does not need to be costed – it is purely a tool to work out what constructions could be used to comply using the modelling method – it can deviate from the main construction options if needed. We thus used this construction in this case to keep the thermal mass more consistent. In the case of the medium-density house, the slab was so extreme that no solution could be found in the *House Insulation Guide* that would achieve the required R-values without using slab topper insulation. In this light, it was decided that there was no option but to use the slab topper insulation in the reference model.

[9] Note that these can produce very different results. One may be much easier to achieve compliance with than the other.

[10] Technically, this is also the case for underslab insulation as increased underslab insulation reduces the influence of the mass of the ground.

The external opaque doors were set to have H1 5th edition schedule method minimum R-values of R0.46 or R0.5 depending on the climate zone.

2.2.4 Calculation method calculations

The heat loss calculations showing compliance with the calculation method for the lowest upfront cost construction sets may be found in the attached spreadsheet and are shown in Figure 5 to Figure 7.

Single storey		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	156	6.6	6.6	6.6	6.6	6.6	6.6
Wall	108	2	2	2	2	2	2
Glazing	46	0.46	0.46	0.46	0.46	0.5	0.5
Slab	156	1.5	1.5	1.5	1.5	1.6	1.7
Floor	0	2.5	2.5	2.5	2.8	3	3
	Heat loss	282.86	282.86	282.86	282.86	268.28	262.55
		Lowest cost model complying with calculation method					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	156	3.96	3.96	3.96	3.58	3.58	3.58
Wall	122	2	2	2	2	2.82	2.82
Window	31	0.37	0.37	0.37	0.46	0.37	0.46
Slab	156	1.65	1.65	1.65	1.65	1.65	1.65
Floor	0						
Doors	2	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	282.12	282.12	282.12	269.96	268.22	251.88
	diff	-0.74	-0.74	-0.74	-12.91	-0.06	-10.67

Figure 5: Single-storey house – heat loss calculations for lowest-cost construction method models

Double storey		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	90	6.6	6.6	6.6	6.6	6.6	6.6
Wall	142	2	2	2	2	2	2
Glazing	61	0.46	0.46	0.46	0.46	0.5	0.5
Slab	64	1.5	1.5	1.5	1.5	1.6	1.7
Floor	26	2.5	2.5	2.5	2.8	3	3
	Heat loss	270.06	270.06	270.06	268.97	255.09	252.73
		Lowest cost model complying with calculation method					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	90	3.54	3.54	3.54	3.54	3.54	3.54
Wall	165	2	2	2	2	2.82	2.82
Window	35	0.37	0.37	0.37	0.37	0.37	0.37
Slab	64	1.29	1.29	1.29	1.29	1.1	1.1
Floor	26	2.91	2.91	2.91	2.91	2.91	2.91
Doors	3	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	268.36	268.36	268.36	268.36	252.51	252.51
	diff	-1.70	-1.70	-1.70	-0.60	-2.58	-0.22

Figure 6: Double-storey house – heat loss calculations for lowest-cost calculation method models

Medium density	Reference model						
	R-value						
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	383	6.6	6.6	6.6	6.6	6.6	6.6
Wall	644	2	2	2	2	2	2
Glazing	276	0.46	0.46	0.46	0.46	0.5	0.5
Slab	171	1.5	1.5	1.5	1.5	1.6	1.7
Floor	222	2.5	2.5	2.5	2.8	3	3
	Heat loss	1183.05	1183.05	1183.05	1173.53	1113.11	1106.83
		Lowest cost model complying with calculation method					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	383	4.04	4.04	4.04	3.64	3.64	3.64
Wall	635	2	2	2	2	2	2
Window	150	0.37	0.37	0.37	0.46	0.46	0.46
Slab	171	1.02	1.02	1.02	0.87	1.02	1.02
Floor	222	3.62	3.62	3.62	3.22	3.22	3.62
Retaining	26	2.1	2.1	2.1	2.1	2.1	2.1
Intertenar	65	2.4	2.4	2.4	2.4	2.4	2.4
Door	44	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	1181.13	1181.13	1181.13	1148.91	1112.38	1104.76
	diff	-1.91	-1.91	-1.91	-24.62	-0.72	-2.07

Figure 7: Medium-density house – heat loss calculations for lowest-cost calculation method models

2.2.5 Apartment building compliance

After analysis, it was found that there was no combination of the requested constructions that would allow the apartment building to comply with either the calculation or modelling method. This is not a surprise to a degree. The apartments do not have a concrete slab and floor insulation has minimal effect on them, thus there is no scope to improve performance via changes to floor insulation. The highest window R-value in the available constructions is simply the H1/AS1 5th edition schedule values. Roof insulation similarly has limited capacity to improve the performance of the building as it only affects the top floor and the highest batts in the available constructions here were R8.0, not much higher than the R7.0 batts used to meet current H1/AS1 schedule method minimums. This means that the only tool we can use to try to improve energy efficiency in the apartments is increasing the wall thickness, which can only do so much on its own – especially when 47% of the walls are windows.

Following discussion with MBIE, we carried out some brief testing to see how much more we would have to improve insulation levels in order to achieve compliance, focusing on the windows. These changes were done purely for informational purposes and are outside the scope of what has been costed. It should also be noted here that, legally, the apartment building is not allowed to use the calculation method to demonstrate compliance as its WWR is >40% (H1/AS1 2.1.2.2) (though it would have been under the H1/AS1 4th edition, which allowed the calculation method to be used up to 50% WWR).

Using the calculation method and assuming the walls and roof have been set to the highest available R-values here (R8.0 ceiling batts, 140 mm R4.4 wall insulation), the window R-values would need to be at least 0.57 to 0.61 to comply (Figure 8). Using Table E.1.1.1 in H1/AS1, this could be achieved by swapping to uPVC frames (R_w = 0.63 for Ucog = 1.3).

		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	413	6.6	6.6	6.6	6.6	6.6	6.6
Wall	1452	2	2	2	2	2	2
Glazing	622	0.46	0.46	0.46	0.46	0.5	0.5
Slab	0	1.5	1.5	1.5	1.5	1.6	1.7
Floor	0	2.5	2.5	2.5	2.8	3	3
	Heat loss	2141.78	2141.78	2141.78	2141.78	2033.54	2033.54
		Indicative model complying with calculation method					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	413	8.31	8.31	8.31	8.31	8.31	8.31
Wall	1105	2.93	2.93	2.93	2.93	2.93	2.93
Window	970	0.57	0.57	0.57	0.57	0.61	0.61
Slab	0						
Floor	0						
	Heat loss	2128.51	2128.51	2128.51	2128.51	2016.92	2016.92
	diff	-13.27	-13.27	-13.27	-13.27	-16.62	-16.62

Figure 8: Illustration of how the apartment building model could comply using the calculation method

Using the modelling method, it was found that this window could comply in the colder climate zones (zones 3–6) but that cooling loads would need to be reduced more in the hotter climate zones (Table 12). This could be achieved by using a low-emissivity low SHGC glass[11] as well as the uPVC frame.

Table 12: Improved windows applied to allow apartment building to comply using the calculation and modelling methods

Nominal R-value	Glass	Frame	Spacer psi	Ucog EN673	Uframe	Frame fraction	SHGC glass
0.63	Clear_glass_4mm, ArgonAir_12mm, PlanithermUltraNII_glass_4mm	uPVC	0.04	1.3	1.8	34%	0.601
0.63	Clear_glass_4mm, ArgonAir_12mm, Planistar_glass_4mm	uPVC	0.04	1.2	1.8	34%	0.434

2.2.6 Model updates

The models used for the current analysis are not identical to the ones used previously. They have over the years been adjusted and updated to reflect BRANZ research and improvements to modelling practice. The overall effect of these changes is, in general, that they produce lower energy use estimates, though this does depend on the model (Figure 9). Cooling loads in particular are dramatically reduced, in large part due to deliberate changes to our modelling assumptions following discussions with MBIE in order to focus H1/VM1 compliance more on heating use than cooling use (Figure 10).

The apartment model is especially affected here. In previous work, its energy use was heavily cooling dominated, and it behaved very differently to the other houses. A number of the model changes here are a result of recent BRANZ research into the modelling of overheating in apartment buildings, which identified issues such as interior surface reflectances, detailed modelling of the surrounding urban environment and the solar distribution algorithm as being particularly important when modelling apartments. These changes significantly reduced its cooling loads. Combined with the other changes here, the modelled energy use is no longer cooling dominated and is in line with that of the houses.

[11] In the model, we used 4 mm Planistar Sun, ID# 21405 in LBNL Window 7.

Base energy comparison		Old		New			
		Cooling (kWh/m2)	Heating (kWh/m2)	Base Cooling (kWh/m2)	Base Heating (kWh/m2)	Relative cooling	Relative heating
Single storey	Zone 1 - Auckland	11.9	18.6	8.7	13.7	73%	74%
Single storey	Zone 2 - Napier	11.2	32.2	8.0	26.6	72%	83%
Single storey	Zone 3 - Wellington	4.6	44.6	1.5	32.0	32%	72%
Single storey	Zone 4 - Taupo	5.9	58.8	3.9	48.7	65%	83%
Single storey	Zone 5 - Christchurch	5.8	69.7	3.4	55.2	58%	79%
Single storey	Zone 6 - Queenstown	4.4	91.2	2.1	76.3	47%	84%
Two storey	Zone 1 - Auckland	25.4	17.7	12.3	13.4	49%	76%
Two storey	Zone 2 - Napier	25.0	32.2	11.0	27.2	44%	84%
Two storey	Zone 3 - Wellington	15.5	42.1	2.3	30.9	15%	73%
Two storey	Zone 4 - Taupo	17.3	54.7	6.2	50.0	36%	91%
Two storey	Zone 5 - Christchurch	17.6	66.2	6.5	55.2	37%	83%
Two storey	Zone 6 - Queenstown	14.8	87.0	5.3	76.4	36%	88%
Medium density	Zone 1 - Auckland	20.6	11.0	8.4	10.7	41%	98%
Medium density	Zone 2 - Napier	20.0	22.7	6.8	22.1	34%	97%
Medium density	Zone 3 - Wellington	10.7	31.1	0.6	27.4	6%	88%
Medium density	Zone 4 - Taupo	13.4	42.7	3.9	43.2	30%	101%
Medium density	Zone 5 - Christchurch	12.3	51.5	3.5	49.0	29%	95%
Medium density	Zone 6 - Queenstown	11.1	69.6	2.2	69.5	20%	100%
Apartment	Zone 1 - Auckland	43.7	3.4	12.4	13.2	28%	395%
Apartment	Zone 2 - Napier	45.1	10.3	12.7	26.3	28%	256%
Apartment	Zone 3 - Wellington	30.5	14.4	5.1	29.3	17%	204%
Apartment	Zone 4 - Taupo	33.3	21.2	7.7	47.6	23%	225%
Apartment	Zone 5 - Christchurch	29.4	27.3	7.7	52.7	26%	193%
Apartment	Zone 6 - Queenstown	30.5	38.2	6.4	72.4	21%	190%

Figure 9: Comparison of the estimated base energy use between the 2020 models and the new versions using the example of the H1/AS1 4th edition schedule method models

Delivered energy comparison		Old		New						
		Cooling (kWh/m2)	Heating (kWh/m2)	Delivered Cooling (kWh/m2)	Delivered Heating (kWh/m2)	Relative cooling	Relative heating	Old total	New total	Relative total
Single storey	Zone 1 - Auckland	9.0	13.7	2.3	8.6	26%	63%	22.75	10.94	48%
Single storey	Zone 2 - Napier	8.3	24.2	2.1	17.1	26%	71%	32.56	19.26	59%
Single storey	Zone 3 - Wellington	3.7	34.1	0.4	20.8	11%	61%	37.75	21.19	56%
Single storey	Zone 4 - Taupo	4.7	45.1	1.0	31.9	22%	71%	49.76	32.95	66%
Single storey	Zone 5 - Christchurch	4.4	53.7	0.9	35.9	21%	67%	58.11	36.83	63%
Single storey	Zone 6 - Queenstown	3.6	70.7	0.5	50.3	15%	71%	74.30	50.84	68%
Two storey	Zone 1 - Auckland	20.2	12.8	3.3	8.5	16%	66%	33.03	11.79	36%
Two storey	Zone 2 - Napier	20.0	23.8	2.9	17.1	15%	72%	43.80	20.08	46%
Two storey	Zone 3 - Wellington	12.5	30.8	0.6	19.3	5%	63%	43.28	19.85	46%
Two storey	Zone 4 - Taupo	13.9	40.1	1.6	30.8	12%	77%	54.03	32.46	60%
Two storey	Zone 5 - Christchurch	14.2	48.4	1.7	34.1	12%	70%	62.64	35.80	57%
Two storey	Zone 6 - Queenstown	12.1	63.6	1.4	46.8	12%	74%	75.71	48.24	64%
Medium density	Zone 1 - Auckland	18.8	8.8	2.2	6.3	12%	72%	27.54	8.54	31%
Medium density	Zone 2 - Napier	18.5	18.2	1.8	12.8	10%	70%	36.67	14.56	40%
Medium density	Zone 3 - Wellington	10.5	24.7	0.2	14.9	2%	60%	35.16	15.04	43%
Medium density	Zone 4 - Taupo	12.7	33.7	1.1	23.0	8%	68%	46.47	24.04	52%
Medium density	Zone 5 - Christchurch	11.6	40.7	0.9	26.2	8%	64%	52.32	27.10	52%
Medium density	Zone 6 - Queenstown	10.7	54.9	0.6	36.6	6%	67%	65.54	37.18	57%
Apartment	Zone 1 - Auckland	34.7	2.5	3.3	8.2	10%	329%	37.19	11.50	31%
Apartment	Zone 2 - Napier	35.8	7.5	3.4	15.9	9%	212%	43.31	19.26	44%
Apartment	Zone 3 - Wellington	24.8	10.5	1.4	17.7	5%	170%	35.30	19.08	54%
Apartment	Zone 4 - Taupo	26.9	15.3	2.1	28.1	8%	184%	42.20	30.17	71%
Apartment	Zone 5 - Christchurch	23.8	19.5	2.1	31.2	9%	160%	43.33	33.25	77%
Apartment	Zone 6 - Queenstown	24.9	27.1	1.7	42.4	7%	156%	52.06	44.06	85%

Figure 10: Comparison of the estimated delivered energy use (applying heat pump COPs) between the 2020 models and the new versions using the example of the H1/AS1 4th edition schedule method models

2.2.6.1 Model changes

- Assumed heat pump COP increased from 2.0 to 3.75 and is applied to cooling loads in all zones rather than just the living.
- New TMY3 weather files were updated to include the effects of climate change.
- Ground properties and model – using current H1 ground properties, conductivity raised from 1.2 W/m.K to 2.0 W/m.K. Ground model changed to Kiva, which typically produces warmer results than GroundDomain (though this is climate dependent).
- More slab insulation is applied as a result of the changes to concrete slab R-value assumptions in H1 – uninsulated slabs are no longer deemed to achieve R1.3 as they were before.
- Ventilation setpoint is reduced to 22°C, significantly lowering cooling loads.
- Window modelling – we are no longer using the simple window construction and instead are modelling the windows in detail in EnergyPlus. Window assumptions have also changed – we are assuming higher frame ratios than the old WEERS standard windows and are assuming white window frames, which should lower solar heat gains significantly.
- Internal gains have been reduced to reflect improvements to appliance efficiency and lower metabolic rates when people are sleeping.
- Surface reflectances have been adjusted to be more realistic – this results in models being lighter, particularly the interiors, lowering cooling.
- Solar distribution algorithm set to FullExteriorWithReflections instead of FullExterior.
- Surrounding shading adjusted to reflect real situations more closely (reduced for houses, increased for apartment).
- Thermal mass of timber framing included in models, improving efficiency – particularly cooling.
- Air mixing through internal doors has been added when the house is ventilating.
- Geometry adjustments for the medium-density house to better match plans (increased floor height, some increased window heights). This should increase heating loads.

2.3 Cost-benefit analysis methodology

The cost-benefit analysis was undertaken on both individual building element changes and then for whole-building constructions to answer these research questions:

- For each of the four sample buildings and for the six climate zones, what are the most cost-effective elemental R-values for roofs, walls, windows and floors? Do these combinations comply with the current schedule, calculation and/or modelling methods?
- What are the estimated impacts of changing thermal envelope settings (R-values), compared with the current minimum settings of H1 5th edition amendment 1 for new housing?

The analysis was kept as simple as practical, targeting only the marginal cost differences between using the H1/AS1 5th edition schedule method and alternative methods. The analysis was undertaken over a 50-year period, consistent with the previous study. Given the heating and cooling regime assumed in the thermal modelling that informed this cost-benefit analysis keeps the household within a set temperature range, there are assumed to be no health benefits/costs associated with the analysis. In any case, it would be difficult to quantify any health and wellbeing benefits due to the lack of research in this space. While there is a significant body of work on retrofitting insulation into existing dwellings, the health/wellbeing benefits from incremental changes in insulation levels is not well understood. The process used was as follows:

1. Determine the cost difference between those constructions meeting the schedule method and alternative constructions meeting the calculation or modelling methods.
2. Compare cost differences to the differences in energy costs derived through thermal modelling.
3. Discount the future costs and benefits by our 5% discount rate.
4. Calculate the net present value and benefit-cost ratio.

This methodology is consistent with the other comparable economic analyses previously applied by BRANZ. Costs for construction materials were provided by two quantity surveyor companies contracted separately by MBIE. It should be noted that prices may vary significantly in practice.

To determine appropriate electricity tariffs when calculating energy-related costs, 150 randomly selected, recently constructed New Zealand dwellings were examined. Their tariffs were then investigated, and an average standard and low-user tariff was calculated for each climate zone (Table 13). We tested how sensitive these tariffs were to price increases by using a 1.2% escalation rate (real inflation rate) in each year as well as keeping tariffs stable (0% escalation rate). A 5% discount rate was applied consistent with current Treasury advice[12]. All prices are GST exclusive.

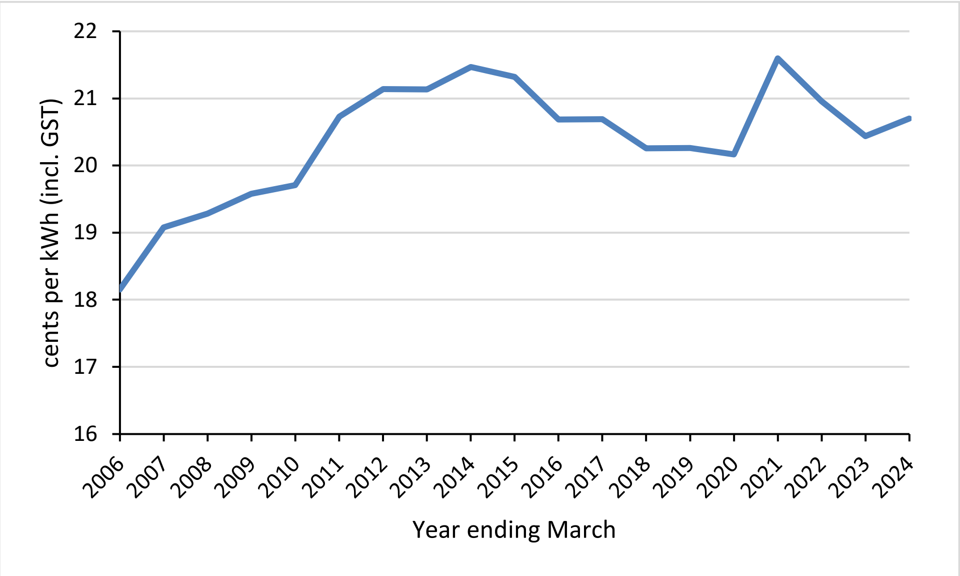
Table 13: Variable electricity charges

Climate zone	Low user	Standard user
Zone 1	24c/kWh	19c/kWh
Zone 2	25c/kWh	23c/kWh
Zone 3	25c/kWh	21c/kWh
Zone 4	26c/kWh	24c/kWh
Zone 5	23c/kWh	20c/kWh
Zone 6	30c/kWh	27c/kWh

Note: Charges rounded to 2 s.f.

2.3.1 Costs

The costs associated with the cost-benefit analysis are those additional heating/cooling costs. MBIE produce a series tracking the real price movements of electricity after excluding lines charges.[13] This shows that there was a rise in variable energy charges between 2006 and 2014 before real prices began to fall through to 2020 (Figure 11). The average annual change in the real variable charge has been 0.7% since 2006 but the real price in 2024 is comparable to the price in 2017.



[12] Note that from October 2024, Treasury has updated their public sector discount rates for cost benefit analysis. The new advice is to use a discount rate of 8% for impacts with private interest benefits and costs. The impact of using an 8% discount rate can be seen in our sensitivity analysis in section 3.1.3.

[13] MBIE household sales-based electricity cost data real residential cost per unit (including GST). https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/energy-prices/electricity-cost-and-price-monitoring

Figure 11: Real residential cost of energy and other components per unit

For the economic analysis that follows, we have models that use either a real variable price escalation rate of 0% or 1.2%. We use 1.2% for consistency with the previous report. We also run comparable models with no real price escalation consistent with recent experience.

2.3.2 Benefits

The benefits are the cost savings associated with less-expensive constructions. The upfront cost savings compared to H1/AS1 5th edition amendment 1 schedule method are presented in Table 14.

Table 14: Upfront cost saving

Upfront cost saving compared to H1 5th edition schedule method												
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	$7,057	$8,184	$6,738	$7,488	$6,925	$7,581	$10,282	$10,933	$10,282	$13,051	$12,801	$18,858
H1 5th ed calculation	$4,297	$4,329	$3,950	$4,108	$4,012	$4,208	$3,898	$4,831	$3,890	$6,152	$3,712	$8,907
H1 5th ed modelling	$9,038	$9,815	$7,036	$7,218	$4,021	$4,337	$3,890	$3,960	$2,318	$4,966	$3,712	$8,907
Double Storey House												
H1 4th ed schedule	$6,246	$9,111	$5,993	$8,469	$6,236	$8,582	$8,523	$9,830	$8,416	$12,371	$9,112	$15,479
H1 5th ed calculation	$7,203	$7,968	$6,935	$7,428	$7,059	$7,492	$7,783	$9,005	$5,748	$6,441	$5,914	$9,565
H1 5th ed modelling	$10,773	$12,213	$9,981	$11,768	$9,090	$10,709	$10,072	$10,905	$9,965	$13,396	$9,204	$15,017
Medium-Density Dwelling (2) (3)												
H1 4th ed schedule	$35,452		$32,408		$33,006		$43,092		$40,041		$44,691	
H1 5th ed calculation	$37,277		$34,808		$35,290		$25,986		$21,934		$25,494	
H1 5th ed modelling	$47,231		$43,909		$38,623		$41,813		$39,141		$26,681	
(1) Based on pricing from two quantity surveyors												
(2) Only one QS gave us cost estimates for timber floors in MDH												
(3) Note that the results for the medium-density dwelling is across 8 dwelling units												

2.4 Hygrothermal analysis methodology

2.4.1 Background

Accumulation of condensation interstitially in New Zealand wall construction has been researched for several decades inside various BRANZ projects as well as internationally. Typical wall and roof construction in the New Zealand context has been of a vapour open flow through design – it is expected that a wall will be designed to minimise the intrusion of liquid water and that the assembly remains vapour open enough to dry both towards the interior and exterior of the dwelling. A key part in achieving reasonable performance with this approach is management of the internal environment – not expecting excess water vapour from occupants to be solely dealt with by the building envelope but that reasonable levels of ventilation and heating are achieved by the occupant.

Earlier work around the time of the leaky building crisis focused on the drying potential of various types of wall configuration and water management strategy. This led to contribution to the international body of work centred on the movement of air in lightweight construction. As part of this work, BRANZ developed a collaboration with the Fraunhofer Institute for Building Physics, incorporating and benchmarking the source and sink model now present in all WUFI releases into the two-dimensional version of the source code.

The basis for this benchmarking was a set of measurement campaigns:

- Moisture was deliberately added into reference wall assemblies with the ability of the wall to recover subsequently measured. This included dosing into the drainage cavity, onto the building wrap and two locations directly onto framing.
- Ventilation rates within the various locations in wall assemblies but mainly focused on the drainage cavity were measured with tracer gas techniques.
- Ventilation rates were measured with multiple ventilation configurations, including bottom vent only (termed open rainscreen), top and bottom vent (drained and vented), drainage plane and direct fixed. Interestingly, the ventilation performance of bottom vent only and top and bottom

vent were closer than expected in terms of performance, mainly due to construction tolerances achievable by the industry.

Experience garnered during this earlier work has underpinned the models created and assessed in the course of this work.

The hygrothermal simulations have focused on understanding whether the recent H1 changes have resulted in increased moisture risks interstitially (inside walls and roofs) or on internal surfaces.

Ostensibly, the requirements for walls have seen very little change in industry practice save for slightly increased insulation R-values being used in some cases. In general, this is likely due to industry acknowledging the impact of framing ratios on achieved performance. However, there is also likely some increased use of the calculation method as a compliance pathway. This pathway gives designers/architects more design freedom in using higher-performing details to trade off thermal resistance elsewhere in the structure.

Roofs differ from walls as there has been a fundamental and significant increase in thermal performance. This has resulted in the question of whether this contributes in a negative way to conditions in roof spaces.

For the above reasons, the analysis has sought to look at the sensitivity of walls to the various factors influencing risk over two nominal R-values that represent 90 mm and 140 mm framing. The same analysis is also applied to roofs for typical schedule method R-values from both H1/AS1 4th edition and H1/AS1 5th edition.

2.4.2 Roof moisture

Roof space moisture accumulation and mould growth in roof spaces has been an issue for the New Zealand building industry for some time. The issues are multi-faceted and depend to a significant extent on factors that are not understood by many in the industry. Typical New Zealand cold roof construction relies on a significant amount of solar radiation to aid in drying of the structure during the daytime, which can be compromised by several factors such as roof solar absorptance, moisture load in the building below (driven by occupants' habits around ventilation and heating), roof colour and roof space ventilation.

It should be noted at this point that the results of hygrothermal simulations are incredibly sensitive to the boundary conditions used as well as site conditions and occupant habits in the real world. It is impossible to consider every single airflow path or potential failure mode. This means the results given here should not be considered an absolute measure of risk of each construction/climate combination but more as an indicator of relative risks between the different combinations.

There are a number of implicit assumptions regarding ventilation rates and moisture generation rates that are difficult to quantify without real-world testing, which means a measured approach should be taken when interpreting the tables in this report.

In a real-world situation, it is also common that a roof void will comprise of multiple pitches sharing a common roof space, and this situation in particular would give results that lie somewhere between the two extremes given here.

2.4.2.1 Roof assessment methodology

Two base models were created in WUFI Pro v6.7.[14] These were of a skillion and a pitched roof and each contained several cases where the roof orientation, colour and insulation level were varied. The roof space air void has also been ventilated using the WUFI source and sink ventilation module and

[14] WUFI® (Wärme und Feuchte instationär) is a software family that allows realistic calculation of the transient coupled one and two-dimensional heat and moisture transport in multi-layer building components exposed to natural weather.

an air layer without additional storage capacity. Roof space ventilation rates were not varied during this study but align with previous BRANZ results calculated from tracer gas experiments.

The models were initially run in the Auckland and Queenstown climate during a testing phase to ensure numerical stability. Once this was completed, a sensitivity analysis was undertaken, varying the external and indoor climates as outlined below.

2.4.2.2 Notes on roof space ventilation

It should be noted that some level of ventilation occurs via unintentional openings in a typical roof structure. Ceiling insulation placed hard against the roof deck has two potential problems – restricting ventilation flow and moisture absorption from condensate on the underside of roofing or underlay, which can impact the service life of the insulation. For these reasons, it is important to maintain clearance.

While roof space ventilation can be a good aid to help reduce condensation risks, there are situations where caution should be raised:

- Where there is shading of a roof due to other structures or topography, it is likely the roof will not receive enough solar radiation to dry during the day, instead accumulating condensate from the very ventilation air that is intended to dry the structure. In these situations, a warm roof is likely a better solution or designing the building so it does not get shaded for extended periods.
- If additional roof ventilation is provided to a roof, more inlet area should be provided at the eaves than at the ridge. Otherwise, there is a high probability additional moist air will be drawn from the living space across the ceiling diaphragm, potentially making any issues worse.
- Climate zones with reasonably high absolute humidity in the external environment have a compromised ability to provide dilution ventilation.

2.4.3 Interstitial moisture in walls

2.4.3.1 Methodology

One base model was created in WUFI Pro v6.7. This was a conventional timber-framed wall with a fibre-cement cladding. The base model contained several cases where the wall orientation, colour and insulation level were varied. The water management/drainage cavity has also been ventilated using the WUFI source and sink ventilation module and an air layer without additional storage capacity. Ventilation rates are set in accordance with the work undertaken in previous experimental campaigns, which were measured with tracer gas techniques.

The models were initially run in the Auckland and Queenstown climates during a testing phase to ensure numerical stability. Once this was completed, a sensitivity analysis was undertaken, varying the external and indoor climates as outlined below.

2.4.4 Climate assumptions

The outdoor climates were taken as the latest climate files for building simulation, recently updated by MBIE/NIWA with testing by BRANZ, Kāinga Ora and various industry representatives. The indoor temperatures were extracted from a base stand-alone model given elsewhere in this report for each climate zone. The internal moisture levels were set assuming a constant ventilation rate with three variations in moisture generation rate following well-established methodology (from ANSI/ASHRAE Standard 160 *Criteria for moisture-control design analysis in buildings*) with a key variation in that the internal relative humidity is allowed to exceed 70% RH.

While a constant ventilation rate in not entirely representative of typical habits, the variation in moisture generation rates does give some sense of the variability of risk to occupant behaviour. A more thorough piece of analysis could be undertaken to test a wider variety of indoor climates.

However, the HEEP2 internal climate dataset would be needed to ensure it is reasonably representative, and this does not conclude for several months.

2.4.5 Key performance indicator (KPI)

After each set of models was run, the KPI used to assess the risk of mould growth was the Finnish VTT mould growth index:

- For the roof models, this was applied to the conditions on the lower side of the roof deck with the full results given in Appendix C.
- For the wall models, two locations were investigated – the conditions at the position of the wall underlay and on the internal surface of the wall lining. Tables of results are given in Appendix C.

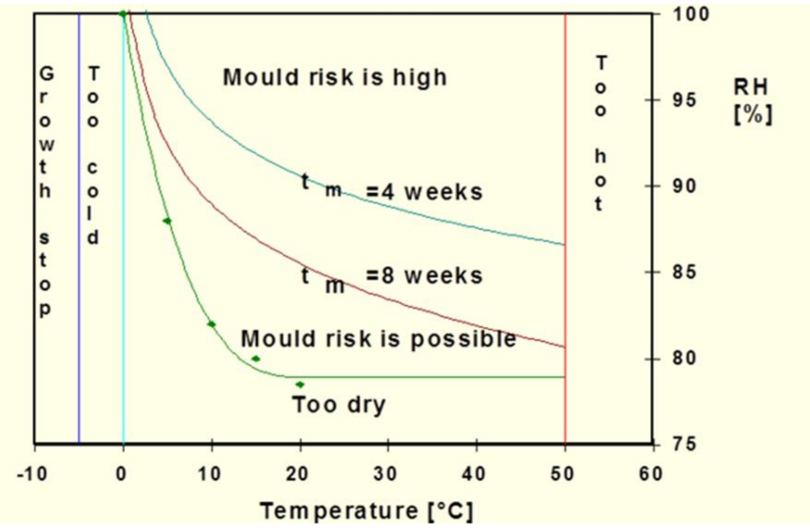
The VTT mould index presents mould growth risk on a scale of 1–6 (Figure 12). Generally, a value above 3 is considered a fail interstitially (inside) the construction whereas a value of 1 or more, is considered unacceptable on surfaces exposed to occupants such as interior linings.

Mould Index	Description of the growth rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or, < 50% coverage of mould (microscope)[1]
4	Visual findings of mould on surface, 10 – 50% coverage, or, > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100 %

Source: Hukka & Viitanen, 1999.

Figure 12: VTT mould index

The VTT index applies best of current knowledge in the growth of mould based on surface temperature and relative humidity. As well as assessing the growth of mould species, the VTT index contains terms that assess the decline of mould populations when conditions are unfavourable. To give some context to this, see Figure 13. Typically observed roof space temperatures exceed 50°C and also drop below 0°C on a regular basis.



Source: Hukka & Viitanen, 1999

Figure 13: Suitable mould growth conditions and some approximations of the time for starting mould growth on the surface of pine sapwood under these conditions

3. Results

3.1 Impacts of changing thermal envelope settings (R-values) for new housing

Direct comparisons to the previous BRANZ H1 analysis undertaken by Jaques et al. (2020) are difficult as the R-values that ended up in H1/AS1 5th edition are not exactly the same as those that were analysed in the 2020 study. While in relative terms the changes in energy use appear similar to those in the previous study (the H1/AS1 5th edition schedule method insulation levels result in ~30–50% lower energy use than the H1/AS1 4th edition), in absolute terms, they are significantly lower. This is due to both model changes such as the new (warmer) climate files and the inclusion of the thermal mass of the timber framing and the significant increase to assumed heat pump COP. Lower energy use means lower energy savings from insulation.

It should be noted that modelled energy efficiency was similar across all buildings. However, using the calculation and modelling methods, you can comply using significantly cheaper constructions than the schedule method – at least as long as the WWR is significantly below 30%. Using the calculation and modelling methods to achieve compliance with less insulation than the schedule method will result in higher energy use. The energy savings people report as a result of upgrading from H1/AS1 4th edition to the H1/AS1 5th edition schedule method insulation levels will be reduced in such situations.

The changes to slab R-value calculations in the H1/AS1 5th edition mean that it is much harder to achieve schedule method R-values. Even H1/AS1 4th edition R-values (R1.3) require underslab insulation now. In some cases with multi-storey houses with lower A/P ratios on the ground floor, the only way to achieve certain R-values was slab topper insulation, which is significantly more expensive while not actually performing better than underslab insulation in the modelling. It is important to remember that the H1/AS1 4th edition schedule method models here represent a hypothetical of what would be constructed now if the schedule method R-values were reduced to those of the H1/AS1 4th edition and are not the same as what was actually constructed under H1.

Even after the reductions to the ventilation setpoint and internal gains, use of the modelling method is still mostly revolved around taking advantage of the increased cooling loads in the reference model to get away with higher heating use. The basic assumption that the reference model system and calculation method is based around – that increasing the window area will result in higher heating use – is not necessarily robust with modern high-performance windows. The reference model often used only slightly more heating than the proposed model with a much lower WWR and in some cases could even need less heating. Cooling differences were always larger.

Models that comply with the modelling method may not comply with the calculation method and vice versa. This does tend to revolve around the fact that the modelling method is working off cooling use, but differences in the handling of slabs is also significant. The modelling method tends to favour lower slab insulation than the calculation method – even making a case for uninsulated slabs as being cost-effective. These differences are not necessarily surprising considering the importance of dynamic mass and ground interactions to slab performance, which is difficult to capture in static R-value calculations.

The apartment building posed a number of problems for analysis due to its high amount of glazing, and should probably be treated separately to the houses. These are the main issues:

- Due to its high WWR, it is technically not legal to use the schedule or calculation methods for compliance (though the calculation method could have been used under the H1/AS1 4th edition).

This also means that comparisons to schedule method constructions need to be caveated with the fact the schedule method models would not comply with H1.

- Due to the high WWR, it was not possible to put together construction sets from the given options that would comply using either the calculation or schedule methods – better windows using uPVC frames are needed.
- The analysis of the individual constructions, however, may still provide an indication of what constructions would be cost-effective in such a building even if they would not comply.
- That the apartment building could not comply using the reference model system in H1/AS1 and H1/VM1 also highlights some of its limitations. Its modelled heating efficiency was very similar to that of the houses that did comply.

3.1.1 Estimated changes to annual household energy costs for space heating and cooling ($/a)

BRANZ modelling suggests relatively modest changes to household energy costs for space heating and cooling. The following tables indicate the estimated additional household energy costs from using the calculation or modelling methods compared to the H1/AS1 5th edition schedule method. Constructions were chosen based on the lowest upfront costs. The calculation and modelling methods provide flexibility that enables the use of different, often lower insulation levels (R-values) than the schedule method. This can reduce upfront costs while potentially increasing energy use and ongoing costs. The cost range indicates the difference based on whether the household is a standard or low-tariff electricity user.

Table 15: Estimated additional annual household energy costs – calculation and modelling method – single-storey house

Climate	Additional energy use calculation method (KWh/a)	Cost calculation method ($/a)	Additional energy use modelling method (KWh/a)	Cost modelling method ($/a)
Zone 1	281	$53 - $66	634	$120 - $149
Zone 2	444	$100 - $112	514	$116 - $129
Zone 3	453	$96 - $112	292	$62 -$72
Zone 4	554	$133 - $146	351	$84 - $92
Zone 5	699	$138 - $160	219	$43 - $50
Zone 6	606	$166 - $181	98	$27 - $29

Table 16: Estimated additional annual household energy costs – calculation and modelling method – double-storey house

Climate	Additional energy use calculation method (KWh/a)	Cost calculation method ($/a)	Additional energy use modelling method (KWh/a)	Cost modelling method ($/a)
Zone 1	412	$78 - $97	909	$172 - $214
Zone 2	637	$144 - $160	1398	$316 - $351
Zone 3	616	$130 - $152	918	$193 - $227
Zone 4	840	$202 - $221	1114	$268 - $293
Zone 5	676	$134 - $155	1302	$257 - $298
Zone 6	791	$216 - $236	1173	$321 - $350

Table 17: Estimated additional annual household energy costs – calculation and modelling method – medium-density dwelling[15]

Climate	Additional energy use calculation method (KWh/a)	Cost calculation method ($/a)	Additional energy use modelling method (KWh/a)	Cost modelling method ($/a)
Zone 1	1938	$366 - $457	2979	$562 - $702
Zone 2	2041	$461 - $513	4397	$993 - $1,105
Zone 3	2253	$475 - $556	1412	$297 - $348
Zone 4	3473	$835 - $914	3473	$835 - $914
Zone 5	3327	$658 - $761	2223	$439 - $508
Zone 6	4299	$1,176 - $1,282	3993	$1,092 - $1,191

[15] Note these are the estimated additional household energy costs across all eight units in the medium-density building.

3.1.2 Cost-benefit analysis at individual dwelling level

Table 18 and Table 19 present the results of the economic analysis. The most notable initial finding is that the estimated additional electricity used by using the calculation or modelling methods instead of the schedule method are relatively modest in comparison to the savings in build costs. This drives the overall findings of the economic analysis. In addition, despite the sometimes-significant differences in pricing between the two quantity surveyor companies, we find this does not have an impact on the overall findings. It does suggest there are some areas that are more sensitive to pricing such as in Christchurch where the difference in upfront cost could be smaller than in other areas (see the single-storey house in zone 5).

Overall, we find that there is a strong economic case for using the calculation or modelling method instead of the schedule method across the different housing typologies and climate zones.

First, we present the net present value (NPV) compared to the H1/AS1 5th edition schedule method across three building typologies and six climate zones (Table 18). We find that there may be some negative NPVs for the H1/AS1 4th edition schedule method across the detached houses outside of zone 1 (Auckland), which suggests reverting to the H1/AS1 4th edition may be uneconomic.

Table 18: Net present value of whole building

Net Present Value compared to H1 5th edition schedule method												
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	$2,731	$5,327	-$442	$2,169	-$213	$2,558	$1,091	$4,009	$1,331	$6,673	-$1,062	$8,380
H1 5th ed calculation	$2,769	$3,320	$1,371	$2,198	$1,459	$2,411	$395	$2,193	$1,483	$4,437	$3,031	$8,392
H1 5th ed modelling	$5,577	$7,530	$4,046	$5,003	$2,396	$3,193	$1,846	$2,420	$598	$3,740	$3,031	$8,392
Double Storey House												
H1 4th ed schedule	$2,048	$6,339	-$885	$3,374	-$265	$4,007	-$408	$3,101	-$518	$6,005	-$5,210	$4,655
H1 5th ed calculation	$5,431	$6,798	$4,023	$5,270	$4,247	$5,514	$3,362	$5,674	$4,371	$5,460	$3,919	$8,057
H1 5th ed modelling	$6,078	$9,112	$2,297	$6,076	$3,824	$7,003	$3,249	$5,765	$3,042	$8,463	$871	$8,718
Medium-Density Dwelling (2)												
H1 4th ed schedule	$19,315	$24,795	$6,438	$13,169	$7,514	$15,067	$9,624	$17,879	$5,999	$15,785	-$11,235	$2,420
H1 5th ed calculation	$31,814	$33,670	$25,833	$28,159	$26,049	$28,787	$13,708	$16,736	$8,861	$12,619	$4,522	$9,643
H1 5th ed modelling	$31,185	$36,635	$17,793	$24,563	$27,038	$30,471	$21,340	$26,389	$20,136	$25,599	$3,971	$9,516
(1) Based on assumptions of the upfront cost differences, electricity tariff type (low/standard), and real inflation in electricity prices (0% or 1.2% p.a.)												
(2) Note that the results for the medium-density dwelling is across 8 dwelling units												

We can transform these NPVs to benefit-cost ratios (BCRs) to better account for the scale of the costs and benefits. A BCR is the ratio of the net cumulative benefits to the net cumulative costs. For the current analysis, the benefits are the cost savings associated with less-expensive constructions while the costs are the additional heating/cooling costs. The BCR makes it easier to compare the alternatives without being biased by the scale of those costs or benefits (Table 19). We find that, by using the BCRs, the calculation method appears the most economic method for demonstrating compliance. This is because the calculation method, in general, uses slightly higher insulation levels than the modelling method. The upfront cost saving is therefore reduced (compared to the modelling method), but the additional energy costs are smaller.

Table 19: Benefit-cost ratios

Benefit-Cost Ratio compared to H1 5th edition schedule method												
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	1.63	2.86	0.94	1.41	0.97	1.51	1.12	1.58	1.15	2.05	0.92	1.80
H1 5th ed calculation	2.81	4.29	1.53	2.15	1.57	2.34	1.11	1.83	1.62	3.59	5.45	17.30
H1 5th ed modelling	2.61	4.29	2.35	3.26	2.47	3.79	1.90	2.57	1.35	4.05	5.45	17.30
Double Storey House												
H1 4th ed schedule	1.49	3.29	0.87	1.66	0.96	1.88	0.95	1.46	0.94	1.94	0.64	1.43
H1 5th ed calculation	4.06	6.81	2.38	3.44	2.51	3.79	1.76	2.70	4.18	6.57	2.96	6.34
H1 5th ed modelling	2.29	3.94	1.30	2.07	1.73	2.89	1.48	2.12	1.44	2.72	1.10	2.38
Medium-Density Density (2)												
H1 4th ed schedule	2.20	3.33	1.25	1.68	1.29	1.84	1.29	1.71	1.18	1.65	0.80	1.06
H1 5th ed calculation	6.82	10.33	3.88	5.24	3.82	5.43	2.12	2.81	1.68	2.35	1.22	1.61
H1 5th ed modelling	2.94	4.46	1.68	2.27	3.33	4.74	2.04	2.71	2.06	2.89	1.17	1.55
(1) Based on assumptions of the upfront cost differences, electricity tariff type (low/standard), and real inflation in electricity prices (0% or 1.2% p.a.)												
(2) Note that the results for the medium-density dwelling is across 8 dwelling units												

3.1.3 Sensitivity analysis

We have tested how sensitive the above whole-building results are against these assumptions:

- The cost-differential between those components that meet the H1/AS1 5th edition schedule method and the alternatives is reduced by 10% and 20%.
- Higher energy use due to using less-efficient space conditioning with a COP of 1.
- Alternative discount rates of 2% and 8%.

3.1.3.1 Cost differentials

The following results show the impact of reducing the cost difference between those components that meet the H1 5th edition schedule method and the alternatives. We run two scenarios – one where the cost difference is reduced by 10% and another where the cost difference is reduced by 20%. This analysis shows us how sensitive the overall results are to the scale of the benefits by reducing the upfront cost saving. We find that, if the cost difference was reduced by 10%, the results do not change significantly (Table 20). We find that, in zone 6 (Queenstown) for the double-storey house, it may be uneconomic to use the H1 5th edition modelling method in some instances.

Table 20: Sensitivity cost difference 10% smaller

Benefit-Cost Ratio compared to H1 5th edition schedule method												
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	1.47	2.58	0.84	1.27	0.87	1.36	1.01	1.42	1.03	1.84	0.83	1.62
H1 5th ed calculation	2.53	3.86	1.38	1.94	1.41	2.11	1.00	1.65	1.45	3.23	4.91	15.57
H1 5th ed modelling	2.35	3.86	2.12	2.93	2.23	3.41	1.71	2.31	1.21	3.65	4.91	15.57
Double Storey House												
H1 4th ed schedule	1.34	2.96	0.78	1.50	0.86	1.69	0.86	1.31	0.85	1.75	0.57	1.29
H1 5th ed calculation	3.66	6.13	2.14	3.10	2.26	3.41	1.58	2.43	3.76	5.91	2.67	5.71
H1 5th ed modelling	2.06	3.54	1.17	1.86	1.55	2.60	1.33	1.91	1.30	2.44	0.99	2.15
Medium-Density Dwelling (2)												
H1 4th ed schedule	1.98	2.99	1.12	1.52	1.17	1.66	1.16	1.54	1.06	1.49	0.72	0.95
H1 5th ed calculation	6.14	9.30	3.49	4.71	3.44	4.88	1.90	2.53	1.51	2.12	1.09	1.45
H1 5th ed modelling	2.65	4.01	1.51	2.04	3.00	4.26	1.84	2.44	1.85	2.60	1.06	1.40
(1) Based on assumptions of the upfront cost differences, electricity tariff type (low/standard), and real inflation in electricity prices (0% or 1.2% p.a.)												
(2) Note that the results for the medium-density dwelling is across 8 dwelling units												

If the cost difference is reduced to 20%, we find the results are to a large extent in line with the 10% case (Table 21). The scale of the cost saving does not appear to be a significant driver of the results.

Table 21: Sensitivity cost difference 20% smaller

Benefit-Cost Ratio compared to H1 5th edition schedule method												
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	1.30	2.29	0.75	1.13	0.78	1.21	0.89	1.26	0.92	1.64	0.74	1.44
H1 5th ed calculation	2.25	3.43	1.23	1.72	1.26	1.87	1.12	1.87	1.30	3.25	7.09	16.90
H1 5th ed modelling	2.21	3.96	1.88	2.61	1.10	2.15	1.52	2.06	0.73	2.01	4.36	13.84
Double Storey House												
H1 4th ed schedule	1.19	2.63	0.70	1.33	0.77	1.50	0.76	1.17	0.75	1.55	0.51	1.14
H1 5th ed calculation	3.34	5.22	1.94	2.65	2.04	2.94	1.45	2.19	3.34	6.58	2.44	5.87
H1 5th ed modelling	1.84	3.15	1.04	1.65	1.43	2.26	1.18	1.70	1.15	2.17	0.88	1.91
Medium-Density Dwelling (2)												
H1 4th ed schedule	1.76	2.66	1.00	1.35	1.04	1.47	1.03	1.37	0.94	1.32	0.64	0.85
H1 5th ed calculation	5.57	8.43	3.19	4.30	3.14	4.46	2.77	3.67	1.44	2.02	1.02	1.35
H1 5th ed modelling	2.35	3.57	1.44	1.94	1.85	2.63	2.77	3.67	1.16	1.63	0.87	1.16
(1) Based on assumptions of the upfront cost differences, electricity tariff type (low/standard), and real inflation in electricity prices (0% or 1.2% p.a.)												
(2) Note that the results for the medium-density dwelling is across 8 dwelling units												

3.1.3.2 Higher energy use

We run a sensitivity analysis to understand the impact of less-efficient space conditioning. If the COP of the space conditioning was reduced to 1, we find it is mostly uneconomic to revert to the H1/AS1 4th edition schedule method. The H1 5th edition modelling method also becomes a lot more marginal where the results are mainly dependent on the upfront cost savings. The H1/AS1 5th edition calculation method looks economic for the double-storey house but is marginal for the single-storey house outside of zone 1 (Auckland) and zone 6 (Queenstown) (Table 22).

Table 22: Sensitivity to energy use

Benefit-Cost Ratio compared to H1 5th edition schedule method	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	0.63	1.11	0.40	0.60	0.45	0.71	0.51	0.72	0.52	0.93	0.43	0.85
H1 5th ed calculation	1.16	1.76	0.69	0.98	0.79	1.18	0.55	0.90	0.75	1.66	2.36	7.49
H1 5th ed modelling	1.21	1.98	1.20	1.67	1.18	1.81	0.87	1.18	0.64	1.93	2.36	7.49
Double Storey House												
H1 4th ed schedule	0.57	1.26	0.36	0.70	0.46	0.90	0.44	0.68	0.44	0.90	0.31	0.69
H1 5th ed calculation	1.63	2.72	1.04	1.51	1.26	1.89	0.86	1.32	1.69	2.66	1.34	2.86
H1 5th ed modelling	0.87	1.49	0.53	0.85	0.72	1.21	0.69	1.00	0.69	1.29	0.55	1.19
Medium-Density Dwelling (2)												
H1 4th ed schedule	0.85	1.29	0.55	0.74	0.63	0.89	0.59	0.78	0.53	0.75	0.37	0.49
H1 5th ed calculation	2.92	4.43	1.96	2.65	2.05	2.92	1.15	1.52	0.92	1.29	0.68	0.90
H1 5th ed modelling	1.15	1.74	0.73	0.99	1.50	2.13	1.00	1.33	1.07	1.50	0.61	0.81

(1) Based on assumptions of the upfront cost differences, electricity tariff type (low/standard), and real inflation in electricity prices (0% or 1.2% p.a.)
(2) Note that the results for the medium-density dwelling is across 8 dwelling units

3.1.3.3 Alternative discount rates

Using the lower discount rate of 2% increases the costs associated with ongoing energy use into the future (Table 23). We find that these increased cumulative costs suggest that, for detached housing, the H1/AS1 4th edition schedule method is likely uneconomic outside of zone 1. We also find that there are some instances where using the H1 5th edition calculation method or modelling method could be uneconomic in our high energy use assumptions.

Table 23: Sensitivity to discount rate 2%

Benefit-Cost Ratio compared to H1 5th edition schedule method	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	0.91	1.71	0.53	0.84	0.54	0.90	0.63	0.94	0.64	1.22	0.52	1.08
H1 5th ed calculation	1.58	2.57	0.86	1.29	0.88	1.40	0.62	1.10	0.91	2.15	3.05	10.35
H1 5th ed modelling	1.46	2.57	1.32	1.95	1.39	2.27	1.07	1.54	0.76	2.42	3.05	10.35
Double Storey House												
H1 4th ed schedule	0.83	1.97	0.49	0.99	0.54	1.12	0.53	0.87	0.53	1.16	0.36	0.86
H1 5th ed calculation	2.28	4.07	1.33	2.06	1.41	2.26	0.99	1.62	2.34	3.93	1.66	3.79
H1 5th ed modelling	1.29	2.36	0.73	1.24	0.97	1.73	0.83	1.27	0.81	1.62	0.62	1.43
Medium-Density Dwelling (2)												
H1 4th ed schedule	1.23	1.99	0.70	1.01	0.73	1.10	0.72	1.02	0.66	0.99	0.45	0.63
H1 5th ed calculation	3.82	6.18	2.17	3.13	2.14	3.25	1.19	1.68	0.94	1.41	0.68	0.96
H1 5th ed modelling	1.65	2.67	0.94	1.36	1.87	2.83	1.14	1.62	1.15	1.73	0.66	0.93

(1) Based on assumptions of the upfront cost differences, electricity tariff type (low/standard), and real inflation in electricity prices (0% or 1.2% p.a.)
(2) Note that the results for the medium-density dwelling is across 8 dwelling units

Using the higher discount rate of 8% decreases the costs associated with ongoing energy use into the future (Table 24). Therefore, this has the opposite effect of using the 2% discount rate, and the economic case for using the calculation method or modelling method to prove compliance is stronger. We still find that there is one instance where using the H1/AS1 4th edition schedule method may be uneconomic compared to the H1/AS1 5th edition schedule method in zone 6 (Queenstown) for the double-storey house.

Table 24: Sensitivity to discount rate 8%

Benefit-Cost Ratio compared to H1 5th edition schedule method	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	2.48	4.16	1.43	2.04	1.48	2.19	1.70	2.29	1.75	2.97	1.41	2.61
H1 5th ed calculation	4.28	6.22	2.33	3.12	2.39	3.40	1.70	2.66	2.46	5.21	8.30	25.10
H1 5th ed modelling	3.98	6.23	3.58	4.73	3.77	5.50	2.90	3.73	2.05	5.88	8.30	25.10
Double Storey House												
H1 4th ed schedule	2.27	4.77	1.33	2.41	1.46	2.72	1.45	2.12	1.43	2.82	0.97	2.07
H1 5th ed calculation	6.19	9.88	3.63	5.00	3.82	5.49	2.68	3.92	6.36	9.53	4.52	9.20
H1 5th ed modelling	3.49	5.71	1.98	3.00	2.63	4.19	2.25	3.08	2.19	3.94	1.68	3.46
Medium-Density Dwelling (2)												
H1 4th ed schedule	3.35	4.83	1.90	2.44	1.97	2.67	1.96	2.48	1.79	2.40	1.22	1.53
H1 5th ed calculation	10.39	14.99	5.91	7.60	5.82	7.87	3.22	4.08	2.56	3.42	1.85	2.33
H1 5th ed modelling	4.48	6.47	2.56	3.29	5.08	6.87	3.11	3.93	3.14	4.19	1.79	2.26

(1) Based on assumptions of the upfront cost differences, electricity tariff type (low/standard), and real inflation in electricity prices (0% or 1.2% p.a.)
(2) Note that the results for the medium-density dwelling is across 8 dwelling units

3.2 Highest net present value (NPV) constructions

3.2.1 Summary

It should be noted there is a high degree of uncertainty in these results and the cost-effectiveness or net present value (NPV) – the value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present – of different constructions may overlap significantly. Different options could be selected with different houses, different suppliers and different modelling assumptions. These should be read more as examples that illustrate tendencies rather than assuming that what was most cost-effective here would apply universally in all situations.

- The highest NPV constructions have significantly lower R-values than schedule method minimums:
  - Uninsulated concrete slabs were favoured outside of the coldest climates. This varied between houses – the single-storey house with the largest slab favours underslab insulation in zones 4–6, while the double-storey and medium-density houses with much smaller A/P ratios favour it only in zone 6. Edge insulation and slab topper insulation were avoided.
  - Wall insulation was mostly kept at current schedule method levels but was increased to 140 mm in some cases in zone 6.
  - The highest NPV roof batts were R3.6. However, it should be noted that choice was derived from the average NPV and the costs of insulation could vary widely. The cheapest R7.0 ceiling batts might have a higher NPV than R3.6 batts depending on the situation.
  - The highest NPV option for floor insulation was the highest R3.2 batts.
  - Window R-values were lowered to R0.37 in most zones and could go as low as R0.26 in Auckland.
- Most of these did not comply with the calculation method or modelling method, in large part because of the lower concrete slab R-values. The next highest NPV constructions that would comply with the calculation method required significant increases to slab and roof insulation as well as avoiding basic aluminium double glazing.
- These alternative highest NPV constructions that comply, while having slightly lower NPVs, had substantially better benefit-cost ratios than the highest NPV constructions and may be argued to be more economical.
- The 50% rule stands out as a particular issue here for concrete slabs as the uninsulated slabs could fall below 50% of the minimum and thus not comply with the calculation method. That being said, simply removing this rule would not necessarily allow uninsulated slabs to comply. In the examples here, uninsulated slabs would still struggle to comply due to their low R-values. In our alternative highest NPV constructions that would comply options, we needed to insulate the slabs to achieve compliance with the calculation method.
- Alternatively, the reference R-values could be adjusted to allow compliance. Again, the changes needed here would be significant, especially in zones 1–3 where the changes would verge on H1 4th edition R-values in part due to the low R-values of uninsulated concrete slabs using current calculation approaches.
- These findings are not inconsistent with previous 2020 analysis. BCRs for most of the insulation upgrades were marginal and risked falling if energy savings fell (such as due to more efficient heat pumps) or construction costs increased. The primary standout is the fall of roof insulation, which seems to be due to the relatively high cost of R7.0 batts compared to R3.6 batts. It may be more cost-effective to simply layer R3.6 batts instead of using R7.0 batts if roof space permits.
- Changes to the schedule method or reference model R-values should be approached with caution. If designers get used to using the calculation or modelling methods to support lower insulation levels, insulation could fall much further than intended. It should be noted that it is already, for example, entirely possible to make houses with less insulation than that used under the H1 4th edition comply with the modelling method as it currently stands.

- We found that, although the cost-effective constructions mostly have slightly higher NPVs than the compliant cost-effective constructions, those compliant constructions still have positive NPVs. More importantly, however, when we look at the BCRs, the compliant constructions outperform the cost-effective constructions. Despite the compliant constructions having a higher upfront construction cost, the savings in energy use are sufficient to suggest that the compliant constructions are more economic than the highest NPV constructions.

3.2.2 Identifying the most cost-effective constructions

The most cost-effective constructions were identified by looking at the effects of the individual construction options for each model and taking the one with the highest NPV based on the delivered energy savings (accounting for assumed heat pump efficiency). It should be noted that there is a wide range of uncertainty in the economic analysis. For the sake of selecting a single construction option, we took the NPV as the midpoint of the upper and lower bound for each construction (see Appendix B for detailed results). It should be noted that material costs can vary significantly depending on suppliers and other factors. Similarly, as noted in the sensitivity analysis, there is significant uncertainty in the energy use estimates and different modelling assumptions may produce different results.

These factors mean that the selections here should be seen as indicative of what might be the most cost-effective options – there is not a single simple answer, and depending on the house design, model, and suppliers, different answers may be found. The chosen constructions are outlined in Table 25 to Table 28.

What is very apparent is that the most cost-effective options here present significantly lower insulation levels than current schedule method minimums:

- The highest NPV roof insulation option falls to R3.6 batts across the board (based off the average NPV).
- Uninsulated slabs are favoured outside of the coldest climate zones. This appears to vary based on the house characteristics – the single-storey house with the largest slab favours underslab insulation in zones 4–6, while the double-storey and medium-density houses with much smaller slab A/P ratios favour it only in zone 6.
- R0.37 windows are favoured in the colder climates, with basic clear double glazing favoured in Auckland. Zones 2 and 3 see mixed results, with the highest NPV model being either R0.26 or R0.37 windows depending on the house.
- Interestingly, 140 mm R4.0 wall insulation was selected for the detached houses and apartment building in Queenstown. Note though that this modelling was done with a 24% framing ratio. Higher framing ratios such as those found by Ryan et al. (2021) could reduce the effectiveness of such insulation and change the cost-effectiveness.

This means that, in many cases, the most cost-effective constructions are not much higher than those used under the H1/AS1 4th edition, with the windows being the largest source of improvements.

These results are not necessarily out of line with the previous analysis where it was found that, while the BCRs for insulation upgrades were positive, most of them were not particularly strong – typically between 1–2. It was noted at the time that the economic benefits may not be robust to different assumptions that reduced the energy savings and that the case was much stronger from a carbon perspective.

Table 25: Single-storey house – highest individual construction NPV

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	Cost effective (Q3)	R2.8 batts	R3.6 batts	.	Uninsulated	Aluminium double glazing
Zone 2 - Napier	Cost effective (Q3)	R2.8 batts	R3.6 batts	.	Uninsulated	Aluminium double glazing
Zone 3 - Wellington	Cost effective (Q3)	R2.8 batts	R3.6 batts	.	Uninsulated	Aluminium double glazing
Zone 4 - Taupo	Cost effective (Q3)	R2.8 batts	R3.6 batts	.	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	Cost effective (Q3)	R2.8 batts	R3.6 batts	.	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	Cost effective (Q3)	R4.0 batts	R3.6 batts	.	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1

Table 26: Double-storey house – highest individual construction NPV

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	Uninsulated	Aluminium double glazing
Zone 2 - Napier	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	Uninsulated	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 3 - Wellington	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	Uninsulated	Aluminium double glazing
Zone 4 - Taupo	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	Uninsulated	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	Uninsulated	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	Cost effective (Q3)	R4.0 batts	R3.6 batts	R3.2 batts	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1

Table 27: Medium-density house – highest individual construction NPV

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	Uninsulated	Aluminium double glazing
Zone 2 - Napier	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	Uninsulated	Aluminium double glazing
Zone 3 - Wellington	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	Uninsulated	Aluminium double glazing
Zone 4 - Taupo	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	Uninsulated	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	Uninsulated	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	Cost effective (Q3)	R2.8 batts	R3.6 batts	R3.2 batts	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1

Table 28: Apartment building – highest individual construction NPV

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	Cost effective (Q3)	R2.8 batts	R3.3 batts	.	.	Aluminium double glazing
Zone 2 - Napier	Cost effective (Q3)	R2.8 batts	R3.6 batts	.	.	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 3 - Wellington	Cost effective (Q3)	R2.8 batts	R3.6 batts	.	.	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 4 - Taupo	Cost effective (Q3)	R2.8 batts	R3.6 batts	.	.	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	Cost effective (Q3)	R2.8 batts	R3.6 batts	.	.	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	Cost effective (Q3)	R4.0 batts	R3.6 batts	.	.	Aluminium low-E3 argon double glazing Ucog 1.1

In this analysis, we have made a number of changes to the model assumptions that reduced the energy use such as the new warmer weather files and the use of more-efficient modern heat pumps. Combined with general increases in the cost of construction products, the fall in the apparent cost-effectiveness of insulation is not unexpected. Indeed, the R-values that were ultimately chosen were not the most cost-effective options. Favouring uninsulated slabs for instance is hardly surprising when we consider that slab insulation was not cost-effective in most cases in the previous analysis. Slab insulation options used for the single-storey house are actually an improvement over what the previous analysis suggested, likely as a result of the increase to assumed soil conductivity.

A notable fall is roof insulation, which previously had the best cost-effectiveness. However, it should be noted that, while the R6.6 option had the highest NPV:

- R3.6 batts always had a better BCR than the R6.6 option[16]
- the R6.6 construction settled on mostly achieved strong BCRs in zones 4–6.

The relative weakness in the BCR meant its cost-effectiveness was vulnerable to changes in energy savings and construction costs. In particular, we may observe significant differences in the costs of the roof insulation. The previous work achieved R6.6 by stacking R3.2 and R3.6 ceiling batts on top of each other for a marginal cost increase of ~\$12–13/m². The R7.0 batts being used here are around \$24–31/m² more expensive than R3.6 batts in zones 4-6, making it far less cost-effective with the cost data we have been provided. That being said, we may also observe significant variation in the cost data for roof insulation, with R7.0 batts, for example, varying from \$20/m² to \$47/m² depending on the supplier. As a result, the lower-end NPV estimates would actually favour R7.0 batts instead of R3.6 in zones 2 and 3 (but not in zones 4-6 because the cost difference between R3.6 and R7.0 batts appears to increase significantly in zones 4-6 in the data provided). Hence, while we have selected R3.6 batts as the highest NPV option, based off the average cost here, they may not always be the most cost-effective option.

3.2.3 Compliance with the modelling method

Comparing the energy use of these highest NPV construction models against that of the reference models, we find they mostly fail to achieve compliance with the H1/VM1 modelling method (Figure 14). The main exception is the double-storey house where nearly all the models comply as well as the zone 1 and 2 models for the medium-density house. This may be explained by high cooling loads of those houses making compliance easier. The apartment building models all fail as no combination of the tested constructions can comply due to the high WWR.

Single Storey	Base Total Heating + Cooling (kWh)				Reference R-value changes			
	Reference model	Cost effective model	Complies?	3b. Adjusted reference model	Roof	Wall	Window	Slab
Zone 1 - Auckland	2985	3379	FALSE	3454	3.5	2.0	0.46	1.6
Zone 2 - Napier	4256	5411	FALSE	5514	3.5	2.0	0.37	1.4
Zone 3 - Wellington	3634	5562	FALSE	5695	6.6	2.0	0.26	1.4
Zone 4 - Taupo	6254	7210	FALSE	7331	3.9	2.0	0.46	1.4
Zone 5 - Christchurch	6838	8078	FALSE	8178	3.9	2.0	0.46	1.4
Zone 6 - Queenstown	9313	9495	FALSE	9833	5.8	2.0	0.46	1.7

Medium density	Base Total Heating + Cooling (kWh)				Reference R-value changes				
	Reference model	Cost effective model	Complies?	3b. Adjusted reference model	Roof	Walls	Windows	Slab	Timber Floor
Zone 1 - Auckland	17062	12354	TRUE	.					
Zone 2 - Napier	21092	18858	TRUE	.					
Zone 3 - Wellington	15828	18921	FALSE	29581	6.6	2.0	0.26	1.7	2.5
Zone 4 - Taupo	28839	29056	FALSE	30845	4.0	2.0	0.46	1.7	2.8
Zone 5 - Christchurch	30946	32304	FALSE	34168	4.0	2.0	0.46	1.7	3.0
Zone 6 - Queenstown	40893	43191	FALSE	43750	5.0	2.0	0.46	1.7	3.0

Double Storey	Base Total Heating + Cooling (kWh)				Reference R-value changes				
	Reference model	Cost effective model	Complies?	3b. Adjusted reference model	Roof	Walls	Windows	Slab	Timber Floor
Zone 1 - Auckland	4926	3901	TRUE	.					
Zone 2 - Napier	6622	4634	TRUE	.					
Zone 3 - Wellington	4928	5135	FALSE	8158	6.6	2.0	0.26	1.6	2.5
Zone 4 - Taupo	8049	7713	TRUE	.					
Zone 5 - Christchurch	8879	8443	TRUE	.					
Zone 6 - Queenstown	10925	9371	TRUE	.					

Apartments	Base Total Heating + Cooling (kWh)				Reference R-value changes		
	Reference model	Cost effective model	Complies?	3b. Adjusted reference model	Roof	Wall	Window
Zone 1 - Auckland	36428	91781	FALSE	76989	2.9	1.6	0.15
Zone 2 - Napier	66775	104645	FALSE	106877	6.6	2.0	0.18
Zone 3 - Wellington	59930	89462	FALSE	89750	5.3	2.0	0.24
Zone 4 - Taupo	116087	155380	FALSE	155484	5.3	2.0	0.24
Zone 5 - Christchurch	125054	171030	FALSE	171289	5.3	2.0	0.24
Zone 6 - Queenstown	174860	216713	FALSE	223872	6.6	2.0	0.26

16 Note this was not assuming any compression at the edges. Indeed, the only reason R3.6 batts did not have the best BCR in the 2020 analysis was that QV Costbuilder was reporting R4.0 batts to have very similar costs. This is no longer the case.

Figure 14: Energy use of the most cost-effective models compared to the reference model(s)

3.2.4 Compliance with the calculation method

Applying the calculation method to the highest NPV construction models, we find that nearly none of the house models comply (Figure 15 to Figure 19). This is likely in part because of how the thermal modelling that the constructions were selected from presents a more favourable impression of uninsulated slabs compared to simple heat loss calculations. Even without that, the R-values are simply significantly lower than the reference values.

Indeed, the uninsulated slabs in the double-storey and medium-density house would fail the calculation method regardless due to the 50% rule (H1/AS1 2.1.3.8) as they are less than half the reference R-value of R1.5[17].

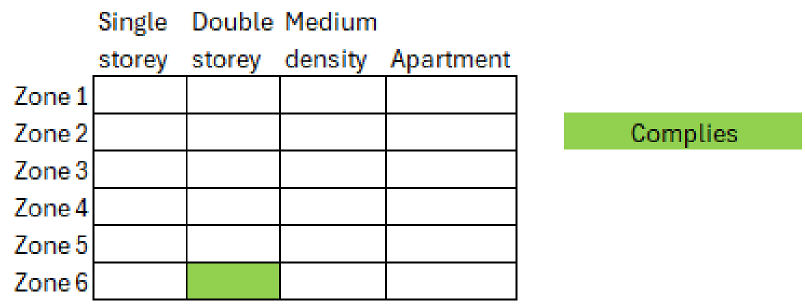


Figure 15: Summary of which of the most cost-effective constructions combinations complies with the calculation method

The apartment building of course, fails on all counts and has too much glazing to use the calculation method for compliance.

		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	156	6.6	6.6	6.6	6.6	6.6	6.6
Wall	108	2	2	2	2	2	2
Glazing	46	0.46	0.46	0.46	0.46	0.5	0.5
Slab	156	1.5	1.5	1.5	1.5	1.6	1.7
Floor	0	2.5	2.5	2.5	2.8	3	3
	Heat loss	282.86	282.86	282.86	282.86	268.28	262.55
		Most cost effective model					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	156	3.58	3.58	3.58	3.58	3.58	3.58
Wall	122	2	2	2	2	2	2.82
Window	31	0.26	0.26	0.26	0.37	0.37	0.37
Slab	156	0.94	0.94	0.94	1.4	1.4	1.65
Floor	0						
Doors	2	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	393.03	393.03	393.03	303.18	302.90	268.22
	diff	110.17	110.17	110.17	20.31	34.62	5.67

[17] If this rule was removed, uninsulated slabs may still struggle to comply due to their low R-values. When compiling options that would comply, we needed to insulate the slabs to achieve compliance with the calculation method.

Figure 16: Single-storey house – highest NPV model using the calculation method

		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	90	6.6	6.6	6.6	6.6	6.6	6.6
Wall	142	2	2	2	2	2	2
Glazing	61	0.46	0.46	0.46	0.46	0.5	0.5
Slab	64	1.5	1.5	1.5	1.5	1.6	1.7
Floor	26	2.5	2.5	2.5	2.8	3	3
	Heat loss	270.06	270.06	270.06	268.97	255.09	252.73
		Most cost effective model					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	90	3.54	3.54	3.54	3.54	3.54	3.54
Wall	165	2	2	2	2	2	2.82
Window	35	0.26	0.37	0.26	0.37	0.37	0.37
Slab	64	0.71	0.71	0.71	0.71	0.71	1.1
Floor	26	3.34	3.34	3.34	3.34	3.34	3.34
Doors	3	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	348.26	307.97	348.26	307.97	307.42	251.38
	diff	78.20	37.91	78.20	39.00	52.33	-1.35

Figure 17: Double-storey house – most cost-effective model using the calculation method

		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	383	6.6	6.6	6.6	6.6	6.6	6.6
Wall	599	2	2	2	2	2	2
Glazing	257	0.46	0.46	0.46	0.46	0.5	0.5
Slab	171	1.5	1.5	1.5	1.5	1.6	1.7
Floor	222	2.5	2.5	2.5	2.8	3	3
	Heat loss	1117.56	1117.56	1117.56	1108.04	1051.03	1044.76
		Most cost effective model					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	383	3.64	3.64	3.64	3.64	3.64	3.64
Wall	635	2	2	2	2	2	2
Window	150	0.26	0.26	0.26	0.37	0.37	0.37
Slab	171	0.54	0.54	0.54	0.54	0.54	0.87
Floor	222	3.62	3.62	3.62	3.62	3.62	3.62
Retaining v	26	2.1	2.1	2.1	2.1	2.1	2.1
Intertenan	65	2.4	2.4	2.4	2.4	2.4	2.4
Door	44	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	1511.36	1511.36	1511.36	1340.28	1332.60	1212.72
	diff	328.31	328.31	328.31	166.75	219.49	105.89

Figure 18: Medium-density house – most cost-effective model using the calculation method

		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	413	6.6	6.6	6.6	6.6	6.6	6.6
Wall	1452	2	2	2	2	2	2
Glazing	622	0.46	0.46	0.46	0.46	0.5	0.5
Slab	0	1.5	1.5	1.5	1.5	1.6	1.7
Floor	0	2.5	2.5	2.5	2.8	3	3
	Heat loss	2141.78	2141.78	2141.78	2141.78	2033.54	2033.54
		Most cost effective model					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	413	3.61	3.91	3.91	3.91	3.91	3.91
Wall	1105	2	2	2	2	2	2.82
Window	970	0.26	0.37	0.37	0.37	0.37	0.37
Slab	0						
Floor	0						
	Heat loss	4397.60	3279.67	3279.67	3279.67	3279.67	3119.07
	diff	2255.83	1137.89	1137.89	1137.89	1246.13	1085.53

Figure 19: Apartment building – most cost-effective model using the calculation method

3.2.5 Alternative constructions

Where the highest NPV constructions failed to comply – particularly using the calculation method – it may be relevant to ask whether there are alternative options that would comply without a significant loss in NPV. These are shown in Figure 20 to Figure 22. The constructions used are described in Table 29 to Table 31. To do this, the constructions were adjusted through the next best NPV options until a combination that would comply with the calculation method was found. This required significant increases to roof insulation, insulation of the concrete slab and not using basic aluminium double glazing. Note that these changes would (nearly) also all comply using the modelling method (Figure 23). The one exception is the zone 4 single-storey model, which fails by a hair. Slightly different modelling assumptions such as lower ventilation rates or darker window frames would allow it to comply.

Single storey		**Alternative cost effective model that would comply**					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	156	6.78	6.78	6.78	6.78	6.78	6.78
Wall	122	2	2	2	2	2	2.82
Window	31	0.37	0.37	0.37	0.37	0.37	0.37
Slab	156	1.4	1.4	1.4	1.4	1.65	1.65
Floor	0						
Doors	2	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	282.62	282.62	282.62	282.62	265.46	247.66
	diff	-0.24	-0.24	-0.24	-0.24	-2.82	-14.88

Figure 20: Single-storey – next highest NPV constructions complying with calculation method

Double storey		Alternative cost effective model that would comply					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	90	4.81	4.81	4.81	6.63	6.63	3.54
Wall	165	2	2	2	2	2	2.82
Window	35	0.37	0.37	0.37	0.37	0.37	0.37
Slab	64	1.1	1.1	1.1	1.1	1.29	1.1
Floor	26	3.34	3.34	3.34	3.34	3.34	3.34
Doors	3	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	269.14	269.14	269.14	264.01	254.85	251.38
	diff	-0.92	-0.92	-0.92	-4.95	-0.24	-1.35

Figure 21: Double-storey – next highest NPV constructions complying with calculation method

Medium density		Alternative cost effective model that would comply					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	383	5.04	5.04	5.04	5.04	3.64	3.64
Wall	635	2	2	2	2	2.82	2.82
Window	150	0.37	0.37	0.37	0.37	0.37	0.37
Slab	171	1.02	1.02	1.02	1.02	1.02	1.02
Floor	222	3.62	3.62	3.62	3.62	3.62	3.62
Retaining v	26	2.1	2.1	2.1	2.1	2.1	2.1
Intertenan	65	2.4	2.4	2.4	2.4	2.4	2.4
Door	44	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	1162.31	1162.31	1162.31	1162.31	1091.59	1091.59
	diff	-20.74	-20.74	-20.74	-11.22	-21.52	-15.24

Figure 22: Medium-density– next highest NPV constructions complying with calculation method

Alternative 2nd most cost effective constructions that would comply with the calculation method

Single Storey	Base Total Heating + Cooling (kWh)			
	Reference model	Cost effective model	Complies?	Change
Zone 1 - Auckland	2985	2083	TRUE	R7.0 roof, R1.2 underslab, R0.37 windows
Zone 2 - Napier	4256	3467	TRUE	R7.0 roof, R1.2 underslab, R0.37 windows
Zone 3 - Wellington	3634	3568	TRUE	R7.0 roof, R1.2 underslab, R0.37 windows
Zone 4 - Taupo	6254	6262	FALSE	R7.0 roof
Zone 5 - Christchurch	6838	6732	TRUE	R7.0 roof, R2.4 underslab
Zone 6 - Queenstown	9313	8282	TRUE	R7.0 roof

Medium density	Base Total Heating + Cooling (kWh)			
	Reference model	Cost effective model	Complies?	Change
Zone 1 - Auckland	17062	8659	TRUE	R5.0 roof, R2.4 underslab, R0.37 windows
Zone 2 - Napier	21092	13812	TRUE	R5.0 roof, R2.4 underslab, R0.37 windows
Zone 3 - Wellington	15828	14037	TRUE	R5.0 roof, R2.4 underslab, R0.37 windows
Zone 4 - Taupo	28839	26069	TRUE	R5.0 roof, R2.4 underslab
Zone 5 - Christchurch	30946	27092	TRUE	R4.0 walls, R2.4 underslab
Zone 6 - Queenstown	40893	37962	TRUE	R4.0 walls, R2.4 underslab

Double Storey	Base Total Heating + Cooling			
	Reference model	Cost effective model	Complies?	Change
Zone 1 - Auckland	4926	2790	TRUE	R5.0 roof, R1.2 underslab, R0.37 windows
Zone 2 - Napier	6622	4222	TRUE	R5.0 roof, R1.2 underslab
Zone 3 - Wellington	4928	3773	TRUE	R5.0 roof, R1.2 underslab, R0.37 windows
Zone 4 - Taupo	8049	6656	TRUE	R7.0 roof, R1.2 underslab
Zone 5 - Christchurch	8879	7261	TRUE	R7.0 roof, R2.4 underslab

Figure 23: Modelling method compliance for alternative cost-effective construction sets

Table 29: Single-storey house – alternative cost-effective constructions

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	Alt. compliant cost effective	R2.8 batts	R7.0 batts	.	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 2 - Napier	Alt. compliant cost effective	R2.8 batts	R7.0 batts	.	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 3 - Wellington	Alt. compliant cost effective	R2.8 batts	R7.0 batts	.	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 4 - Taupo	Alt. compliant cost effective	R2.8 batts	R7.0 batts	.	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	Alt. compliant cost effective	R2.8 batts	R7.0 batts	.	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	Alt. compliant cost effective	R4.0 batts	R7.0 batts	.	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1

Table 30: Double-storey house – alternative cost-effective construction

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	Alt. compliant cost effective	R2.8 batts	R5.0 batts	R3.2 batts	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 2 - Napier	Alt. compliant cost effective	R2.8 batts	R5.0 batts	R3.2 batts	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 3 - Wellington	Alt. compliant cost effective	R2.8 batts	R5.0 batts	R3.2 batts	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 4 - Taupo	Alt. compliant cost effective	R2.8 batts	R7.0 batts	R3.2 batts	R1.2 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	Alt. compliant cost effective	R2.8 batts	R7.0 batts	R3.2 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1

Table 31: Medium-density house – alternative cost-effective constructions

Climate	Label	Walls	Roof	Floor	Slab	Windows
Zone 1 - Auckland	Alt. compliant cost effective	R2.8 batts	R5.0 batts	R3.2 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 2 - Napier	Alt. compliant cost effective	R2.8 batts	R5.0 batts	R3.2 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 3 - Wellington	Alt. compliant cost effective	R2.8 batts	R5.0 batts	R3.2 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 4 - Taupo	Alt. compliant cost effective	R2.8 batts	R5.0 batts	R3.2 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 5 - Christchurch	Alt. compliant cost effective	R4.0 batts	R3.6 batts	R3.2 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1
Zone 6 - Queenstown	Alt. compliant cost effective	R4.0 batts	R3.6 batts	R3.2 batts	R2.4 underslab	Aluminium low-E3 argon double glazing Ucog 1.1

In Table 32 and Table 33, we present the NPVs and BCRs of the highest NPV constructions (labelled 'Cost effective (Q3)') identified previously and compare them to the lowest upfront cost constructions that are compliant with the H1/AS1 4th edition schedule method, the H1/AS1 5th edition calculation method , and the alternative constructions that achieve the next best NPV whilst complying with the H1/AS1 5th edition calculation method (labelled 'Alt. compliant cost effective'). As in the previous analysis, the NPVs and BCRs are based on the upfront build cost and ongoing heating and cooling energy cost comparisons to those constructions that would meet the H1/AS1 5th edition amendment 1 schedule method.

Table 32: NPV cost-effective construction[18]

Net Present Value compared to H1 5th edition schedule method	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	$2,731	$5,327	-$442	$2,169	-$213	$2,558	$1,091	$4,009	$1,331	$6,673	-$1,062	$8,380
Cost effective (Q3)	$6,668	$10,356	$3,239	$6,909	$2,675	$6,767	$2,244	$4,149	$2,331	$6,583	$3,202	$9,747
Alt. compliant cost effective	$3,351	$4,191	$2,598	$3,296	$2,345	$3,157	$1,340	$2,571	$529	$3,691	$3,852	$6,557
H1 5th ed calculation	$2,769	$3,320	$1,371	$2,198	$1,459	$2,411	$395	$2,193	$1,483	$4,437	$3,031	$8,392
Double Storey House												
H1 4th ed schedule	$2,048	$6,339	-$885	$3,374	-$265	$4,007	-$408	$3,101	-$518	$6,005	-$5,210	$4,655
Cost effective (Q3)	$7,345	$9,942	$5,090	$7,287	$5,111	$7,557	$4,482	$6,216	$4,408	$8,824	$4,756	$8,142
Alt. compliant cost effective	$5,033	$8,045	$4,047	$6,651	$4,092	$6,776	$4,411	$4,982	$3,481	$6,803	$4,756	$8,142
H1 5th ed calculation	$5,431	$6,798	$4,023	$5,270	$4,247	$5,514	$3,362	$5,674	$4,371	$5,460	$3,919	$8,057
Medium-Density House (2)												
H1 4th ed schedule	$19,315	$24,795	$6,438	$13,169	$7,514	$15,067	$9,624	$17,879	$5,999	$15,785	-$11,235	$2,420
Cost effective (Q3)	$44,755	$49,669	$31,491	$37,556	$31,689	$38,911	$24,936	$30,414	$20,738	$27,327	$11,724	$20,164
Alt. compliant cost effective	$37,966	$39,491	$31,955	$33,833	$32,091	$34,457	$29,041	$32,146	$21,567	$24,332	$11,706	$15,529
H1 5th ed calculation	$31,814	$33,670	$25,833	$28,159	$26,049	$28,787	$13,708	$16,736	$8,861	$12,619	$4,522	$9,643
(1) Based on assumptions of the upfront cost differences, electricity tariff type (low/standard), and real inflation in electricity prices (0% or 1.2% p.a.)												
(2) Note that the results for the medium-density house is across 8 dwelling units												

Table 33: BCRs cost-effective construction

Benefit-Cost Ratio compared to H1 5th edition schedule method	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)	Low (1)	High (1)
Single Storey House												
H1 4th ed schedule	1.63	2.86	0.94	1.41	0.97	1.51	1.12	1.58	1.15	2.05	0.92	1.80
Cost effective (Q3)	2.50	4.52	1.43	2.25	1.33	2.17	1.36	1.88	1.38	2.50	2.08	5.37
Alt. compliant cost effective	5.78	10.06	2.97	4.37	2.40	3.68	1.50	2.27	1.30	3.90	++	++
H1 5th ed calculation	2.81	4.29	1.53	2.15	1.57	2.34	1.11	1.83	1.62	3.59	5.45	17.30
Double Storey House												
H1 4th ed schedule	1.49	3.29	0.87	1.66	0.96	1.88	0.95	1.46	0.94	1.94	0.64	1.43
Cost effective (Q3)	2.75	4.59	2.44	3.79	1.82	2.72	1.76	2.39	1.72	3.02	3.73	7.18
Alt. compliant cost effective	4.99	10.65	2.97	5.37	2.91	5.50	3.11	4.16	2.47	5.04	3.73	7.18
H1 5th ed calculation	4.06	6.81	2.38	3.44	2.51	3.79	1.76	2.70	4.18	6.57	2.96	6.34
Medium-Density House (2)												
H1 4th ed schedule	2.20	3.33	1.25	1.68	1.29	1.84	1.29	1.71	1.18	1.65	0.80	1.06
Cost effective (Q3)	4.09	6.20	2.35	3.17	2.30	3.27	2.12	2.82	1.90	2.67	1.34	1.77
Alt. compliant cost effective	9.46	14.32	5.41	7.30	5.02	7.13	3.31	4.39	3.24	4.55	1.75	2.31
H1 5th ed calculation	6.82	10.33	3.88	5.24	3.82	5.43	2.12	2.81	1.68	2.35	1.22	1.61
(1) Based on assumptions of the upfront cost differences, electricity tariff type (low/standard), and real inflation in electricity prices (0% or 1.2% p.a.)												
(2) Note that the results for the medium-density house is across 8 dwelling units												

We find that, although the cost-effective (i.e. highest NPV) constructions mostly have slightly higher NPVs than the compliant cost-effective constructions, those compliant constructions still have positive NPVs. More importantly, however, when we look at the BCRs, the compliant constructions outperform the cost-effective constructions. Despite the compliant constructions having a higher upfront construction cost, the savings in energy use are sufficient to suggest that the compliant constructions are more economic than the highest NPV constructions.

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[18] The lowest-cost calculation method model for the Single Storey house in Zone 5 has a better NPV than the Alt. compliant cost effective model, but would not comply with the modelling method. In this instance, we chose a construction (R7.0 ceiling batts) that would allow the alt. cost effective model to comply with both the calculation and modelling methods and to illustrate more options than just repeating the model already run for the calculation method option (which used 140mm walls). That being said, one could also take the lowest up-front cost calculation method option as being a valid example of the highest NPV compliant model here.

3.2.6 Maximum WWR that would still comply

For the highest NPV models that did comply, MBIE asked what was the maximum WWR they could comply with.

3.2.6.1 Calculation method

As the models mainly failed, and the alternative constructions were set to the minimum R-values that would comply, the allowed WWR are very low and not much above the actual WWRs of the houses. Maximum WWR ranged from 17% to 24% for the single-storey zone 6 model (Figure 24). That was achieved purely because the R7.0 batts were more than was needed to comply there, but they were a more cost-effective option than R5.0 or R6.0 batts.

	Single storey	Double storey	Medium density	Apartment
Zone 1	20%	17%	17%	
Zone 2	20%	17%	17%	
Zone 3	20%	17%	17%	
Zone 4	20%	18%	16%	
Zone 5	20%	17%	17%	
Zone 6	24%	17%	16%	

Highest NPV construction
Alternative construction

Figure 24: Maximum WWR complying with the calculation method for the highest NPV models

3.2.6.2 Modelling method

The maximum WWR that complied using the modelling method differed compared to the calculation method. This is because compliance and the effects of window area mainly revolved around cooling loads rather than heating. While in some cases the maximum WWR was lower, the overall tendency is higher WWRs for these example houses using the modelling method (Figure 25). Results were found by adjusting the WWR in the models at 1% intervals, evenly adjusting all windows (up to the limits of the available wall area) as was done to create the reference models.

	Single storey	Double storey	Medium density	Apartment
Zone 1	27%	20%	21%	
Zone 2	26%	24%	19%	
Zone 3	21%	24%	25%	
Zone 4		19%	25%	
Zone 5	21%	19%	26%	
Zone 6	28%	23%	25%	

Highest NPV construction
Alternative construction

Figure 25: Maximum WWR complying with the modelling method for the highest NPV models

3.2.7 Adjusting reference model R-values to allow compliance

For the models that failed to comply with either the calculation or modelling method, MBIE asked how the reference model R-values could be adjusted so as to enable them to comply.

3.2.7.1 Calculation method

As noted, using the calculation method, most of the highest NPV models fail to comply. As the houses and apartment building suffer from very different issues (the apartment building has too many windows and technically cannot use the calculation method), we address them separately.

To determine how we could adjust the reference model R-values and allow the houses to comply, we tested the same adjustments on all the houses rather than adjusting the reference model differently for each (Figure 26 to Figure 28 – red numbers show changed R-values). It is acknowledged that there are potentially a range of combinations that could work – the examples shown here are illustrative. They were put together keeping in mind general principles of trying to keep the reduction in insulation levels as small as possible, supporting constructions with good NPVs and not lowering R-values below those of the H1 4th edition. Despite this, the reductions needed to allow all the houses to comply were substantial:

- Zones 1–3: R-values reduced to not much higher than those of the 4th edition, with the roof lowered to R3.8, the slab reduced to R1.3 and glazing lowered to R0.26.
- Zones 4–5: Slab reduced to R1.4, glazing reduced to R0.37.
- Zone 6: Glazing reduced to R0.45, slab reduced to R1.5.

		Single Storey					
		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	156	3.8	3.8	3.8	6.6	6.6	6.6
Wall	108	2	2	2	2	2	2
Glazing	46	0.26	0.26	0.26	0.36	0.36	0.43
Slab	156	1.3	1.3	1.3	1.4	1.4	1.4
Floor	0	2.5	2.5	2.5	2.8	3	3
	Heat loss	394.00	394.00	394.00	318.36	318.36	297.34
		Most cost effective model					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	156	3.58	3.58	3.58	3.58	3.58	3.58
Wall	122	2	2	2	2	2	2.82
Window	31	0.26	0.26	0.26	0.37	0.37	0.37
Slab	156	0.94	0.94	0.94	1.4	1.4	1.65
Floor							
Doors	2	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	393.03	393.03	393.03	303.18	302.90	268.22
	diff	-0.97	-0.97	-0.97	-15.18	-15.46	-29.12

Figure 26: Single-storey – adjustment of reference R-values to allow the highest NPV model to comply

		Double Storey					
		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	90	3.8	3.8	3.8	6.6	6.6	6.6
Wall	142	2	2	2	2	2	2
Glazing	61	0.26	0.26	0.26	0.36	0.36	0.43
Slab	64	1.3	1.3	1.3	1.4	1.4	1.4
Floor	26	2.5	2.5	2.5	2.8	3	3
	Heat loss	388.48	388.48	388.48	308.79	308.18	280.65
		Most cost effective model					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	90	3.54	3.54	3.54	3.54	3.54	3.54
Wall	165	2	2	2	2	2	2.82
Window	35	0.26	0.37	0.26	0.37	0.37	0.37
Slab	64	0.71	0.71	0.71	0.71	0.71	1.1
Floor	26	3.34	3.34	3.34	3.34	3.34	3.34
Doors	3	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	348.26	307.97	348.26	307.97	307.42	251.38
	diff	-40.22	-80.51	-40.22	-0.82	-0.76	-29.27

Figure 27: Double-storey – adjustment of reference R-values to allow the highest NPV model to comply

		Medium Density					
		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	383	3.8	3.8	3.8	6.6	6.6	6.6
Wall	644	2	2	2	2	2	2
Glazing	276	0.26	0.26	0.26	0.36	0.36	0.43
Slab	171	1.3	1.3	1.3	1.4	1.4	1.4
Floor	222	2.5	2.5	2.5	2.8	3	3
	Heat loss	1705.05	1705.05	1705.05	1348.38	1343.09	1218.24
		Most cost effective model					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	383	3.64	3.64	3.64	3.64	3.64	3.64
Wall	635	2	2	2	2	2	2
Window	150	0.26	0.26	0.26	0.37	0.37	0.37
Slab	171	0.54	0.54	0.54	0.54	0.54	0.87
Floor	222	3.62	3.62	3.62	3.62	3.62	3.62
Retaining	26	2.1	2.1	2.1	2.1	2.1	2.1
Intertena	65	2.4	2.4	2.4	2.4	2.4	2.4
Door	44	0.46	0.46	0.46	0.46	0.5	0.5
	Heat loss	1511.36	1511.36	1511.36	1340.28	1332.60	1212.72
	diff	-193.69	-193.69	-193.69	-8.10	-10.49	-5.52

Figure 28: Medium-density – adjustment of reference R-values to allow the highest NPV model to comply

The concrete slab is a major issue here, as restricting ourselves to the H1 4th edition R-value of R1.3 leaves the slabs at a significant deficit due to the changes to the underlying slab R-value calculations.

For the apartment building, the question is technically inapplicable as the calculation method is not allowed. If we do apply it, window R-values are critical. We need to reduce the window R-values down to R0.26 or even to the level of single glazing in Auckland to allow compliance (Figure 29).

		Apartment					
		Reference model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	413	2.9	3.3	3.3	3.3	3.3	6.6
Wall	1452	1.9	1.9	1.9	1.9	1.9	2
Glazing	622	0.17	0.26	0.26	0.26	0.26	0.26
Slab							
Floor							
	Heat loss	4568.00	3283.42	3283.42	3283.42	3283.42	3182.56
		Most cost effective model					
		Proposed model					
		R-value					
	Area (m2)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Roof	413	3.61	3.91	3.91	3.91	3.91	3.91
Wall	1105	2	2	2	2	2	2.82
Window	970	0.26	0.37	0.37	0.37	0.37	0.37
Slab							
Floor							
	Heat loss	4397.60	3279.67	3279.67	3279.67	3279.67	3119.07
	diff	-170.40	-3.75	-3.75	-3.75	-3.75	-63.49

Figure 29: Apartment building inappropriately applying the calculation method[19]

3.2.7.2 Modelling method

All of the single-storey highest NPV house models failed to comply with the modelling method as did all of the medium-density models with the exception of zones 1 and 2. All of the apartment models failed as expected due to the high WWR. The houses and apartment models present very different issues, so we will discuss them separately.

As with the calculation method, we attempted to adjust the reference model R-values as little as possible and looked for combinations that would work for all the house models (Figure 30 to Figure 33). Note that this is just an example – there are multiple different combinations of reference R-values that could have fixed these compliance issues. In some cases, the change made was more than needed for one house but was chosen because it worked for both of them. This was achieved primarily by lowering the roof and slab R-values along with some drops to the window R-values in zones 2, 3 and 6. While attempts at a consistent progression were made, this proved difficult. For example, it was hard to achieve compliance in zone 3 for the single storey house without dropping the reference glazing to R0.26 but this was not needed for the other models. It may have been easier if the slab insulation could be lowered further but it was difficult to change the constructions further without dropping below R1.3. The medium-density slab was left at R1.7 because all the other options were below R1.3.

[19] Adjusting reference R-values to allow the highest NPV to comply (red numbers show changed R-values).

	Roof	Walls	Windows	Slab	Timber Floor
Zone 1 - Auckland	3.5	2.0	0.46	1.5	2.5
Zone 2 - Napier	3.5	2.0	0.37	1.4	2.5
Zone 3 - Wellington	6.6	2.0	0.26	1.4	2.5
Zone 4 - Taupo	3.9	2.0	0.46	1.4	2.8
Zone 5 - Christchurch	3.9	2.0	0.46	1.4	3.0
Zone 6 - Queenstown	5.0	2.0	0.46	1.7	3.0

Figure 30: Adjusted reference R-values that would allow all the houses to comply

Single Storey	Base Total Heating + Cooling (kWh)				Reference R-value changes			
	Reference model	Cost effective model	Complies?	3b. Adjusted reference model	Roof	Wall	Window	Slab
Zone 1 - Auckland	2985	3379	FALSE	3454	3.5	2.0	0.46	1.6
Zone 2 - Napier	4256	5411	FALSE	5514	3.5	2.0	0.37	1.4
Zone 3 - Wellington	3634	5562	FALSE	5695	6.6	2.0	0.26	1.4
Zone 4 - Taupo	6254	7210	FALSE	7331	3.9	2.0	0.46	1.4
Zone 5 - Christchurch	6838	8078	FALSE	8178	3.9	2.0	0.46	1.4
Zone 6 - Queenstown	9313	9495	FALSE	9833	5.8	2.0	0.46	1.7

Figure 31: Single-storey house – highest NPV model with modelling method adjusting reference model R-values to allow the model to comply[20]

Double Storey	Base Total Heating + Cooling (kWh)				Reference R-value changes				
	Reference model	Cost effective model	Complies?	3b. Adjusted reference model	Roof	Walls	Windows	Slab	Timber Floor
Zone 1 - Auckland	4926	3901	TRUE	.					
Zone 2 - Napier	6622	4634	TRUE	.					
Zone 3 - Wellington	4928	5135	FALSE	8158	6.6	2.0	0.26	1.6	2.5
Zone 4 - Taupo	8049	7713	TRUE	.					
Zone 5 - Christchurch	8879	8443	TRUE	.					
Zone 6 - Queenstown	10925	9371	TRUE	.					

Figure 32: Double-storey house – highest NPV model with modelling method adjusting reference model R-values to allow the model to comply

[20] Note the R-values here sometimes differ from those in the combined table due to taking the closest matching construction that would allow this particular model to meet the target R-value. For example, achieving the R1.5 slab minimum in Auckland requires using a R1.65 slab.

Medium density	Base Total Heating + Cooling (kWh)				Reference R-value changes				
	Reference model	Cost effective model	Complies?	3b. Adjusted reference model	Roof	Walls	Windows	Slab	Timber Floor
Zone 1 - Auckland	17062	12354	TRUE	.					
Zone 2 - Napier	21092	18858	TRUE	.					
Zone 3 - Wellington	15828	18921	FALSE	29581	6.6	2.0	0.26	1.7	2.5
Zone 4 - Taupo	28839	29056	FALSE	30845	4.0	2.0	0.46	1.7	2.8
Zone 5 - Christchurch	30946	32304	FALSE	34168	4.0	2.0	0.46	1.7	3.0
Zone 6 - Queenstown	40893	43191	FALSE	43750	5.0	2.0	0.46	1.7	3.0

Figure 33: Medium-density house – highest NPV model with modelling method adjusting reference model R-values to allow the model to comply

For the apartment building, the fundamental issue is that it has dramatically higher cooling loads than the reference model – for example, lowering the WWR to 30% cut the cooling by 60% in Auckland. This is hard to address by adjusting insulation levels.

In zone 6, the differences in heating use are sufficient that merely lowering the window R-value to R0.26 suffices (Figure 34). In the other zones, more changes are required – the windows frame U-values needed to be further raised in zones 3–5 as well as reducing the roof and wall insulation. This is still insufficient in the hotter climate zones due to large difference in cooling load. There, to allow compliance, the reference windows must be set to single glazing either with thermally broken frames in zone 2 or aluminium in zone 1. In zone 1, it did not appear to be reasonably practical to reduce the reference R-values to enable compliance – even with aluminium single glazing, R1.6 walls and R2.9 roof, the reference energy use was still substantially below that of the highest NPV constructions model.

Apartments	Base Total Heating + Cooling (kWh)				Reference R-value changes		
	Reference model	Cost effective model	Complies?	3b. Adjusted reference model	Roof	Wall	Window
Zone 1 - Auckland	36428	91781	FALSE	76989	2.9	1.6	0.15
Zone 2 - Napier	66775	104645	FALSE	106877	6.6	2.0	0.18
Zone 3 - Wellington	59930	89462	FALSE	89750	5.3	2.0	0.24
Zone 4 - Taupo	116087	155380	FALSE	155484	5.3	2.0	0.24
Zone 5 - Christchurch	125054	171030	FALSE	171289	5.3	2.0	0.24
Zone 6 - Queenstown	174860	216713	FALSE	223872	6.6	2.0	0.26

Figure 34: Apartment building – highest NPV constructions model with modelling method adjusting reference model R-values to allow the model to comply

This illustrates how much high WWR can increase cooling loads – and this is with a number of modelling assumptions designed to keep cooling loads low (white window frames, lowered ventilation setpoint and internal gains, strong use of natural ventilation). In practice, trying to adjust the reference model R-values to cater to the cooling problems of a building with window areas far above what H1 is designed to support is unlikely to be helpful. The main effect it would have would be to make all the houses have much worse performance.

That being said, this does also highlight significant divergences between model performance and the reference model system. While the apartment building consistently failed to achieve compliance here, its actual energy efficiency in terms of estimated kWh/m² was similar to that of the houses. To address this, however, would require a complete redesign of H1/VM1.

3.3 Effect of H1 5th edition on overheating risk

Key takeaways

- Overheating is a complex product of many factors involving the design of the house and behaviour of the occupants. The Building Code does not currently look to manage this risk, with clause H1 focused on heat loss and insulation levels and clause G4 *Ventilation* focused on providing minimum fresh air requirements rather than ventilation for potential overheating control. Many houses that overheat will overheat because they were never designed not to.
- The effect of the H1 changes and increases to insulation levels have produced complex and mixed effects on overheating risk and cooling loads.
- During the day, the most common result in the studied houses was a reduction in overheating risk – though this could depend on the room, climate and ventilation assumptions. In that light, factors such as ventilation, shading and window size may be seen as more significant risk factors. However, if a house is poorly ventilated and airtight, it may overheat significantly, and this may be exacerbated by high insulation levels.
- Night-time overheating was increased by higher insulation levels. The impact could be significant and may be comparable to or even greater than having no shading or having large windows.
- During the day, we see increased roof, wall and glazing R-values typically reducing overheating risk as solar heat gains through them are lowered.
- Increased slab insulation may increase overheating risk due to reducing the effect of the thermal mass of the ground. This may particularly be the case for slab topper insulation, which reduces the mass benefits of the concrete slab.
- Simply reducing the minimum R-value requirements back to those of the H1 4th edition may actually make overheating worse. This is because changes to the calculation of concrete slab R-values mean that slab insulation is now needed to meet those R-values in many houses, and this is the main source of insulation-related overheating risk.
- Temperatures in houses are complex, and effects of the insulation changes on overheating are variable – different effects may be seen in different houses, rooms and climate zones.
- An increase in overheating risk does not necessarily mean that a house will overheat – this will depend on multiple factors.

3.3.1 Background

MBIE asked BRANZ how the 2021 changes to H1 had affected overheating risk in new houses and how any effects might compare to other drivers.

Before we assess this, we should establish some general context. First, it is important to note that H1/AS1 and H1/VM1 are focused on energy efficiency and insulation levels, not overheating. Similarly, ventilation requirements are focused on fresh air supply (NZS 4303:1990 *Ventilation for acceptable indoor air quality*, clause G4) and not on providing enough ventilation to control overheating. This is a gap in the Building Code as it currently stands. With that in mind, when concerns about overheating in new houses are raised, we must remember that those houses may not have been designed with any thought at all given to overheating.

Second, it should be emphasised that overheating risk is complex and is affected by many factors such as window size, orientation, house shape and location, shading, available openings, whether or not the occupants are actually opening the windows and construction material choices.

Whether or not a factor increases overheating risk in general or in some situations is not the same thing as saying that that factor is causing a house to overheat. Whether or not a house overheats will be a product of the overall design, climate and behaviour of the occupants.

In this light, evaluating effects can be challenging – a design change may increase or decrease overheating risk, but whether or not this is important will depend on context. For example, one might have a very cold and shaded house in a valley that simply will not overheat significantly regardless of what is done – changes that increase its overheating risk do not make it overheat enough to matter. At the other end of the spectrum, one might have a heavily glazed house with poor ventilation that overheats a lot, and while changes to the constructions might increase or decrease the overheating risk, it is going to have excessive overheating regardless. Focusing on any individual factor may be a distraction from the greater concern of the house just needing to be significantly redesigned if it is to be comfortable.

Finally, it should be noted that most overheating occurs during the day when it is hot. This does not mean that night-time overheating is negligible – merely that it will tend to be outweighed by daytime overheating when put together. On the same basis, cooling loads will tend to track daytime overheating trends as well. It is because of this that we will discuss daytime and night-time overheating separately.

3.3.2 Model assumptions

To test the effect of the changes made in the 2021 H1 update on overheating, we compare the room temperatures in the H1/AS1 4th and 5th edition schedule method models with no space conditioning. Overheating is measured by degree-hours (°C over threshold x # hours) above the overheating threshold – traditionally 25°C following H1/VM1's cooling setpoint, but we have also run analysis using the CIBSE TM59 adaptive threshold (Chartered Institution of Building Services Engineers, 2013, 2017).

Note, however, that whether or not the H1 5th edition update has increased the overheating risk is a different question to whether or not H1 5th edition R-values increase the overheating risk compared to H1/AS1 4th edition. This is due to the changes to concrete slab R-value calculations. Using 5th edition methods, to achieve R1.3, our slabs are all insulated. Under the H1 4th edition, however, these slabs would have typically been uninsulated. For this reason, we modelled a second version of the H1 4th edition models with uninsulated slabs instead.[21]

To better fit the needs of overheating assessments, the models were adjusted as follows:

- The new Design Summer Year (DSY1) weather files produced by NIWA were used rather than the TMY3 files. These are designed to represent a year with a hot summer to test overheating risk.
- The internal gain schedules were shifted to ones used in BRANZ research based on HEEP data (see Appendix D). These make better assumptions about what rooms internal gains are likely to be in (cooking, fridge gains in the kitchen) rather than simply applying them on a per m² basis over the whole house. Such differences between zones are very important for overheating assessments as this is highly dependent on heat gains being concentrated in specific rooms.

Additionally, to explore the sensitivity of the conclusions to model assumptions and compare the effects of insulation to other drivers of overheating, a number of model variations were produced:

- **Ventilation:** Natural ventilation assumptions have a large effect on overheating predictions, but are also highly uncertain and heavily dependent on assumed occupant behaviour. There are many different ways one can model natural ventilation and so we have provided results using different methods in EnergyPlus:
  - **Simple ventilation:** The first are the simple ventilation assumptions we have already used – assuming a maximum of 30 ACH in living spaces with open doors and cross-ventilation and 10 ACH elsewhere (15 ACH and 5 ACH in the apartment building).

[21] Using a regular or raft slab following the plans. The single-storey and medium-density houses used regular slabs, the double-storey house used a raft slab.

- **Simple wind-driven:** The second are simple wind-driven estimates using EnergyPlus's ZoneVentilation:WindAndStackOpenArea object. These vary the ventilation rate according to the available wind, assuming either single-sided or cross-ventilation. Windows were assumed to have up to 20% effective open area.[22] For simplicity, we assumed here that there would be no cross-ventilation between zones – if a zone had only a single window or windows on only one wall, it was categorised as having single-sided ventilation with an effectiveness of 0.025 (CIBSE, 2006). If a zone had openings on different walls, it was allowed cross-ventilation with the primary orientation being set to the face with the largest opening area.
- **Airflow Network EMS:** The third are complex estimates using EnergyPlus's AirflowNetwork model to estimate the airflow through windows and between zones. Again, windows were assumed to have up to 20% open area. For reasons of the size of the model and the complexity of the urban environment and its effect on the surrounding wind, this was not applied to the apartment model. Custom EMS scripts were used to make the windows begin to open at 22°C and slowly increase in opening area until they were fully open at 24°C. Windows were assumed to be closed overnight. Due to facilitating cross-ventilation through multiple zones and being willing to open all the windows in a house, this can produce very high estimates of the ventilation rate.
- **No mixing:** Comparisons indicated that the simple interzonal air mixing assumptions made in the simple ventilation models significantly affect overheating results, so to examine this, the interzonal air mixing through open internal doors on hot days was removed.
- **Moderate/low/no ventilation:** As there appeared to be potential interactions with ventilation rate and our base assumptions assumed very aggressive and active window opening behaviour (opening all windows, making use of cross-ventilation), we ran extra versions of the model with lower ventilation assumptions as sensitivity analysis. For the moderate ventilation scenario, the ventilation rate was reduced to 10 ACH in the main spaces and 3 ACH elsewhere (7.5 ACH and 1.5 ACH in the apartments). For the low scenario, it was 5 ACH and 1 ACH (5 ACH and 0.5 ACH in the apartments). For the no-ventilation scenario, the ventilation was set to 0.

- **Airtightness:** Building on the ventilation adjustments, the models were further adjusted by lowering the infiltration rate from 0.5 ACH to 0.3 ACH and 0.1 ACH in order to look at the effect increasing airtightness in modern houses may have on overheating (McNeil & Rupp, 2018). These adjustments were applied to the 0 ventilation model as the background airtightness is not particularly relevant when a house is being well ventilated.
- **Night ventilation:** The base models assumed that windows were typically closed overnight or at least not actively used to manage overheating. To examine how night ventilation might impact on the night-time overheating results, night ventilation was added in using EnergyPlus's ZoneVentilation:WindAndStackOpenArea objects. At the same time, the infiltration rate was lowered to 0.1 ACH as the 0.5 ACH infiltration assumed by H1/VM1 would typically require some level of window opening in new houses (McNeil et al., 2015). Two levels were modelled:
  - A basic night ventilation scenario assuming that doors would not be opened and that only single-sided ventilation would be available. Note here that we do not consider any potential impacts of curtains on the ventilation rate.
  - A high night ventilation scenario assuming that rooms with windows on multiple faces would use them for cross-ventilation and that high up balcony doors in apartments could potentially be left open overnight.
- **Dark window frames:** The base model assumed white window frames (80% reflectance) to minimise cooling loads. The window frames had their reflectance set to 10% to show the effect of this on overheating.

[22] Using the discharge coefficient calculator: https://www.gov.uk/government/publications/classvent-and-classcool-school-ventilation-design-tool

- **Window area:** Window area can also significantly affect heat gains. To illustrate the impact of having a window area close to the limit allowed by the schedule method, the WWR in the houses was increased to 27% of the wall area (approximately the 80th percentile WWR observed in a sample of new housing consented between 2012 and 2020). For the apartment building, the window area was lowered to 30% of the wall area.
- **No shading:** To illustrate the impact of the shading in the models, the eaves and balconies were removed. The effect of this could potentially be larger if one examined deeper shading.

3.3.3 Results – daytime overheating

To begin, we provide a general summary of the relative impact of different factors on overheating risk before discussing the details.

Figure 35 shows the effects of different factors on modelled overheating in the single-storey house.

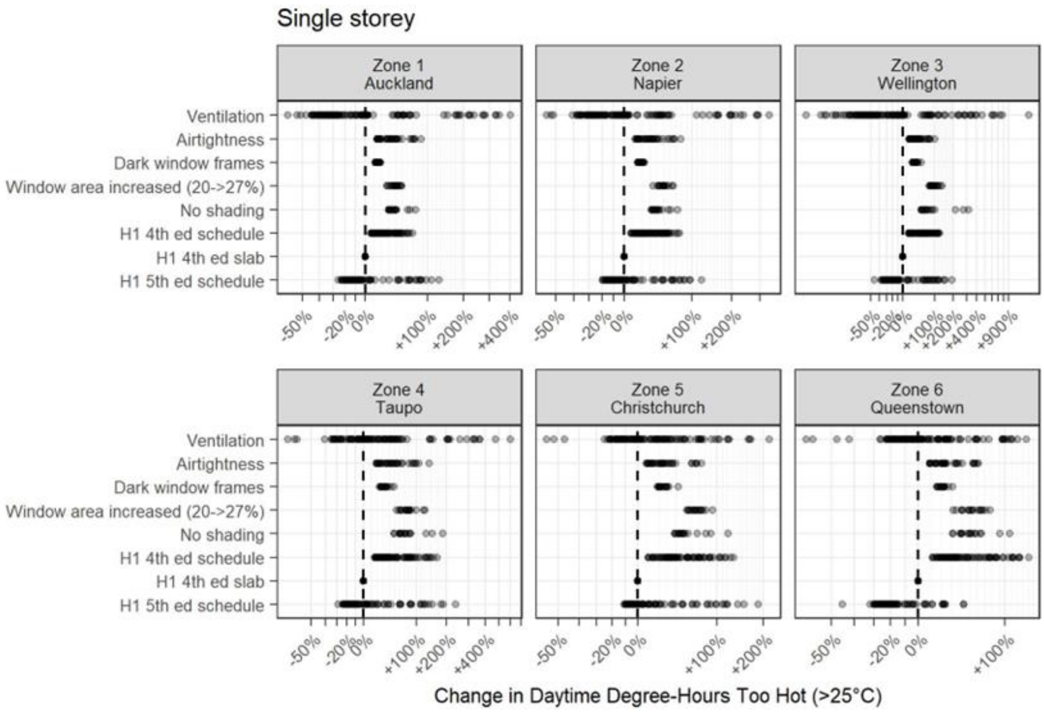

Figure 35: Relative change in daytime overheating in the single-storey house as a result of different factors[23]

Every point represents the change in overheating observed in a specific room for a specific set of model assumptions in a specific climate zone. Thus, for each factor (changing ventilation, changing insulation etc.), there are multiple points on the graph because there are multiple rooms in the model as well as different model assumptions and these may all have different changes in overheating risk. For example, increasing insulation might increase overheating risk more in the living room than the bathroom, or overheating risk might increase more when there is less ventilation. For simplicity in this summary, all the ventilation models have been grouped together as have the airtightness variations and the different insulation levels under different assumptions. Overheating is highly variable and uncertain, being dependent on many factors, and the range of results here reflects this. There is no one simple answer.

To calculate the effect of a factor on overheating, the overheating results from each model were compared against a reference. For the ventilation results, they are compared to the moderate ventilation scenario and for the airtightness results, the no ventilation scenario. For the dark window frame/window area/shading changes, the results plotted show how overheating risk changes relative

[23] Figures with the individual assumptions all separated can be found in Appendix F.

to the baseline model with white window frames, eaves and the designed window area. For the Code insulation changes (H1/AS1 4th edition schedule method, H1/AS1 5th edition schedule method), results are compared against H1/AS1 4th edition slab model, which reflects uninsulated slabs actually constructed under the 4th edition.

Looking at the results, we observe the following:

- For the single-storey house, the H1/AS1 4th edition schedule method R-value model presents higher levels of overheating than what was constructed under the H1/AS1 4th edition. The only difference here is underslab insulation, highlighting that its presence increases overheating risk.
- The increase in insulation levels for the H1/AS1 5th edition model has a wide range of impacts showing both increases and decreases in overheating risk relative to what was built under the H1/AS1 4th edition (H1 4th ed. Slab). Relative to the H1/AS1 4th edition schedule method R-value model, though it is perhaps lower but this does depend on the model. We will discuss the detail later, but a lot of the increases are from low-ventilation scenarios. This does however highlight one important point – simply lowering the schedule method R-values back to those of the H1/AS1 4th edition may actually make overheating risk worse.
- Removing eaves, increasing window area, using black window frames and having a more airtight house all significantly increase overheating risk. Going from black to white window frames has the smallest effect here, but for a relatively minor design decision, its impact is not insignificant – potentially increasing overheating risk by 20–40%.
- Ventilation has the largest potential impact on overheating – if you ventilate well, making good use of cross-ventilation, the overheating risk may be significantly lowered. If you do not open windows, the overheating risk may be many times higher.
- If we were to rank the importance of the various factors as drivers of overheating, poor ventilation would be the biggest driver with high airtightness, large windows, lack of shading and underslab insulation following. Dark window frames are a lesser driver. The H1 5th edition insulation upgrades arguably present the least risk, often lowering the risk. However, they also show high uncertainty and in some situations may increase the risk to a degree comparable to the other factors.

Looking at the other houses, we see similar patterns but some differences (Figure 36 to Figure 38):

- The two-storey house presents a more favourable position on the insulation upgrades, trending more towards them lowering overheating risk. A key difference here is not just that as a multi-storey building it is less affected by the slab insulation but also that it needed edge insulation to achieve the required R-values.
- The medium-density house and apartment building tend towards lower daytime overheating risk with H1 5th edition insulation levels, though it does still clearly depend on other factors.
- Shading is less impactful than on the single-storey house due to the eaves on the multi-storey houses not covering the lower floor. This also depends heavily on the situation – the medium-density house shows two groups of shading effects here – while removing the eaves has only small effects, removing the balconies has a much larger impact on the adjacent zones.
- Increasing the window area has a greater impact on the double-storey and medium-density houses likely in part because they were starting from a lower WWR but potentially also because the upper floors do not have a concrete slab to help absorb extra heat gains.

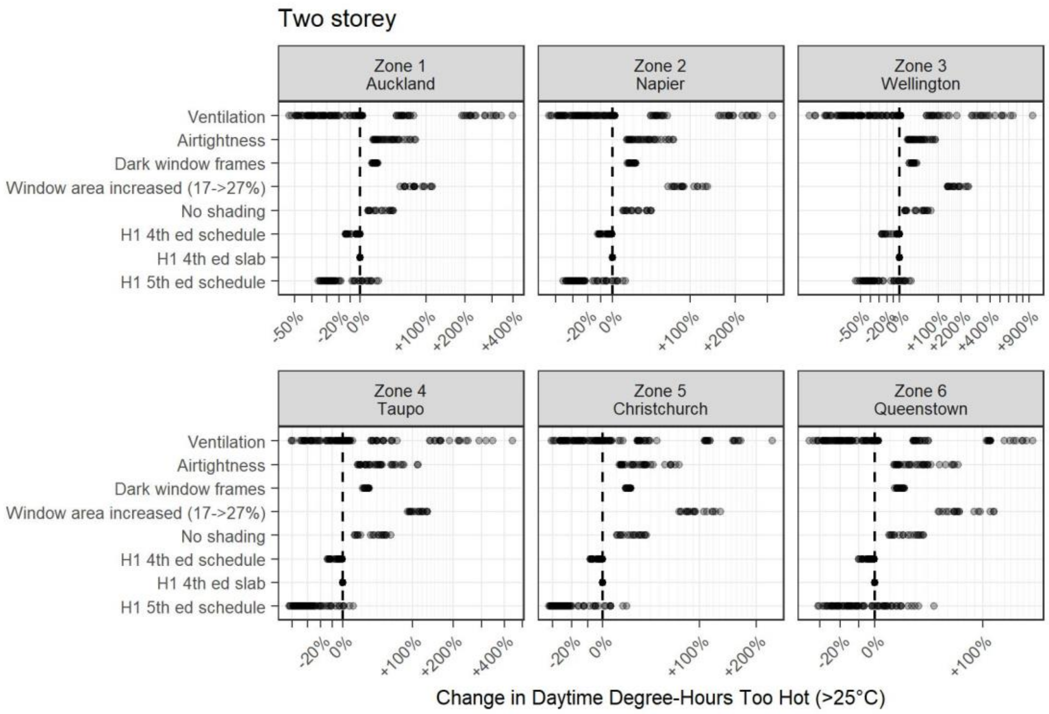

Figure 36: Relative change in daytime overheating in the double-storey house as a result of different factors

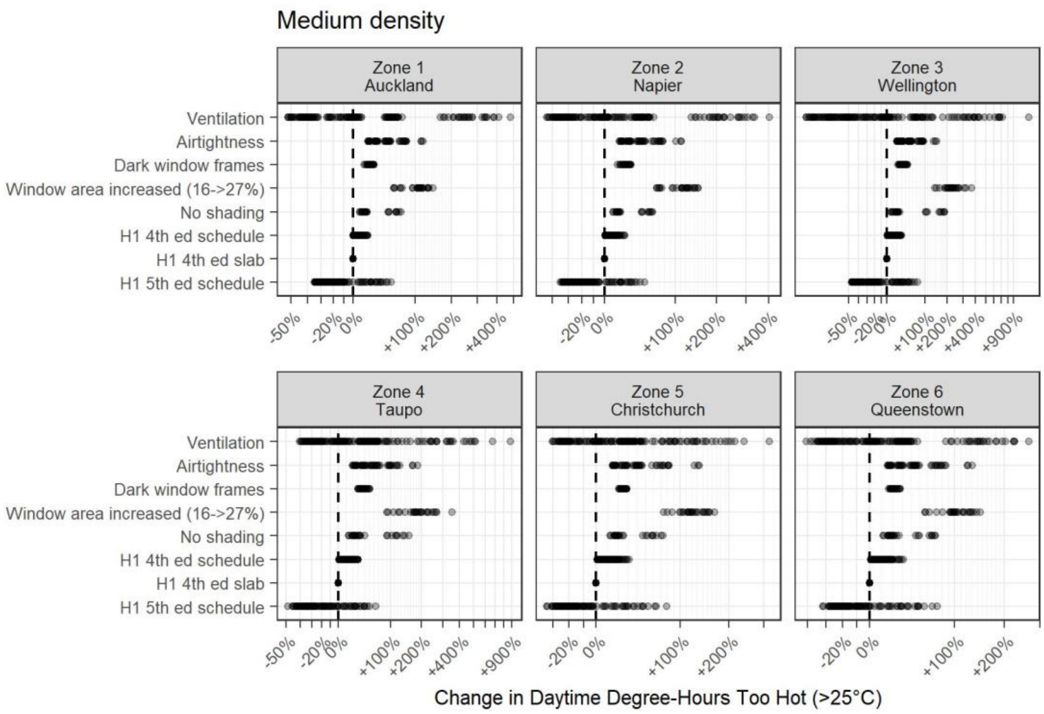

Figure 37: Relative change in daytime overheating in the medium-density house as a result of different factors

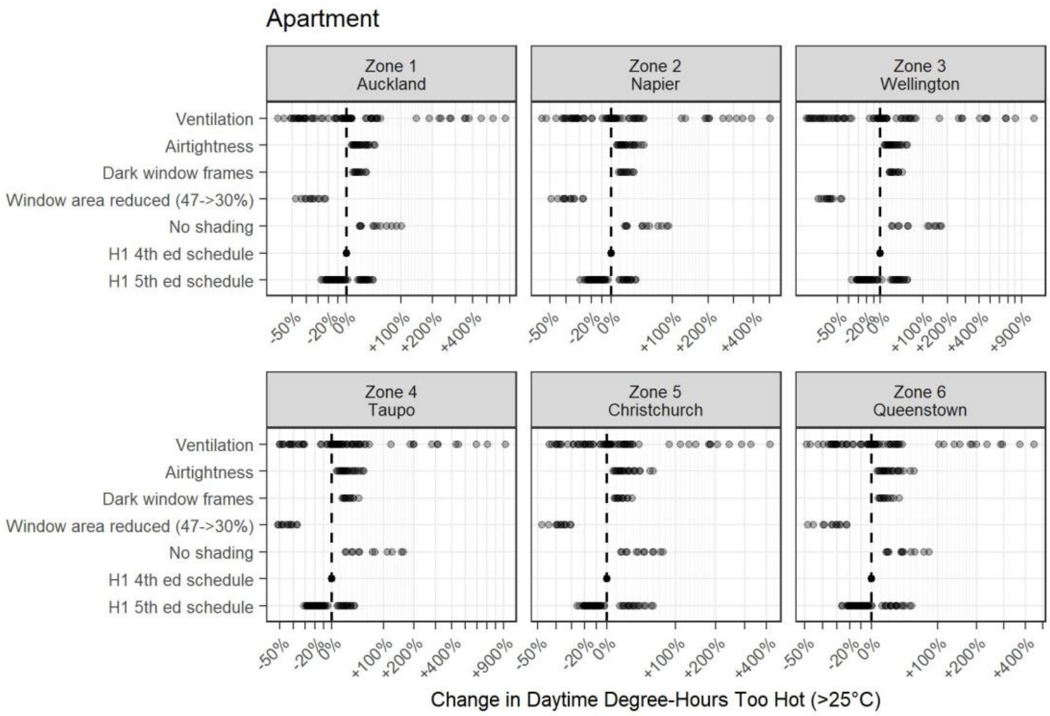

Figure 38: Relative change in daytime overheating in the apartment building as a result of different factors

3.3.3.1 Discussion – additional details

The insulation changes have produced a mixed set of results with a number of nuances. Here, we discuss some of the details and interactions observed using selected graphs. More figures can be found in Appendix F.

As noted, the increase in insulation levels under the H1 5th edition appears to have uncertain effects on overheating risk, potentially increasing it or decreasing it depending on the situation. This appears to be heavily influenced by the amount of ventilation – at high ventilation levels, we mostly see a decrease in daytime overheating risk. However, at very low ventilation levels, we see significant increases (Figure 39). That being said, in such situations we see very high levels of overheating regardless of the insulation level.

Many differences discussed may be linked to concrete slab insulation. Comparing the effects of the different elements from the main construction comparisons we see the following trends (Figure 40):

- Increasing external roof, wall R-values reduces daytime overheating risk, increases night-time overheating risk.
- Increasing window R-values reduces daytime overheating risk, mixed effects on night-time risk – it sometimes increases it and sometimes decreases it depending on the house and climate.
- Increasing floor insulation levels increases overheating risk to a small degree.
- Increasing slab floor insulation levels – underslab and slab topper insulation increases overheating risk. Edge insulation may reduce it.

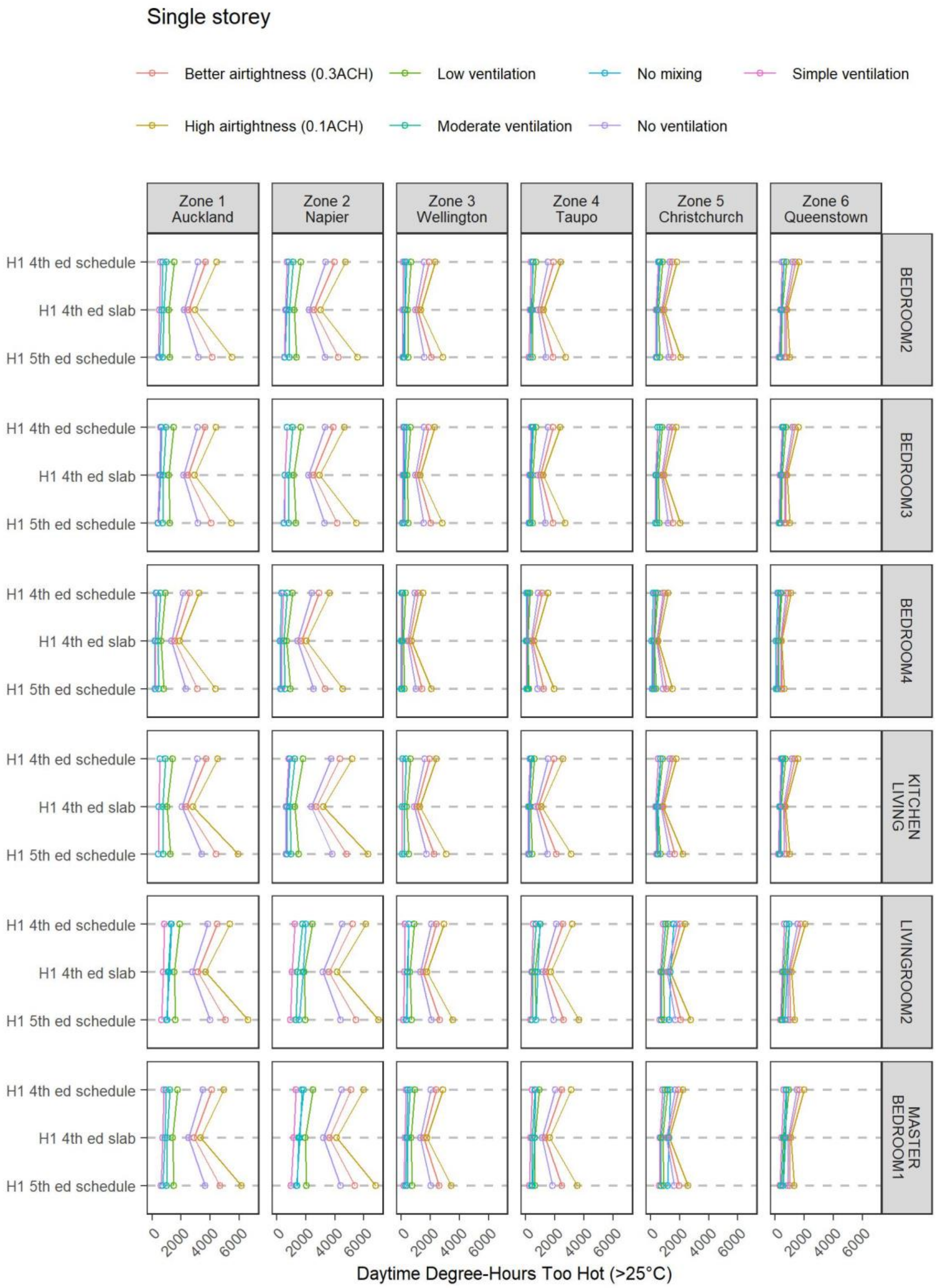

Figure 39: Effect of insulation levels on observed overheating in the single-storey house under different ventilation level assumptions

Climate	Element	Label	Base Cooling (kWh/m2)	Degree hours too hot	Night Degree hours too hot
Zone 2 - Napier	Walls	R2.5 batt 90mm 24%	6.1	107	48
Zone 2 - Napier	Walls	R2.8 batt 90mm 24%	6.1	106	49
Zone 2 - Napier	Walls	R4.0 batt 140mm 24%	5.5	95	64
Zone 2 - Napier	Walls	R4.4 batt 140mm 24%	5.5	95	64
Zone 2 - Napier	Roof	R3.0 batt, 90 chord @ 900crs	6.6	111	38
Zone 2 - Napier	Roof	R3.3 batt, 90 chord @ 900crs	6.6	110	39
Zone 2 - Napier	Roof	R3.4 batt, 90 chord @ 900crs	6.5	110	40
Zone 2 - Napier	Roof	R3.6 batt, 90 chord @ 900crs	6.5	110	41
Zone 2 - Napier	Roof	R4.0 batt, 90 chord @ 900crs	6.4	109	42
Zone 2 - Napier	Roof	R4.5 batt, 90 chord @ 900crs	6.3	108	44
Zone 2 - Napier	Roof	R5.0 batt, 90 chord @ 900crs	6.2	108	45
Zone 2 - Napier	Roof	R6.0 batt, 90 chord @ 900crs	6.2	107	47
Zone 2 - Napier	Roof	R7.0 batt, 90 chord @ 900crs	6.1	106	49
Zone 2 - Napier	Roof	R8.0 batt, 90 chord @ 900crs	6.0	106	51
Zone 2 - Napier	Floor	R1.5 batt, 140 joist @ 450crs	6.1	106	45
Zone 2 - Napier	Floor	R1.8 batt, 140 joist @ 450crs	6.1	106	46
Zone 2 - Napier	Floor	R2.0 batt, 140 joist @ 450crs	6.1	106	47
Zone 2 - Napier	Floor	R2.6 batt, 140 joist @ 450crs	6.1	106	49
Zone 2 - Napier	Floor	R2.8 batt, 140 joist @ 450crs	6.1	106	50
Zone 2 - Napier	Floor	R3.0 batt, 140 joist @ 450crs	6.1	106	50
Zone 2 - Napier	Floor	R3.2 batt, 140 joist @ 450crs	6.1	106	51
Zone 2 - Napier	Windows	Aluminium double glazing	10.7	160	57
Zone 2 - Napier	Windows	Low-E3 double glazing w. 16mm argon + aluminium frame	6.9	117	51
Zone 2 - Napier	Windows	Low-E3 double glazing w. 12mm argon + thermally broken frame	6.1	106	49
Zone 2 - Napier	Windows	Low-E3 double glazing w. 16mm argon + thermally broken frame	6.2	108	52
Zone 2 - Napier	Slab	Uninsulated	6.0	101	48
Zone 2 - Napier	Slab	R1.0 edge insulation	5.4	73	44
Zone 2 - Napier	Slab	R1.2 underslab insulation	6.5	130	53
Zone 2 - Napier	Slab	R2.4 underslab insulation	6.7	141	54
Zone 2 - Napier	Slab	R1.2 underslab + edge insulation	5.9	98	48
Zone 2 - Napier	Slab	R2.4 underslab + edge insulation	6.1	106	49
Zone 2 - Napier	Slab	40mm R1.0 slab topper insulation	7.5	194	54
Zone 2 - Napier	Slab	Raft slab	6.4	125	52
Zone 2 - Napier	Slab	Raft + R1.0 edge insulation	6.0	101	48
Zone 2 - Napier	Slab	Raft + R1.0 slab topper insulation	7.7	203	56

Figure 40: Section of individual construction energy use results from the double-storey house in Napier[24]

From a physics standpoint, overheating in houses is heavily driven by solar gains during the day driving up temperatures. Solar heat may be transferred through the roof, walls and windows, so reducing heat transfer through those elements will tend to reduce peak daytime temperatures.

In contrast, little solar gain comes through the floor and so insulating the floor may also increase overheating risk by reducing heat loss – though this effect is typically minor when looking at timber floors. With concrete floors, however, the effects may be much more significant due to the effects insulation can have on thermal mass. Adding underslab insulation may reduce the benefits from the thermal mass of the ground and so increase overheating significantly. Placing insulation on top of the slab is an even greater risk as it cuts the connection to both the mass of the ground and the mass of

[24] Note how increasing window, wall and roof R-values lowers cooling use but adding slab insulation generally increases it. Technically, increasing floor insulation also increases cooling use but it's insignificant. Daytime overheating is measured in the living room, night overheating is measured in the master bedroom. The living room on the ground floor is less affected by the roof and timber floor over the garage. The master bedroom on the upper floor is less impacted by the concrete slab.

the concrete slab. If designers feel pushed to use slab topper insulation as a way of achieving schedule R-values, this may increase overheating risk.

Slab edge insulation might reduce overheating risk. The Kiva foundation model used here predicts that there may be significant heat gains through the edge of the slab in summer and so adding edge insulation may reduce these. Some measurements of concrete slabs suggest that this prediction may have validity (Liu et al., 2021; Parker et al., 2016). That being said, the GroundDomain model in EnergyPlus does not predict this, and there is a need for work in the New Zealand context to assess how accurate this is, so there is uncertainty here.

Interactions with other factors appear to have little effect on the trends. Dark window frames, increased window area and the removal of shading all significantly increase the daytime overheating risk. However, they do not appear to significantly alter the effect of the insulation levels and whether or not higher insulation increases or decreases the risk.

The double-storey house highlights various differences (Figure 41):

- While it mostly shows strong decreases in overheating risk from increasing insulation, zone 6 is an exception. There we see an increase in overheating risk in the kitchen/living zone on the ground floor. This can be linked to the fact that, to achieve the R1.7 H1 5th edition schedule method minimum there, it had to use slab topper insulation, which significantly reduces the thermal mass benefits.
- The double-storey house also differs from the single-storey in that using an uninsulated (raft) slab did not appear to reduce overheating risk relative to the insulated slabs. This is because, due to its low A/P ratio, the double-storey house needed both edge and underslab insulation to achieve both H1 4th and 5th edition minimum R-values. Edge insulation, according to the Kiva foundation model, may lower overheating risk by reducing heat gains through the slab edge in summer.

Comparing the different ways of modelling the ventilation (simple ventilation rate, simple wind-driven, airflow network), we see that they are sometimes close and sometimes significantly different. Of particular note were the areas where the airflow network model predicted significantly higher levels of overheating than the simpler models – such as in the master bedroom in the single-storey house (Figure 42).

This is notable because the airflow network often produces the highest ventilation rates – regularly getting over 50 ACH or more – so it predicting more overheating in spite of that is surprising. Examining the models found that it was related to the interzonal air mixing assumptions in the simple models. Some simple assumptions about air exchange through open doors had been applied to those models. However, because they are simple models, they lack information about the directionality of any airflow between zones, and so it was simply assumed that air would be evenly mixed between the connected zones. In cases such as this, however, this could allow a zone such as the master bedroom here to effectively cool itself by exchanging air with the adjacent cooler corridor. When the airflow network is used, this does not happen because the air is flowing in from the outdoors through the bedroom and out into the corridor.

If we remove the interzonal mixing from the simple model, we see a significant increase in the projected overheating in certain zones. That being said, while this has significant impacts on overheating assessments and is something that modellers should be aware of, it does not appear to significantly affect the trends of interest here. Whether or not insulation causes an increase or decrease in risk is not affected by this assumption in this instance.

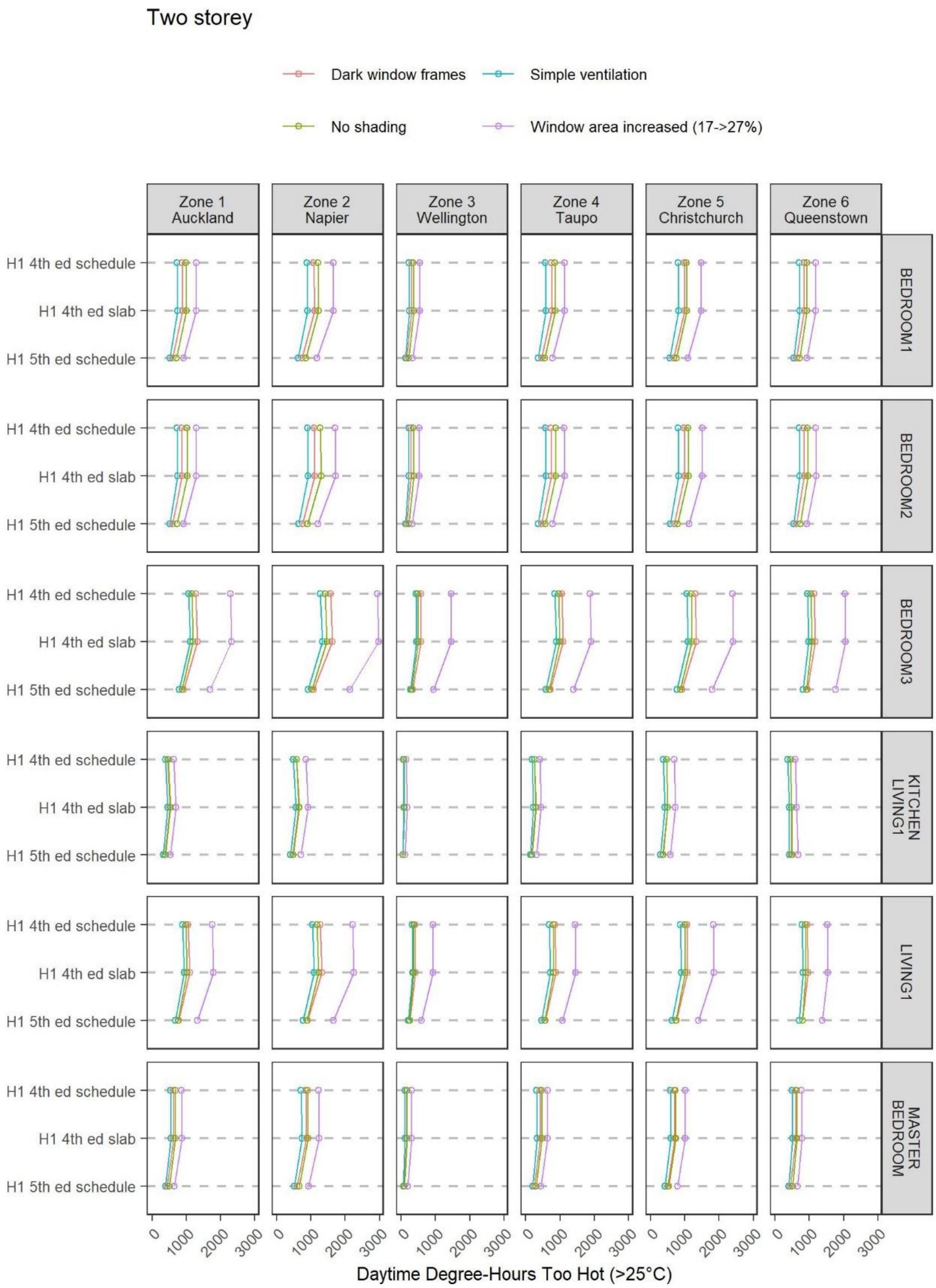

Figure 41: Effect of insulation levels on observed overheating in the double-storey house with different design changes – the simple ventilation model is the baseline for these comparisons

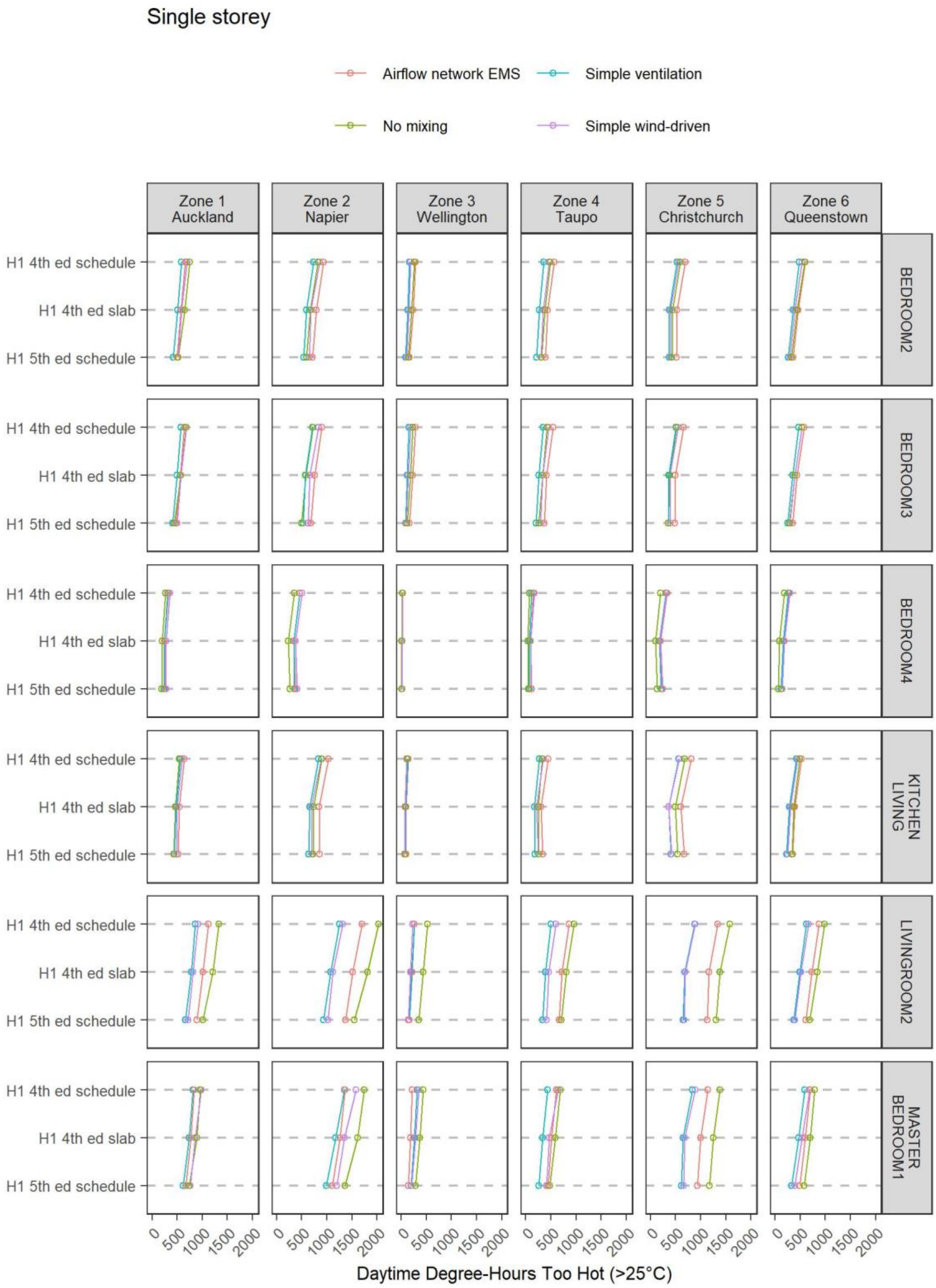

Figure 42: Effect of insulation levels on observed overheating in the single-storey house under different ventilation assumptions

The medium-density house shows similar trends to the double-storey house. We may particularly observe the differences between the kitchen/living zones, where the concrete slab is, and the upper floors, which show much stronger tendencies towards reduced overheating risk with higher insulation levels (Figure 43).

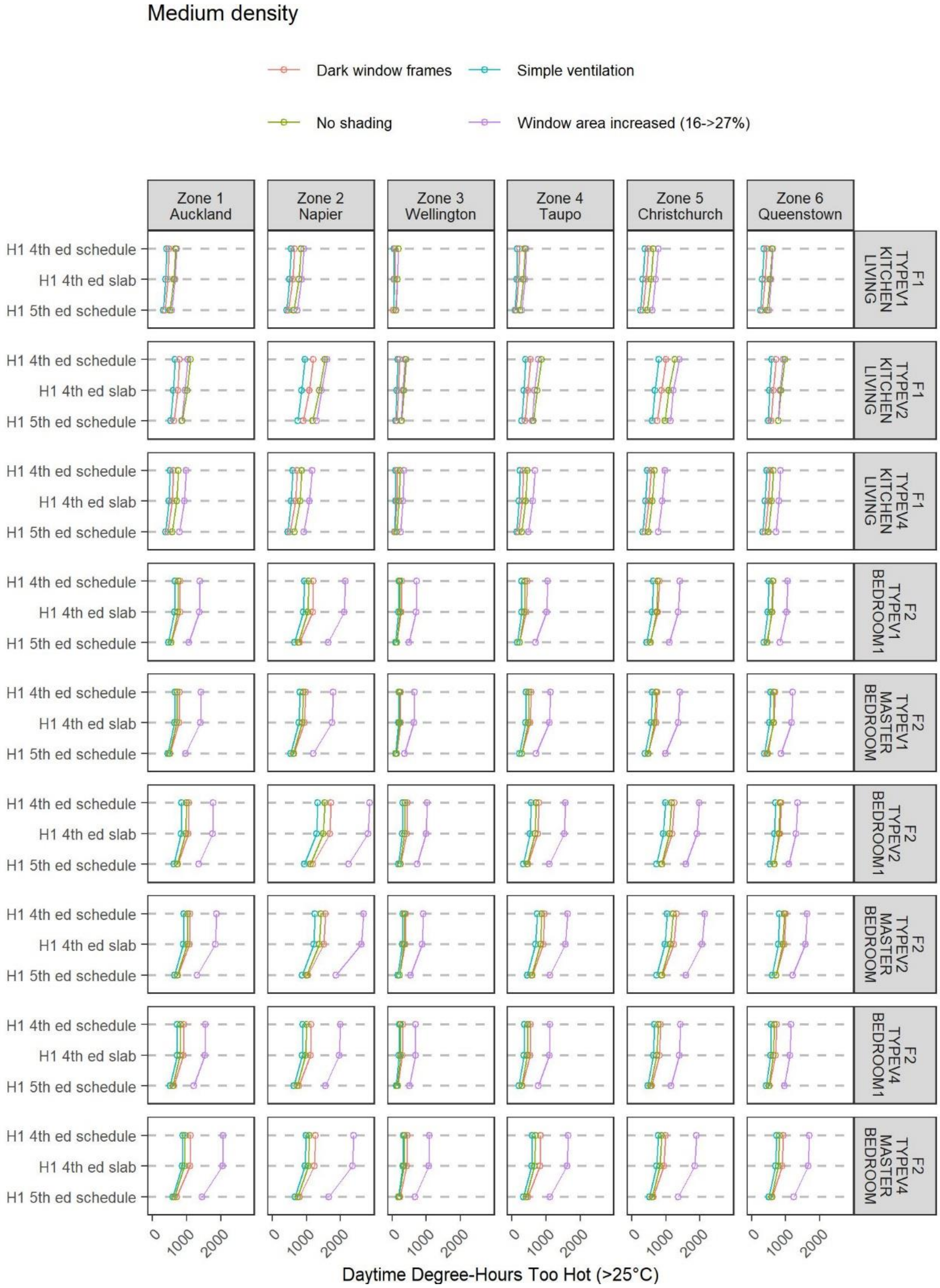

Figure 43: Effect of insulation levels on observed overheating in the medium-density house with different design changes – the simple ventilation model is the baseline for these comparisons

The apartment building also has varying results – overheating risk is most reduced in the north apartments with the highest overheating, but there appears to be less of an effect on the lower south facing apartments (Figure 44). Of course, such rooms are also the ones with the least overheating risk.[25] The variation due to insulation levels is also smaller than the variation between

[25] Though this does not mean insignificant overheating risk – south-facing apartments may still have significant overheating if ventilation is insufficient to remove heat.

apartments – being a north-facing apartment with large windows and limited shading is a much bigger risk factor than having higher insulation levels. The comparison between the top north apartment here (A) and the others illustrates well the effect such design decisions can have on overheating risk.

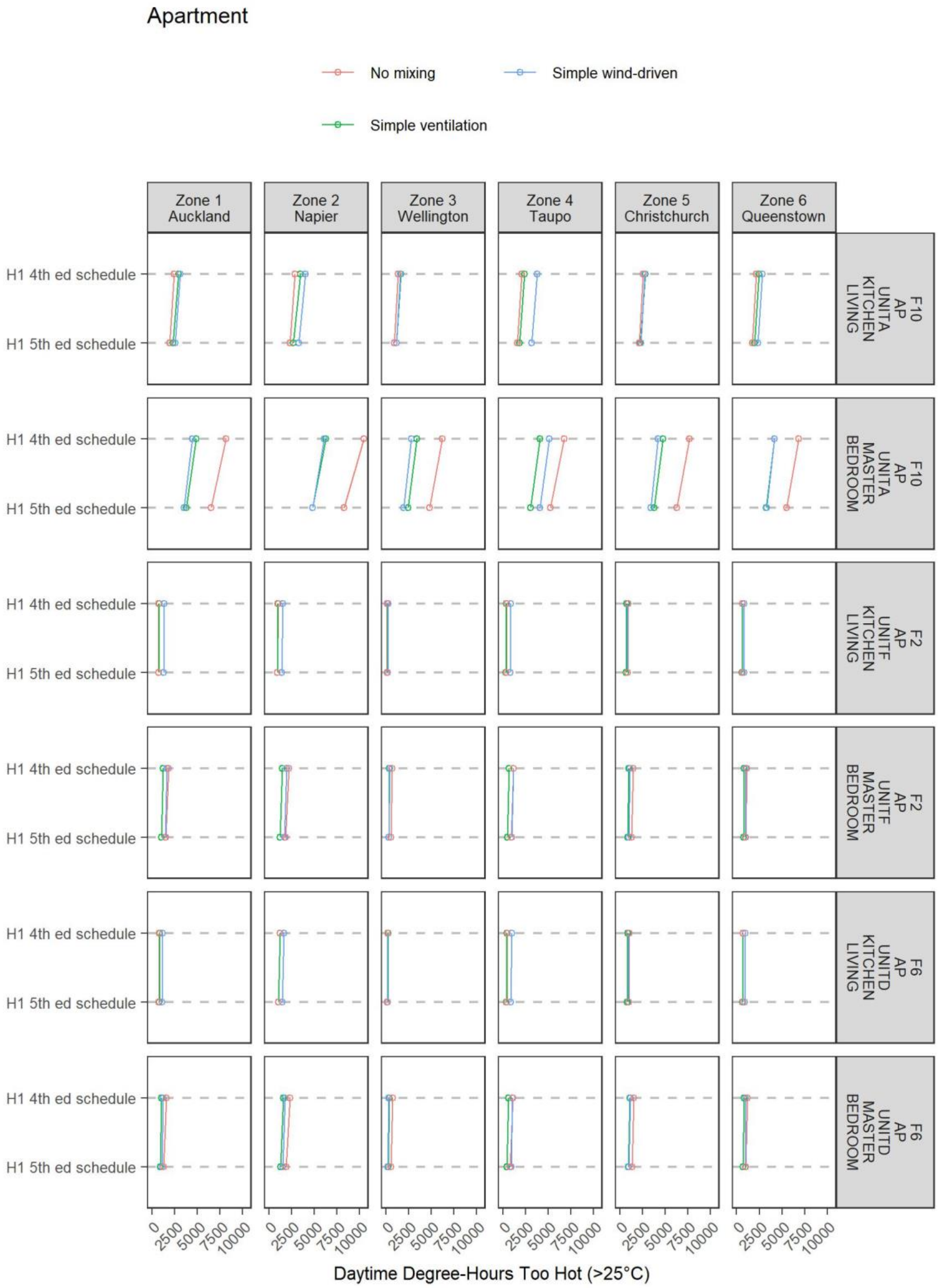

Figure 44: Apartment building showing zone overheating under different construction scenarios – a selection of apartments are shown from a north-facing top floor one (F10 Unit A), an east-facing middle floor (F6 Unit D) and a south-facing lowest floor (F2 Unit F)

3.3.4 Results – night-time overheating

Looking now at the night-time overheating results, we begin with the overall summaries of the relative impacts of the different factors on overheating risk.

One point that can make assessing the impact difficult is that the number of hours of night-time overheating is often very small. Because of this, small changes in absolute terms can be very large in relative terms, causing the scale to explode. An increase from 0.5 hours of overheating to 10 hours of overheating is a 20-fold increase but still not a significant amount of overheating. This is particularly a problem for climates such as Wellington's. The graphs shown in Figure 45 to Figure 48 have had their scales constrained to changes of a factor of 20 to aid legibility.[26]

In general, looking at the results, we see much the same impacts as on daytime overheating as we would expect:

- Ventilation still has the widest potential impact on overheating risk.
- Dark window frames, high airtightness, increased window area and a lack of shading all continue to increase risk to broadly degrees.

However, the effect of insulation has changed significantly – the general tendency is for increased insulation to appear to significantly increase the risk of overheating.

Indeed, in some cases such as the single-storey house, it is arguably the strongest factor after ventilation.

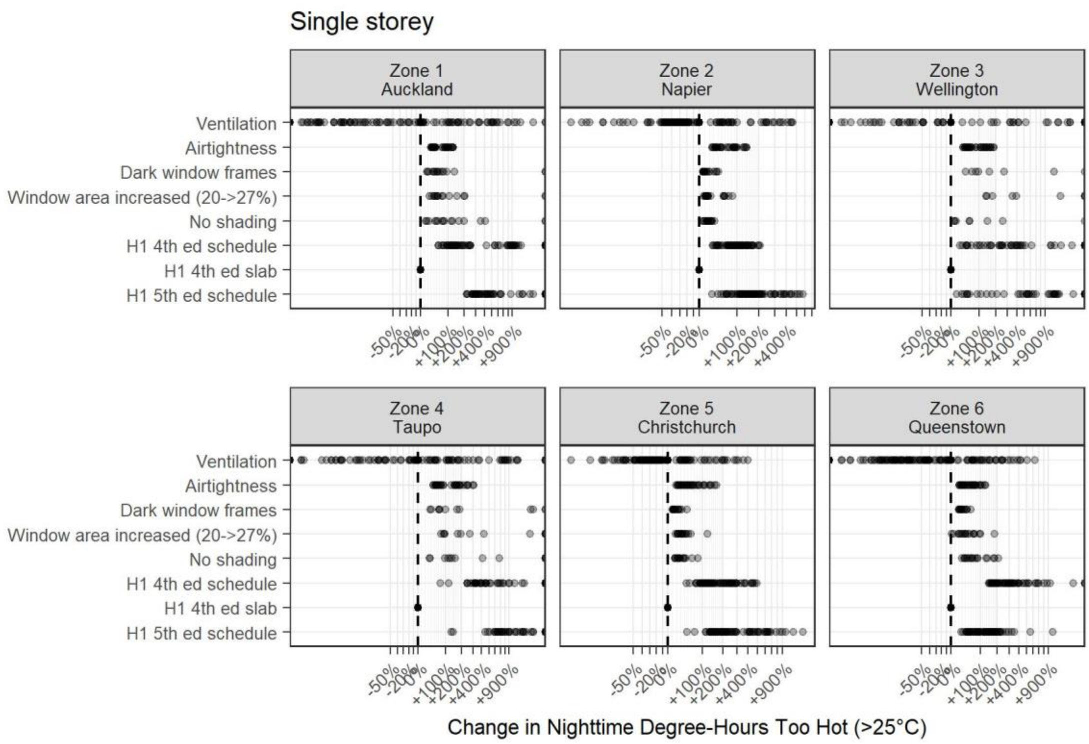

Figure 45: Relative change in night-time overheating in the single-storey house as a result of different factors

[26] Figures without this constraint may be found in Appendix F.

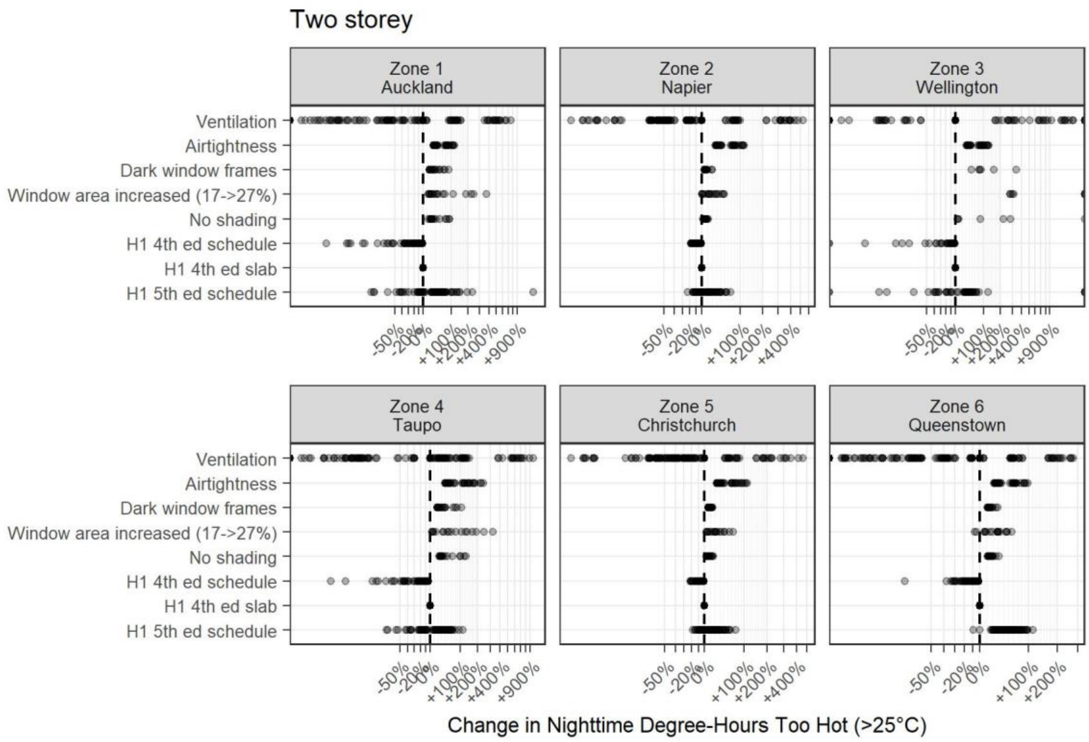

Figure 46: Relative change in night-time overheating in the double-storey house as a result of different factors

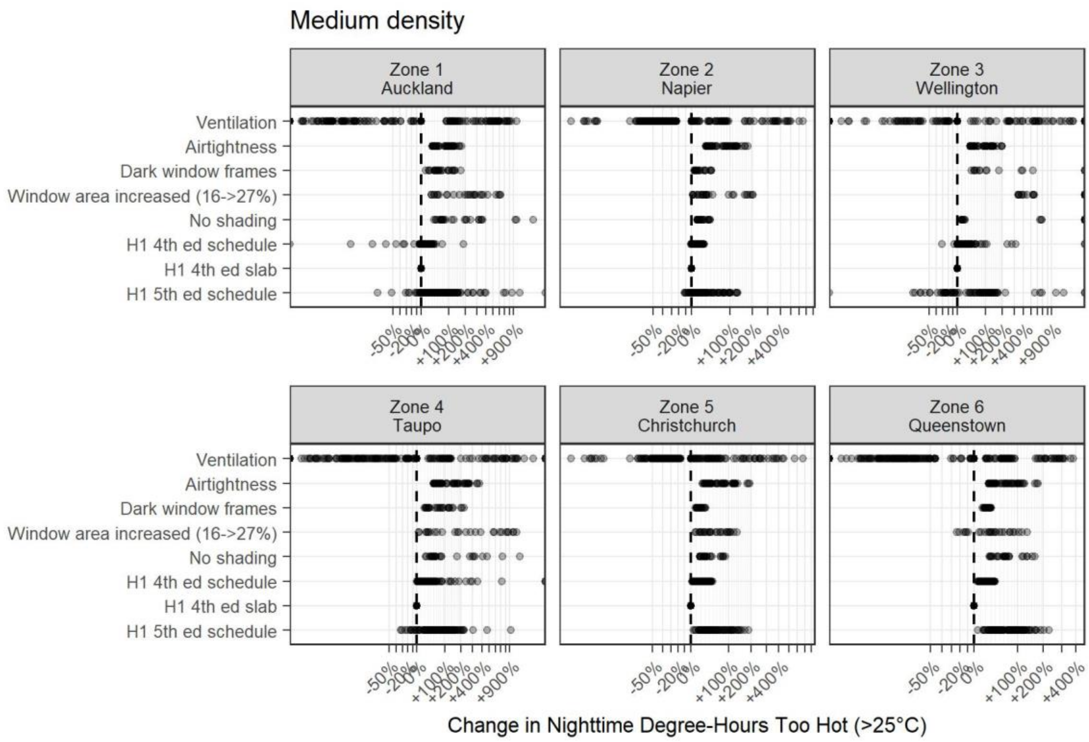

Figure 47: Relative change in night-time overheating in the medium-density house as a result of different factors

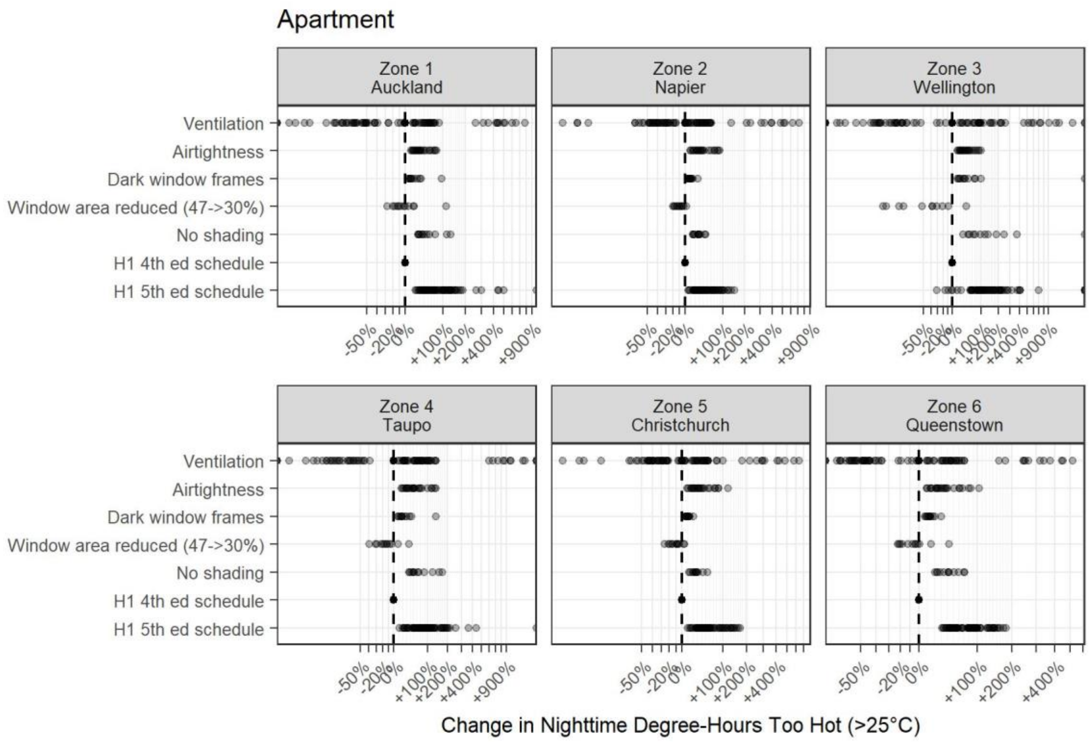

Figure 48: Relative change in night-time overheating in the apartment building as a result of different factors

3.3.4.1 Discussion – additional details

That higher insulation levels pose a greater issue for night-time overheating risk than daytime makes sense. At night, there is no sun and so the insulation cannot reduce heat gains – its only effect is to better retain heat. Thus, overheating risk increases.

Looking at the night-time temperatures, we can see that these incidents of overheating can be significant – in this example, a difference of ~1°C – and that just because the peak daytime temperatures are reduced does not mean that the night-time temperatures will be (Figure 49).

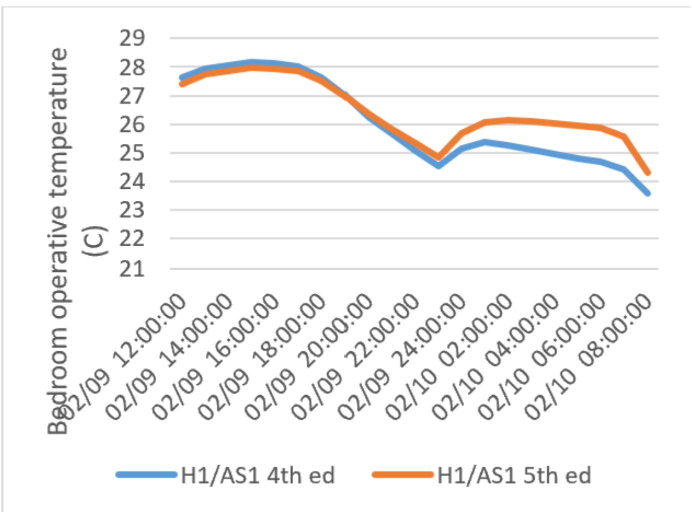

Figure 49: A small temperature slice comparing the temperatures in a bedroom with H1/AS1 4th edition insulation levels and H1/AS1 5th edition insulation levels[27]

[27] While the peak daytime temperatures were slightly lower with the H1/AS1 5th edition insulation, the temperatures rose significantly overnight when the windows and doors in the model were closed.

A question that may arise here is whether the overheating could be managed by ventilating overnight.

Looking at the effects of night ventilation we see that, in general, while it can reduce the differences, it does not really change the overall trends unless there is a lot of it (Figure 50). Basic levels of single-sided ventilation still tend to leave us with insulation increasing overheating risk. That being said, if cross-ventilation can be provided, the overheating and increased risk from insulation can potentially be eliminated. Whether or not this is practical depends on a range of factors and individual circumstances.

First, the design of the house must support it – in this example, we see very little effect from night ventilation in bedroom 3 of the double-story house. This is because it only has a single small window and a sliding door, which we have assumed is closed overnight for security reasons. This means its ventilation potential is limited, while the other rooms have multiple openable windows. Other factors are whether or not people open the windows overnight, how much they are willing to do so and whether or not they are willing to leave their bedroom door open.

That being said, even if there is a general tendency towards increasing the risk of overheating, the degree to which this is a concern can vary substantially depending on the specifics of the situation, and we can see examples across the spectrum in the results here:

- If we look at Wellington and Taupo's results, we see examples where increased risk is not a concern because there just are not significant levels of overheating.
- In other places, we can see the overheating risk almost double and potentially reach significant levels. For example, if overheating increases from ~20 hours a year to ~40 hours, this could be the difference between a few nights of overheating to a week of overheating. We can see even larger effects if we look at the single-storey house without ventilation (Figure 51). Here, we could see an increase from ~500 degree-hours of overheating to over 1,500 in the master bedroom. This is arguably a major increase in overheating. At the same time, 500 degree-hours could already be seen as excessive and is enough to see overheating for a third of the nights over summer. It could be argued that even if the insulation is making the overheating risk significantly worse, the core driver of the overheating is that the house is not being ventilated.

Whether or not there is a problem also depends on another factor – what temperatures we classify as overheated. We have been using 25°C as the threshold to define overheating partly as it is a value that has historically been used in New Zealand and is consistent with H1/VM1 but also because it allows us to actually measure differences in night-time overheating.

Overseas research has argued, however, that such thresholds are much too low and people can tolerate much higher temperatures overnight (Kim et al., 2023; Lomas & Li, 2023). Work from the UK and Australia has suggested that thresholds of 28°C or even 29°C may be more appropriate. If we use a threshold of 28°C, nearly all of the overheating outside of very low ventilation scenarios disappears (Figure 52 and Figure 53).

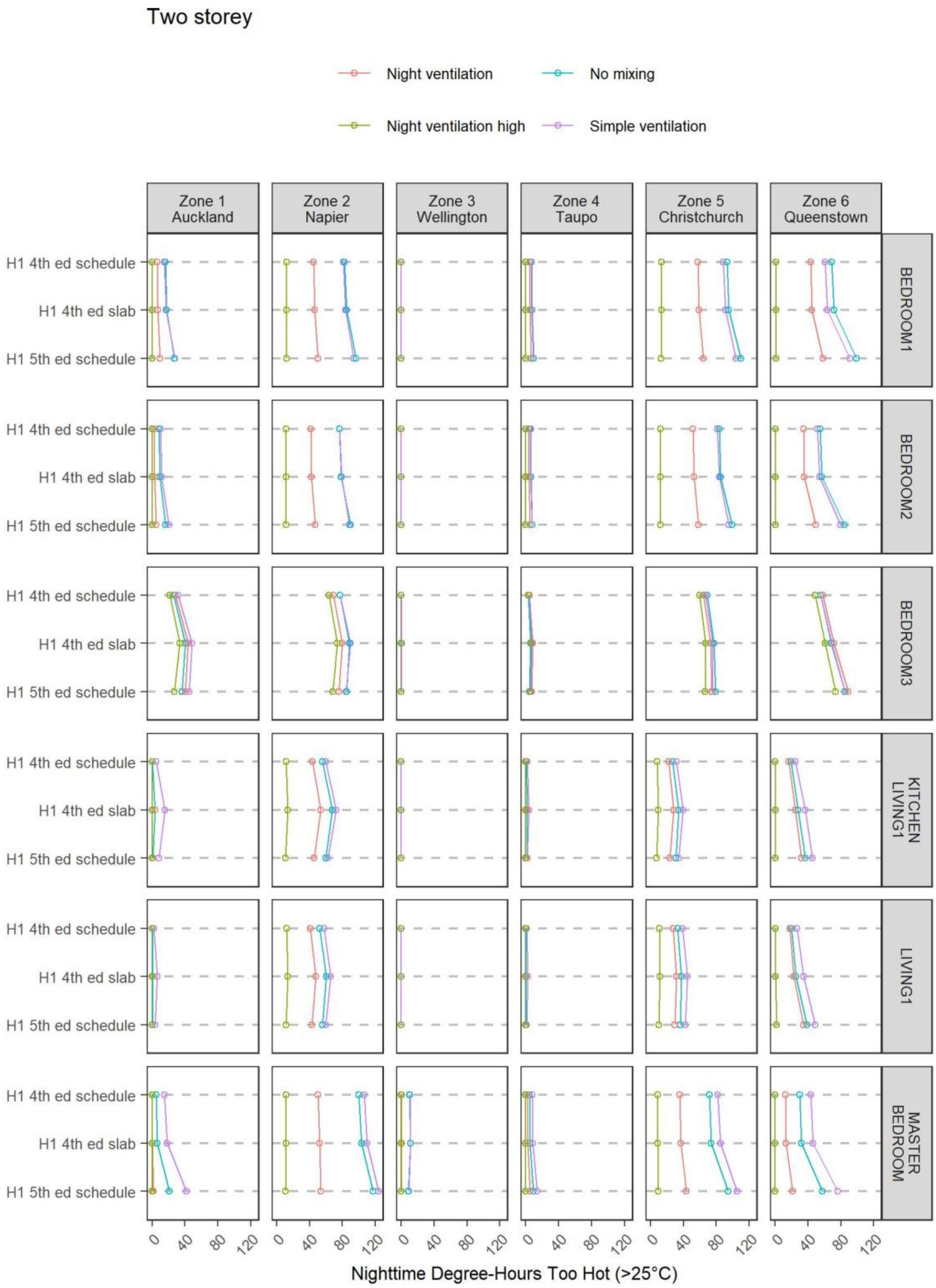

Figure 50: Effect of insulation levels on observed night-time overheating in the double-storey house with different ventilation assumptions

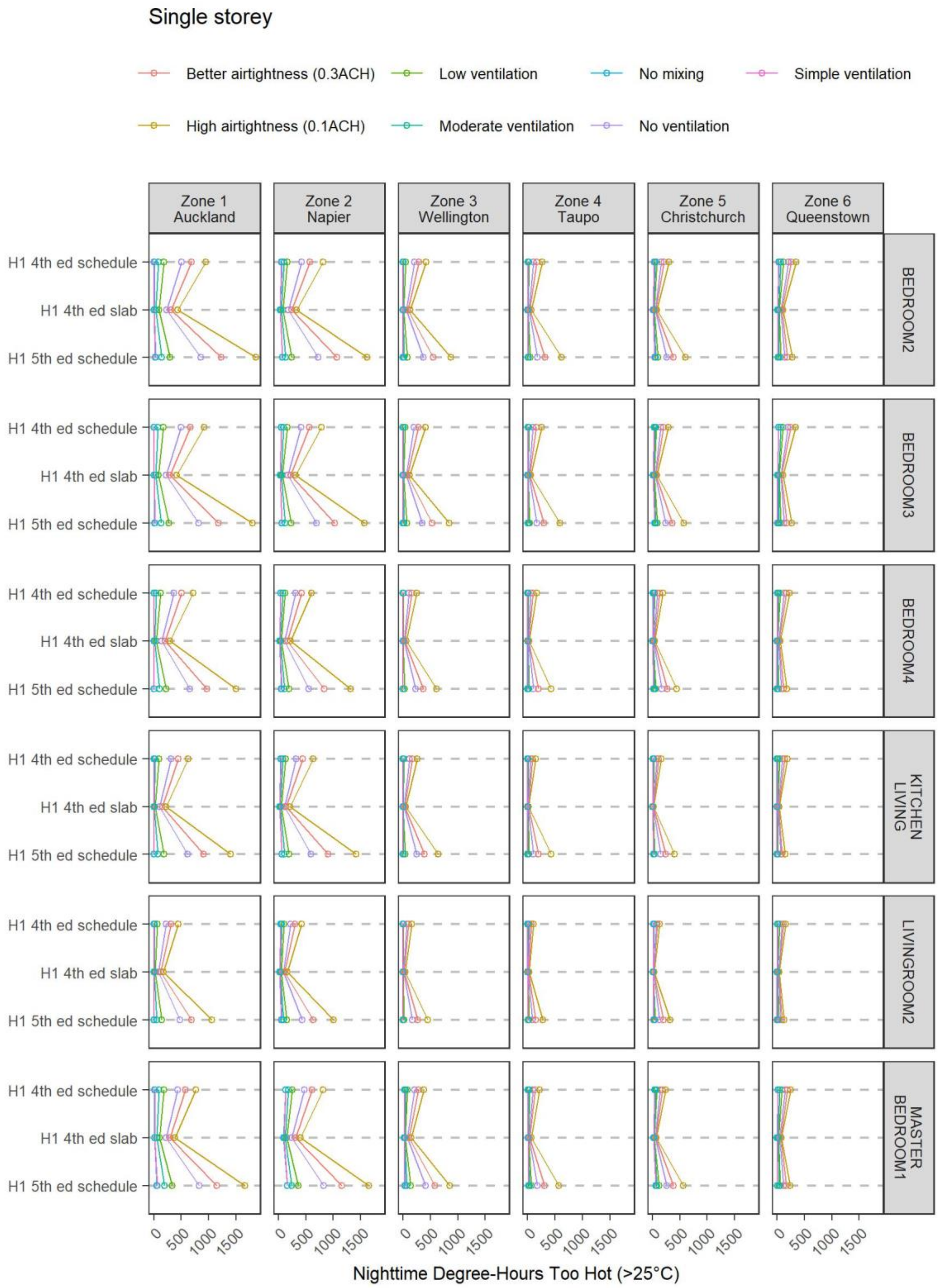

Figure 51: Effect of insulation levels on observed night-time overheating in the single-storey house with different ventilation assumptions

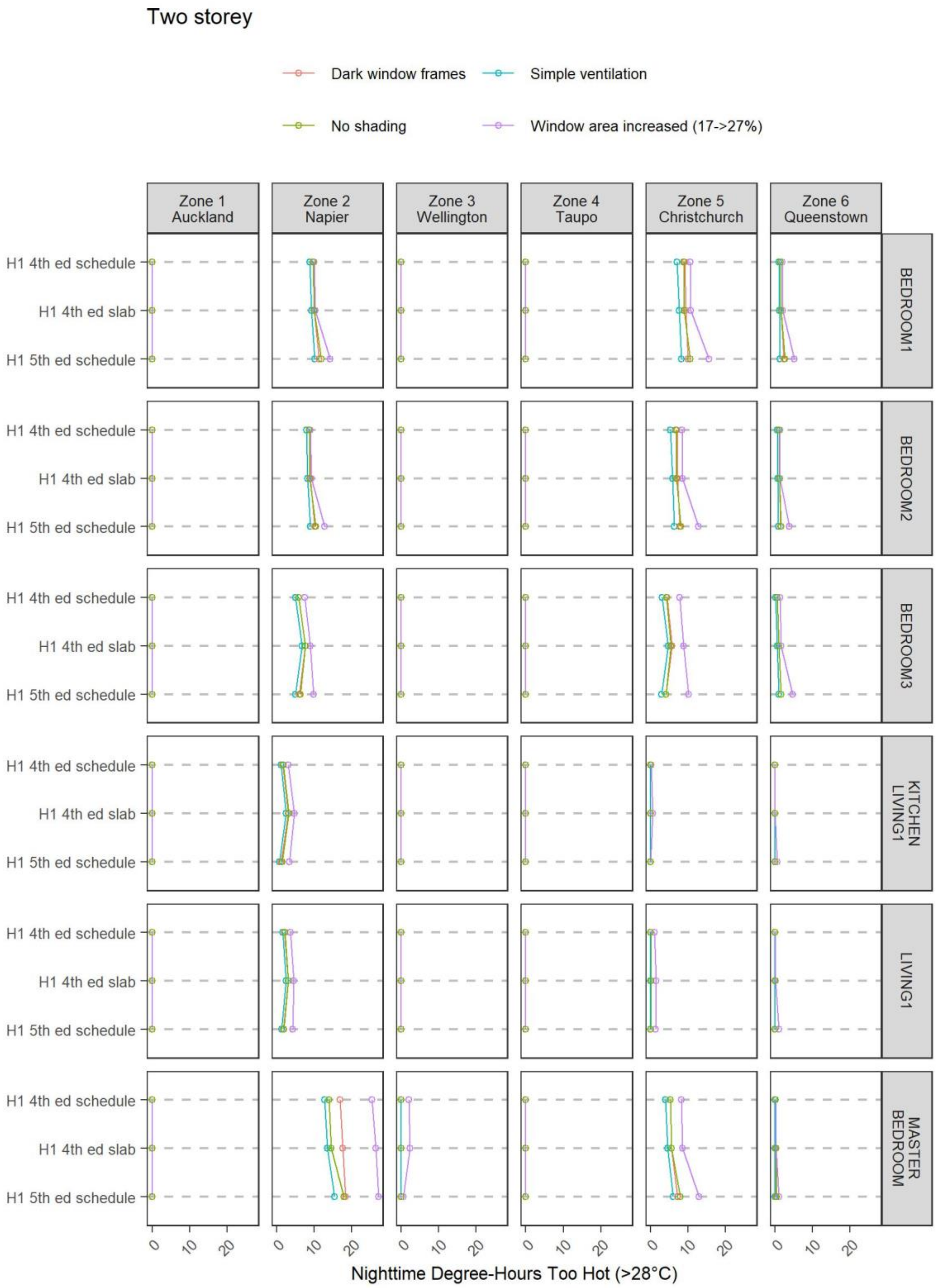

Figure 52: Overheating threshold raised to 28°C – effect of insulation levels on observed night-time overheating in the double-storey house with different design assumptions

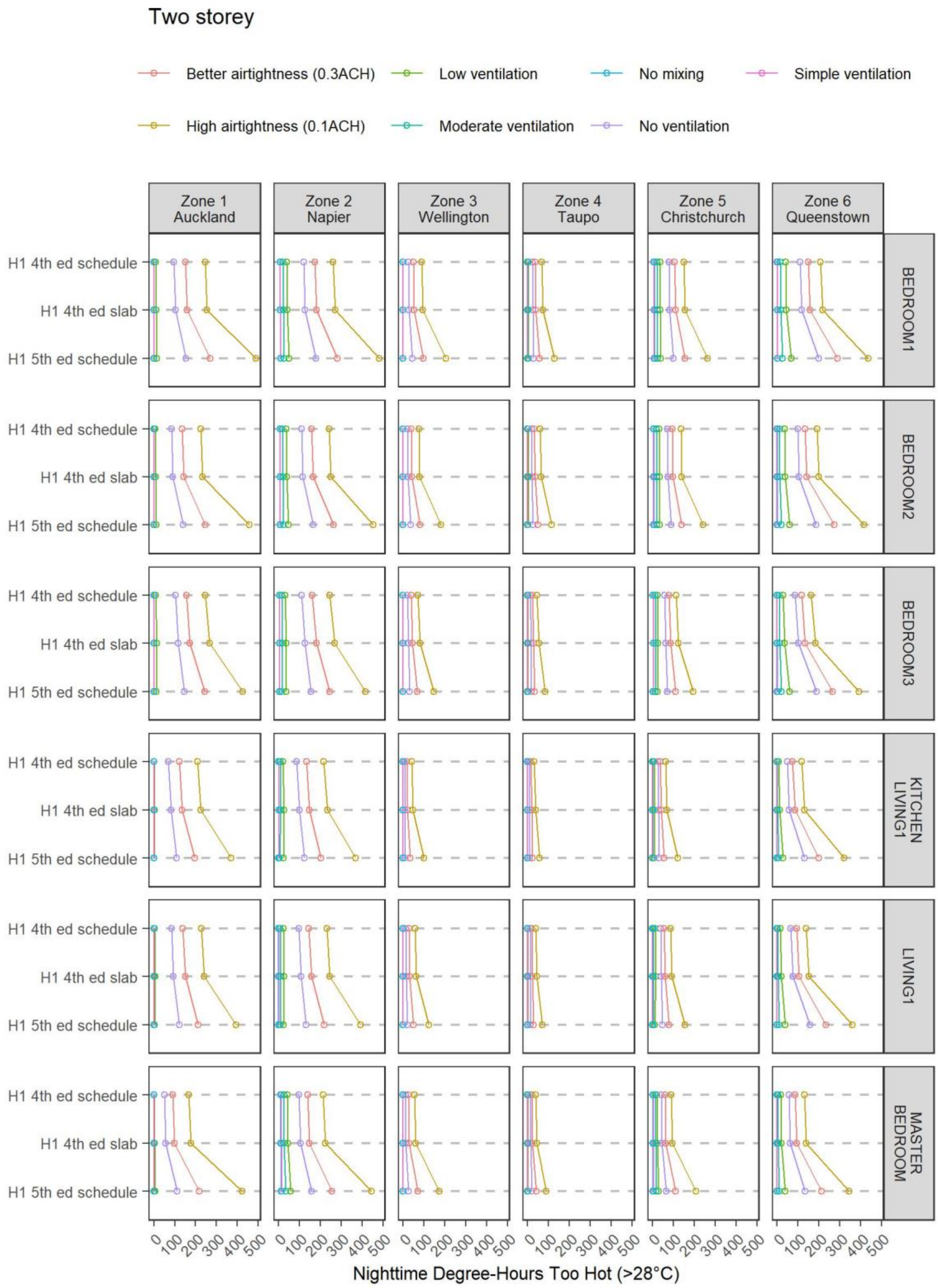

Figure 53: Overheating threshold raised to 28°C – effect of insulation levels on observed night-time overheating in the double-storey house with different ventilation assumptions

3.3.5 Summary

Overall, we are presented with a complex picture. Overheating is a product of a range of factors pertaining to the design of a house and how the occupants live. How the changes to H1 insulation levels have affected overheating is similarly complex and depends on how the occupants use their house. If we were to provide a simplistic summary of the general trends here, we could say the following:

- Insulation below or on top of the concrete slab tends to increase overheating risk.
- Increased insulation in the walls, roof and windows will tend to decrease overheating risk during the day where most overheating occurs as long as the house is being ventilated.
- Increased insulation levels in general tend to increase overheating risk overnight.
- If a house is not ventilated, it will likely see significant overheating that may be worsened by higher insulation levels, further exacerbated by high levels of airtightness in modern homes.
- With this in mind, the overall tendency is that the changes to H1 have decreased overheating risk during the day as long as a house is well ventilated to control overheating and have increased it overnight. If occupants do not open windows, the changes will likely make the overheating worse.

Increases or decreases in overheating risk are, however, not the same as saying that changes to insulation are causing overheating. Whether a house overheats will depend on multiple factors. Noting there is significant uncertainty here and impacts will depend heavily on the specifics of any house and its occupants, the factor with the largest potential impact is probably ventilation. During the daytime, increases to insulation may reduce overheating risk overall – though slab insulation may be increasing it. In cases where insulation increases the risk, the case studies here suggest that may be better framed as the insulation exacerbating a situation of high overheating caused by inadequate ventilation. Other factors such as window size and shading may be more important factors.

With regards to night-time ventilation, the increase in insulation levels does indeed appear to increase overheating risk, potentially very significantly. The impact may be comparable or even greater than the effect of having no shading or having large windows. This general tendency means it may be fair to suggest that increased insulation along with factors such as increased airtightness could be a driver for increased night-time overheating risk in new homes. Whether this risk results in overheating will depend heavily on the situation. Many houses may not suffer from any significant night-time overheating regardless. Others may be able to manage any overheating by opening windows overnight.

How to value the potentially reduced daytime overheating risk versus increased night-time risk is not a question with any simple answer. If we assign overheating economic value based on the cooling energy that would be needed to address it using a heat pump, we find that any night-time effects are relatively insignificant compared to the day when most cooling energy would be used. The typical New Zealand household does not have air conditioning in their bedrooms (Burrough et al., 2015), so this hypothetical is also not necessarily very helpful in describing the impact on people. If we try to compare the impact in terms of comfort hours, we are left with no good answers. Are 100 fewer daytime overheating hours equivalent to 30 more night-time overheating hours? More? Less? CIBSE TM59 requires overheating assessments to meet performance targets for daytime and night-time overheating separately for good reason.

Finally, we should remember that these results are examples from a small number of case study houses run under a limited set of modelling assumptions. As they have illustrated, the effects of insulation and other factors can vary widely depending on the specifics of the house and situation. Managing overheating risk properly would require that the Building Code address overheating directly and require designers to try to minimise overheating risk in new homes.

3.4 Moisture risk

The following tables and discussion describe the VTT mould indices calculated with WUFI for each of the test cases in relation to questions 5 and 6. The tables below cover indices at internal linings (clear wall only) and interstitially for 90 mm and 140 mm walls, skillion and pitched roofs in each climate zone across the various sensitivity tests.

3.4.1 Wall moisture

Hygrothermal simulations have been undertaken across the six climates zones for both 90 mm and 140 mm framing with conventional insulation and building techniques. These simulations contain sensitivity sweeps that look at the dependence of mould growth risk on:

- R-value of the insulation
- cladding colour
- orientation
- internal moisture load in the dwelling below.

Key climate zone results in terms of mould growth indices are presented in Table 34 and Table 35 for the exposed interior lining and interstitially at the plane of the wall underlay for the two different wall thicknesses. Full results are in Appendix C.

The tables should be read with the KPI for the mould growth index in section 2.4.5 in mind – achieving <1 for surfaces exposed to the indoors of the building and <3 for the interstitial surfaces.

3.4.1.1 Internal surface mould risk

The results in Table 34 for Auckland, Napier and Queenstown show that, under the assumptions in this modelling (including heating and ventilation), the risk of mould growth on internal clear wall surfaces is low and does not materially change with the change in thermal performance between the two wall thicknesses (or indeed the other variables).

That being said, mould growth is prevalent in a wide range of building stock both old and new and it should be recognised that the limitation of a one-dimensional hygrothermal study apply and that the influence of framing or other possible thermal bridges is not able to be accounted for.

The limitations with the internal climate assumptions are also a compounding factor that should be considered when interpreting these results. At the conclusion of HEEP2, there will be a comprehensive dataset available to understand the different ways occupants are using their homes to better guide risk assessments such as these.

At this time, it would be beneficial to undertake a dynamic two-dimensional modelling exercise to better appreciate the levels of risk. While simplified steady-state techniques like the surface temperature factor (Standaert, 1985) exist, they are unable to resolve daily effects and cyclic changes which are a key determinant of the risk of mould species flourishing. A dynamic tool is the preferred method, particularly as occupant usage patterns and profiles have shown to be a strong determinant of risk (Cherrill, 2024).

3.4.1.2 Interstitial mould risk (walls)

Table 35: Wall underlay mould index results for Auckland, Napier and Queenstown gives the interstitial (at the plane of the underlay) mould index results for Auckland, Napier and Queenstown.

What is important to note is the steady increase for our more humid climates under certain assumptions, with Auckland given as the example here. Factors such as orientation, cladding colour indoor moisture load are having an increasingly significant effect on the reported indices.

While reaching mould growth indices of 2.0 and 2.4 (for the worst cases) are not a cause for serious concern, it should be noted the idealised nature of the assumptions in this modelling may obfuscate a potential issue in the future. A proactive means to alleviate any upside risk would be to improve outcomes for homeowners when it come to achieving good indoor environmental quality such a ventilation and heating of buildings. This will in turn reduce risk exposure.

Table 34: Mould index results for internal wall surface for Auckland, Napier and Queenstown

Auckland

Moisture Load			R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing		0.1	0.1	0.1	0.1
	South Facing		0.1	0.1	0.1	0.1
Medium	North Facing		0.1	0.1	0.1	0.1
	South Facing		0.1	0.1	0.1	0.1
High	North Facing		0.1	0.1	0.1	0.1
	South Facing		0.1	0.1	0.1	0.1

Napier

Moisture Load			R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing		0.0	0.0	0.0	0.0
	South Facing		0.0	0.0	0.0	0.0
Medium	North Facing		0.0	0.0	0.0	0.0
	South Facing		0.0	0.0	0.0	0.0
High	North Facing		0.0	0.0	0.0	0.0
	South Facing		0.0	0.0	0.0	0.0

Queenstown

Moisture Load			R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing		0.0	0.0	0.0	0.0
	South Facing		0.0	0.0	0.0	0.0
Medium	North Facing		0.0	0.0	0.0	0.0
	South Facing		0.0	0.0	0.0	0.0
High	North Facing		0.0	0.0	0.0	0.0
	South Facing		0.0	0.0	0.0	0.0

Table 35: Wall underlay mould index results for Auckland, Napier and Queenstown

Auckland

Moisture Load	Facing	R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.1	0.0	0.1
	South Facing	0.7	1.2	0.7	1.2
Medium	North Facing	0.0	0.2	0.0	0.1
	South Facing	0.9	1.5	0.9	1.5
High	North Facing	0.1	0.3	0.0	0.1
	South Facing	1.2	2.0	1.1	2.4

Napier

Moisture Load	Facing	R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
Medium	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.1	0.0	0.1
High	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.1	0.1	0.0	0.1

Queenstown

Moisture Load	Facing	R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
Medium	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
High	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.1	0.1	0.1	0.1

Applying the KPI for interstitial surfaces, of the mould index being below 3 – all combinations pass.

3.4.2 Roof moisture

Hygrothermal simulations have been undertaken across the six climates zones for both skillion and pitched roofs. These contain sensitivity sweeps that look at the dependence of mould growth risk at the plane of the underlay on:

- R-value at the ceiling line
- roof colour
- orientation
- internal moisture load in the dwelling below.

3.4.2.1 Skillion roofs

Table 36 give the skillion roof results for Auckland, Napier and Queenstown. These cover the main effects of note – the other climate zones are given in Appendix C for reference.

What is clear for all cases is that the roof colour and orientation are very significant factors in determining the level of risk the roof space is being exposed to. In general terms, a south-facing light-coloured roof gives rise to the highest exposure to mould growth risk. While there is an effect with each factor independently, the combination of the two factors gives the strongest effect.

This is likely due to temperature swings in roofs being of greater amplitude as the roof space is more effectively decoupled from the space below. These temperatures swings take conditions in the roof space outside the range for ideal mould growth for a greater period of time compared to the H1 4th edition. The temperature range for mould growth is given in figure 13.

3.4.2.2 Pitched roofs

Table 37 gives the pitched roof results for Auckland, Napier and Queenstown. The indices presented give a very similar message to that of skillion roofs. The same combination of factors gives rise to the highest levels of risk, orientation and roof colour.

In general terms, Auckland and Napier perform slightly better overall, where the colder climate of Queenstown is showing slightly greater risk. This could be an example of a case where the additional ventilation in case of a pitched roof is allowing greater deposition of moisture into the assembly, everything else being equal.

Again, the level of risk has not materially increased for a roof with higher insulation. In many cases, a slight reduction is evident.

Table 36: Skillion roof mould index results for Auckland, Napier and Queenstown

Auckland

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
Moisture Load	Low	North Facing	0.0	0.8	0.0	0.4
		South Facing	1.0	4.1	0.6	3.7
	Medium	North Facing	0.0	1.2	0.0	0.7
		South Facing	1.4	4.6	1.0	4.0
	High	North Facing	0.0	1.5	0.0	1.0
		South Facing	1.7	5.3	1.3	4.4

Napier

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
Moisture Load	Low	North Facing	0.0	0.0	0.0	0.0
		South Facing	0.1	1.1	0.0	0.7
	Medium	North Facing	0.0	0.1	0.0	0.0
		South Facing	0.2	1.4	0.1	1.1
	High	North Facing	0.0	0.1	0.0	0.0
		South Facing	0.3	1.9	0.1	1.3

Queenstown

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
Moisture Load	Low	North Facing	0.0	0.2	0.0	0.1
		South Facing	0.4	2.3	0.3	1.5
	Medium	North Facing	0.0	0.3	0.0	0.2
		South Facing	0.9	3.6	0.4	2.0
	High	North Facing	0.0	0.6	0.0	0.3
		South Facing	1.3	5.1	0.8	4.8

Table 37: Pitched roof mould index results for Auckland, Napier and Queenstown

Auckland

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
Moisture Load	Low	North Facing	0.0	0.5	0.0	0.4
		South Facing	0.7	3.9	0.4	3.5
	Medium	North Facing	0.0	0.8	0.0	0.8
		South Facing	1.0	4.3	0.6	3.8
	High	North Facing	0.0	1.1	0.0	1.2
		South Facing	1.3	5.3	0.8	4.1

Napier

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
Moisture Load	Low	North Facing	0.0	0.0	0.0	0.0
		South Facing	0.0	0.6	0.0	0.4
	Medium	North Facing	0.0	0.0	0.0	0.0
		South Facing	0.1	1.0	0.0	0.7
	High	North Facing	0.0	0.1	0.0	0.0
		South Facing	0.1	1.3	0.1	1.0

Queenstown

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
Moisture Load	Low	North Facing	0.0	0.1	0.0	0.1
		South Facing	0.3	5.3	0.2	1.3
	Medium	North Facing	0.0	0.2	0.0	0.2
		South Facing	0.5	5.3	0.3	5.2
	High	North Facing	0.0	0.3	0.0	0.3
		South Facing	2.0	5.3	0.4	5.3

3.4.3 Summary

3.4.3.1 Walls

In terms of the initial question, the H1 5th edition insulation changes themselves had little impact on altering moisture risk both in and on the internal surface of walls, the more dominant factors being orientation, cladding colour and moisture generation rate. The discussion below looks at the various factors that determine risk of moisture and mould issues in more detail.

For the particular heating and ventilation regimes under test here, the climate zone that shows the greatest risk is that of Auckland, though still not to the point of failure with the current assumptions. The Auckland results are likely a reflection of the humid external environment and the limited effectiveness of ventilation in removing moisture in this climate zone. While the Auckland walls did not exceed a mould index of 3, other factors in the real world could push some buildings into the space where they fail. Mitigating these potential issues by strengthening ventilation and heating provisions or employing a strategy to mitigate moisture flow could be steps taken to isolate the risk potential. This stresses the importance of thorough field investigation of failures by independent experts in a consistent manner to act as a barometer of the real-world impacts.

The results are also a reflection on the lower risk that walls pose when compared to roofs. This is mainly due to walls overcooling (dropping below ambient temperature) less than roofs as they lose less energy to the night sky.

It is important to note that, while the other climate zones do not show the same risk as Auckland under these scenarios, the following should be mentioned as risk factors:

- Darker-coloured cladding generally show less risk than lighter.
- South-facing façades are higher risk.
- Higher moisture generation rates internally present higher risk.

As mentioned above, these results are for clear wall sections – we have not looked into the impact of thermal bridges. Given the increased heat flow at thermal bridge locations from inside the dwelling, they are likely to moderate the risk of mould growth interstitially to some degree (provided there is heating in the building) while at the same time increasing the risk at the internal lining.

For the case of rigid air barriers, the outcomes are possibly going to have higher risk, though the additional modelling has not been undertaken here.

Variation in heating was not considered for this work and if desired should be benchmarked against measurements from HEEP2 data once this is available.

At that point, it would also be a sensible time to include infiltration air leakage as a potential load on the assembly, which has not been done in this modelling exercise.

Key takeaways in terms of mitigation of risk in the future would be to ensure that buildings are able to be reliably heated and ventilated, ideally mechanically. Vapour control layers are also a potential safety net, whether by using membranes or taped and sealed plywood as a bracing element on the internal side of the structural frame.

3.4.3.2 Roofs

The simulations undertaken in the course of this work do not suggest that the increased ceiling insulation from the H1 5th edition changes have increased roof space moisture risks. In fact, the modelling results suggest that the increased insulation may even reduce these risks slightly due to conditions being outside those favourable for mould growth for a slightly longer period.

The following can be observed based on Table 36 and Table 37 and the mould indices extracted from the hygrothermal simulations:

- The primary risk factors for roof space moisture accumulation are orientation and colour (solar absorption) of roof cladding. Light-coloured roofs facing south are particularly sensitive.
- Building moisture load is also a significant factor and shows a consistent trend across the simulations. Increases in moisture load will typically increase the mould growth index. In some cases, it is the difference between a pass and a fail for the same roof structure. See the south-facing light-coloured roof in Queenstown as an example.
- Comparing the indoor climates used here to those found using HEEP2 data will be an important piece of establishing the level of risk in real-world situations.

General commentary on the modelling results:

- Climates that are seen as warmer or drier are lower risk. Napier is an obvious example here, and Queenstown and Christchurch are important to recognise – the external climate, while relatively cool, is substantially drier than other parts of the country. The lower absolute humidity in the surrounding environment means that, where ventilation is provided, it will be more effective at removing moisture – provided enough heat enters the building. The difference between the light and dark roofs in the case of Queenstown serve as an example here.
- More humid warm climates are not risk free. Auckland in general has the highest risk profile of the simulations that have been undertaken here. The main reason for this is that the absolute humidity in Auckland is high enough that ventilation effectiveness in the roof space is reasonably poor in comparison to other centres. In short, this means that the relative humidity in Auckland will tend to stay in an ideal range for mould growth longer than other climates even when the roof space is quite warm.
- While public commentary has suggested that the increase in ceiling R-value may increase the likelihood of mould growth, the simulations we have performed do not give the same result. This also aligns with the lack of an increase in calls to the BRANZ helpline and the pre-existing nature of the problems. That being said, in some situations, the increase in ceiling R-value could result in an increase in mould growth, if the airtightness of the ceiling diaphragm is insufficient.

There are a number of factors to be aware of regarding the above results:

- Both the H1/AS1 4th and 5th edition schedule method R-values allow significantly less heat flux across them than what is transmitted by the roof deck either through solar gains or night-time overcooling. This means that, while the heat flow from the building to the roof space has been effectively halved, it is still a fraction of the heat flux that the roof space sees on a daily basis.
- The higher the insulation level, the better isolated the ceiling cavity from the dwelling. This does mean that, in general terms, the roof void will tend to get hotter during the day and cooler at night than before the change to schedule method R-values.
- It is likely that the increased magnitude of temperature swings for the cases with R6.6 ceiling insulation are reducing the risk of mould growth.

3.5 Window/wall ratios in new housing

3.5.1 Key points

- The vast majority of new detached homes observed in 2012–2020 were below 30% WWR, with the average being around 22% WWR.
- The H1 AS and VMs provide no particular guidance as to how the total wall area should be defined when calculating WWR. While differences may be minor in many cases, in some situations, the use of external dimensions may produce a significantly greater wall area and thus lower WWR than internal dimensions. It may be desirable to clarify this.

The BRANZ benchmarking study examined the sustainability of samples of ~70 houses from Auckland, Hamilton and Christchurch in 2012, 2016 and 2020 (Jaques, 2015, 2019; Jaques and Sullivan, 2023). The WWRs here were extracted from the energy models. External envelope area was calculated taking the internal wall to the garage as part of the external wall area. Garage windows were excluded as outside the thermal envelope. Note that, as the models used internal dimensions and occasional geometric simplifications, the areas may differ from what was reported in the building consents. In some cases, this can produce significant differences – one of the models with a 43% WWR here was reported as having a 34% WWR in the consent documentation. This was due to a combination of thick walls, complex geometry and the inclusion of the roof and floor framing in the reported external height of the walls.[28] H1 AS1 and VM1 are ambiguous on how the wall area should be measured, so neither approach is inherently more correct than the other. The use of external dimensions, however, will produce lower WWRs and make it easier to comply. It may be desirable to clarify this.

In any case, due to this ambiguity, the WWRs reported here should be taken as an indication of the range of WWRs found in new houses and not necessarily the only answer that could be produced.

In the samples modelled, the typical WWR of a new detached house was ~22%, though glazing levels were higher in the Christchurch sample in 2012 and 2016 (Table 38).

Table 38: Average WWR of samples of detached houses consented in different years and regions

Regions	2012	2016	2020
Auckland	22%	.	22%
Hamilton	22%	.	21%
Christchurch	27%	26%	22%

The majority of houses have WWRs below 30% (Figure 54).

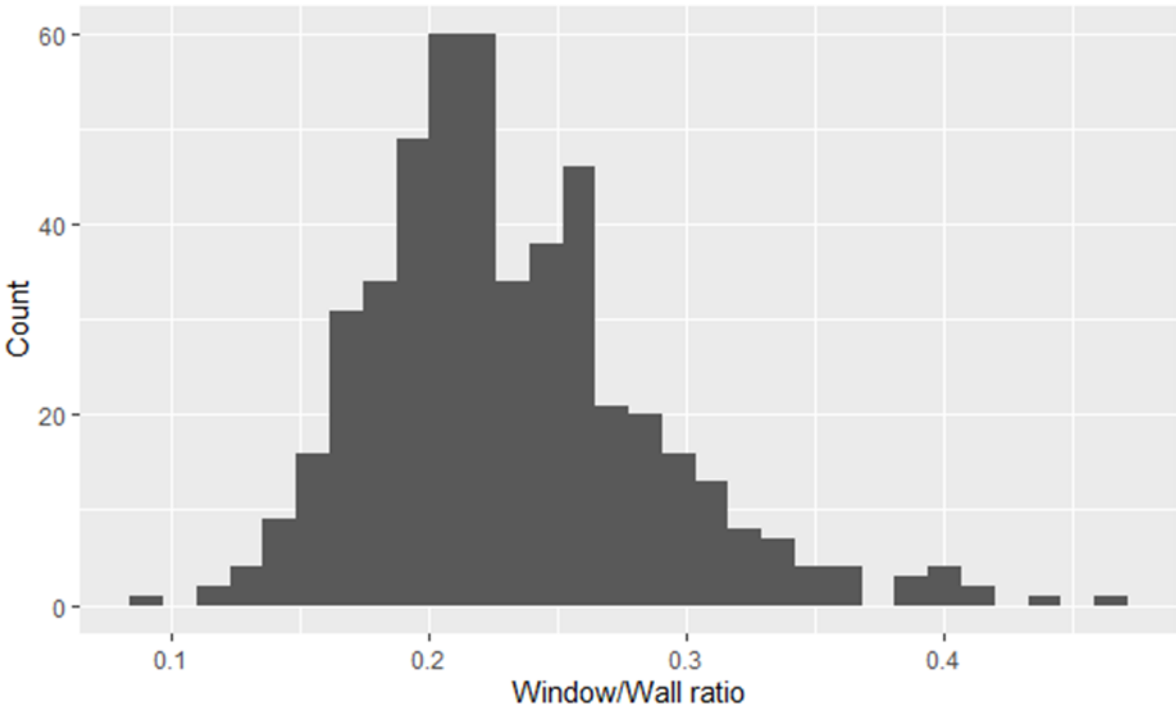

Figure 54: Distribution of WWRs in sample

[28] This is an extreme example – most houses would not see such large differences.

Only around 10% in the sample had WWRs above 30%, 1.4% had WWRs of 40% or higher and 29% had WWRs below 20%. Note also that the higher numbers derive from the 2012 and 2016 Christchurch sample – if we restrict the sample to 2020 consents, only 2.7% were over 30% WWR. Note also that the houses above 40% WWR were constructed under the old regime, which allowed the calculation method up to 50% WWR as opposed to the 40% limit in the current H1/AS1. It is possible that such houses would have their window areas reduced if built under the H1/AS1 5th edition.

3.6 Thermal benefit of thermal breaks in window joinery

Note that, in this section, we refer to thermally broken exterior aluminium window joinery as warm frames and non-thermally broken exterior aluminium window joinery as cold frames, in line with current industry practice. Solely to differentiate values in this report, instead of using the R_{window} value, we refer to the installation R-value ($R_{Installation}$) as the effective R-value of a window and its installation in the trim cavity, including the thermal performance of centre of glazing, edge of glazing (or psi value), window frame and trim cavity. We refer to the frame and trim equivalent R-value (R_{Eq}) as the effective R-value of the frame and the trim cavity.

The details for the installation of windows shown in E2/AS1 has window joinery installed outside of the structural frame. When this detail is used to install warm frames, both sides of the thermal break are located within the cladding cavity. There is a concern that this reduces the effect of the thermal break.

3.6.1 Thermal breaks in aluminium joinery

The structural parts of exterior aluminium-based joinery for windows and doors are made of aluminium profiles that are extruded through a die, then the lengths are cut and connected together into frames. Insulating glazing units (IGUs) are installed in these frames with beads, wedges and seals, with the window/door product completed with other componentry.

Since aluminium is one of the better thermal conductors available heat is able to travel rapidly by conduction through the cross-section (profile) (typically 50–100 mm) of a cold frame. It is usually the small wall thickness of the aluminium profile (typically 1–3 mm) that is the main restriction to heat flow through a cold frame. To reduce this heat flow, a thermal break can be added into the aluminium profile where the heat transfer is interrupted by the introduction of a highly insulating material (typically a hard plastic).

Often lengths of a warm frame are extruded in long strips and then 'zipped' together with the thermal break between them. This can reduce the conduction of heat across the aluminium profile by around 50% and the conduction through a warm frame by somewhat less than this, given the seals, wedges and other materials involved in the construction.

However, this presupposes that the thermal break is aligned with other systems in the wall so that both ends of the thermal break are not both exposed to cold air, since this would allow heat flow to bypass the thermal break.

3.6.2 E2/AS1 detail

Figure 116 from Acceptable Solution E2/AS1 *External Moisture* is reproduced below as Figure 54, which is one rendering of the E2/AS1 method for installing windows at the outer edge of the cladding. This shows a section through the head, jamb and sill of a cold window frame installed in a light timber-framed wall with ply sheet cladding.

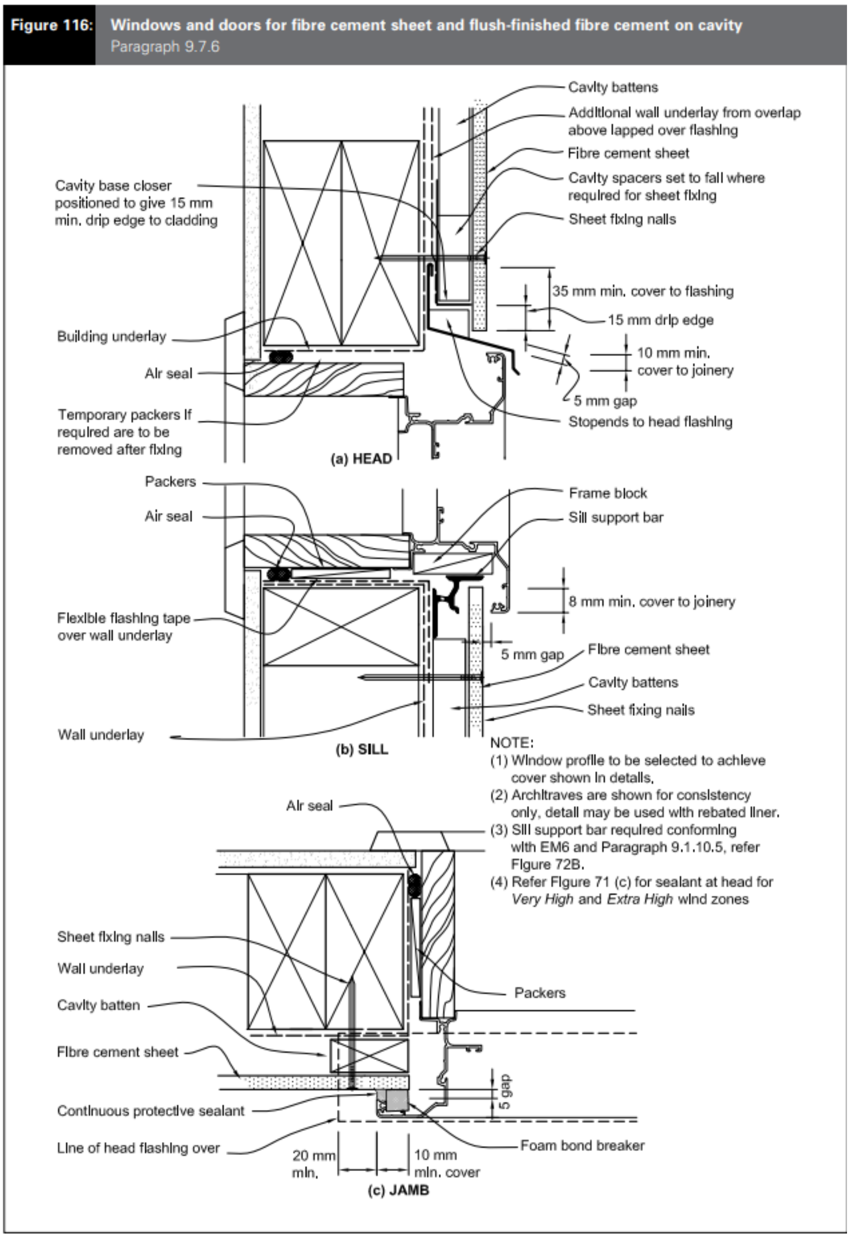

Figure 55: E2/AS1 aluminium window installation detail

3.6.3 Recessed windows

Recessing windows in New Zealand housing refers to the practice of moving exterior joinery back into the cladding and/or structural framing, which ‘hides’ more of the window framing and glazing within the depth of an exterior wall. This practice has thermal benefits in colder climates and is often the default method in northern Europe and America. In a New Zealand winter, the outside of a warm window frame may be exposed to cold outside air that could be at 0°C, while the inside surface of the frame may be exposed to air inside a building at 20°C.

3.6.4 Investigating the thermal benefit of thermal breaks

The reduction in thermal benefit in warm aluminium windows when installed as per E2/AS1 is calculated from the results of a 2021 study (Jaques & Burgess, 2021).

3.6.4.1 The thermal modelling work

In 2018–2021, BRANZ undertook a programme of thermal modelling covering the practical range of potential New Zealand window installations constructed of four different frame materials installed in three different locations in typical timber-framed residential structures. Standard assumptions for thermal modelling were used from ISO 10077:2017 *Thermal performance of windows, doors and shutters – Calculation of thermal transmittance* Parts 1 and 2 and BS EN 673:2011 *Glass in building. Determination of thermal transmittance (U value). Calculation method*.

A flush warm aluminium frame has been modelled in flixo™ (Figure 56). The R_{Eq} has been calculated for a 45.67 mm high frame and installation area from A to B, with a U-value of 5.56 and R_{Eq} value of 0.18. The offset of the frame is 0 mm, and cladding is plywood. This R_{Eq} value is less than the expected window R-value (R_{window} of R0.32 typically used for a clear-on-clear IGU installed in a warm frame as it includes the thermal impact of the trim cavity. As is required in ISO 10077, the IGU is replaced with a highly insulating panel so the thermal impact of the IGU is not relevant. The areas over which the relevant thermal performances are calculated are shown in Figure 56.

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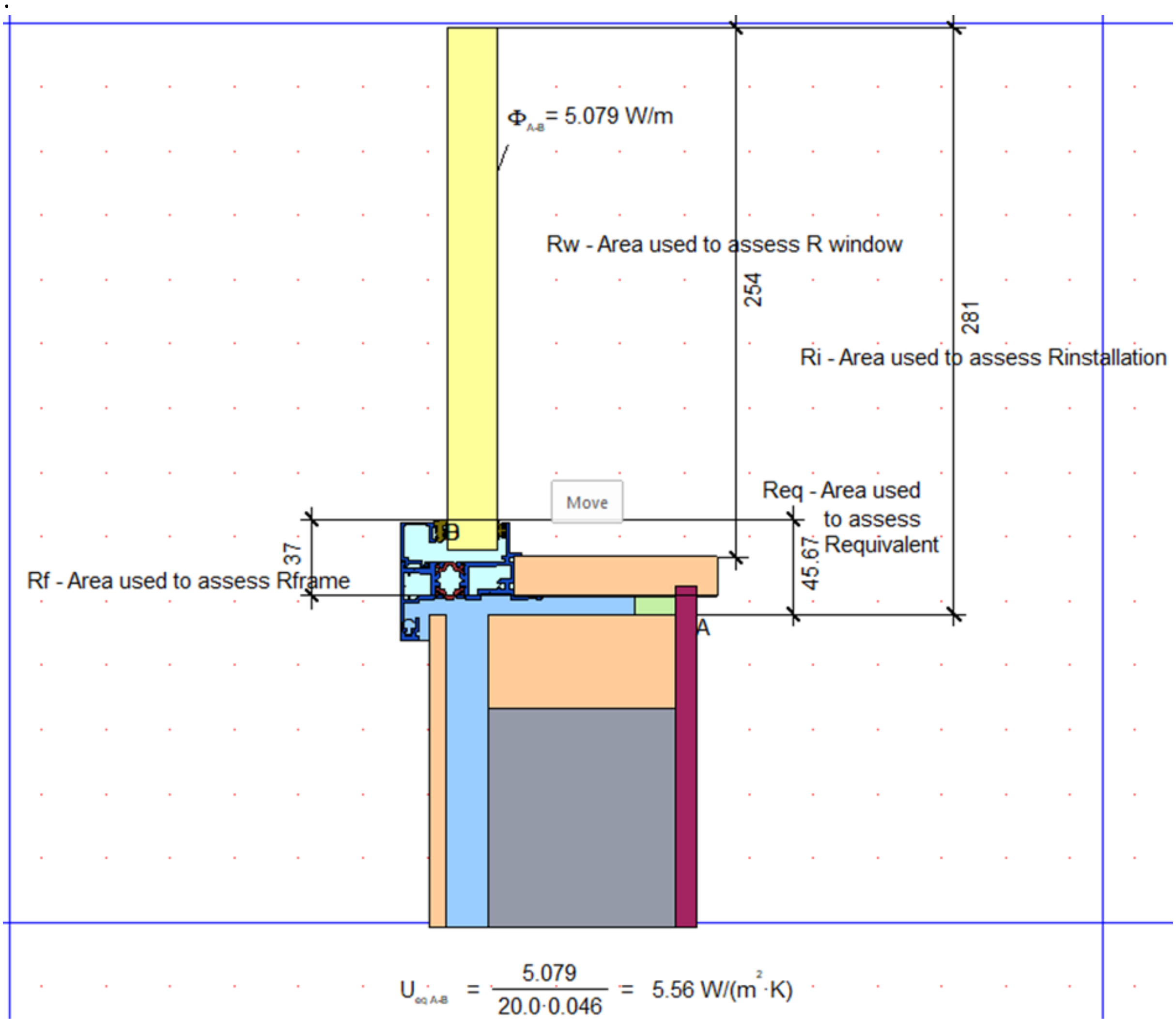


Figure 56: Schematic of typical window frame model for calculation of the R_{Eq} for just the frame and installation, omitting the glazing

The four window frame materials were representative of what was available in the New Zealand market in 2018 (it is understood that these products are still available in 2024), including:

- uPVC framing
- uPVC reinforced framing (with steel bars, channels or sections inserted into the uPVC sections to provide strength and rigidity)
- warm aluminium framing (thermally broken joinery)
- cold aluminium framing (traditional, non-thermally broken aluminium joinery).

3.6.4.2 Installation methods

The three window installation methods differed principally in the distance between the flange of the window frame and the outer face of the timber structure, from a maximum positive distance of around 40 mm (thick cladding) to a negative distance of around 20 mm. (In the 2021 study, the height of the installation gap was also assessed, but this is not relevant in this work.)

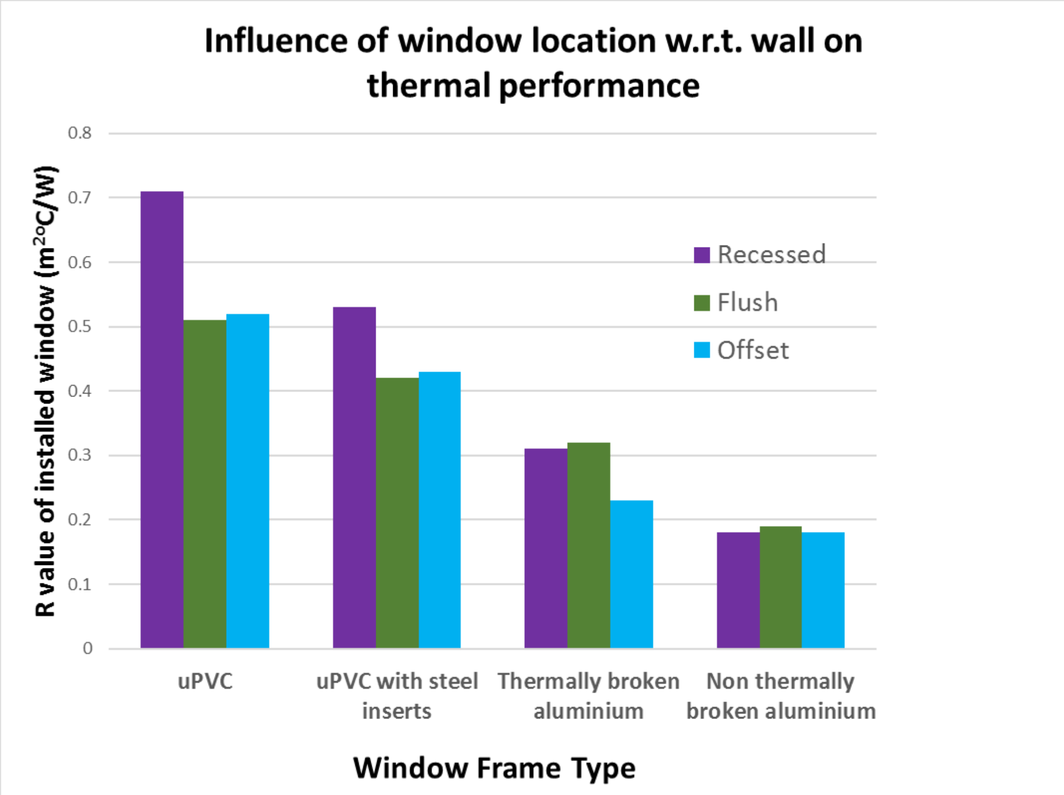
- **Offset (+40 mm):** The window frame is moved horizontally (offset) towards the exterior of the wall so that the outside edge of the frame is outside the cladding and about 40 mm outside the structural frame – in this case, a light timber frame. Any thermal break is within the cladding cavity. This is excellent for weathertightness (provided an adequate head flashing is used) and is the approach taken in the E2/AS1 window details.
- **Flush (0 mm):** The window frame flange is flush (within the thickness of the flange) with the outside of the timber structure. This can pose issues for drainage of water from the window system since it is expected that any water from around the window installation or failure water from within the window system will be drained to outside the structure. This is sometimes what is referred to when talking about recessed windows. These flush windows represent an installation method where outside air is prevented from getting to the inside of the thermal break – the thermal break is located as intended.
- **Recessed (-20 mm):** The window frame is installed within the depth of the wall (about 20 mm inside the framing) so that the complete window frame is within the structure and inside the cladding. Although this installation method is encouraged with durable, absorbent masonry structures in Europe, it has significant issues for drainage of water both from around the window installation and from failure water within the window system.

3.6.4.3 Modelling output

The thermal modelling shown in Figure 56 was used to create an effective R-value for the sill and installation of the different window frames ($R_{Installation}$), using the process described in EM8 (Jaques & Burgess, 2021). It has been assumed that the jamb and head will have a similar performance to the sill so that the window frame and its installation can be assigned an R-value – $R_{Installation}$.

3.6.5 Results

Figure 57 shows the four different frame types with the modelled $R_{Installation}$ value of the three different installation locations (recessed, flush and offset), including the thermal impact of its installation. In all cases the installation can be seen to reduce the performance of the window since no sealing or thermal improvement has been made and air is free to move around the frame.



Source: Jaques & Burgess, 2021, p. 1.

Figure 57: Thermal performance of a variety of window located differently in a wall

For the aluminium-based frames, the warm flush installation has the best thermal performance with an $R_{Installation}$ value of about 0.32 m²K/W. The recessed warm aluminium window has a slightly poorer $R_{Installation}$ value of about 0.31, while the offset warm aluminium window has a considerably poorer $R_{Installation}$ value of about 0.23 m²K/W. This is about a 25% reduction in performance between the flush and recessed installations, which can be assumed to be the case where a warm frame is installed as per the E2/AS1 detail shown in Figure 55. The cold $R_{Installation}$ values show very little variation being all between about 0.18 and 0.19 m²K/W.

The uPVC frames with steel inserts (most uPVC needs internal reinforcing in New Zealand construction) show a similar absolute difference in $R_{Installation}$ depending upon how they are installed, with the recessed installation method having the best performance, as has been seen in European studies.

3.6.6 Installation conclusion

Installing thermally broken (warm) aluminium joinery with the thermal break located within the cladding cavity reduces the thermal performance of these windows since both sides of the thermal break are exposed to the same conditions.

The reduction in installed R-value for a window with a warm frame has been shown in this work to be about 25%. However this is still better thermal performance than (cold) aluminium windows without thermal breaks.

When installed as per the E2/AS1 detail (offset installation), the non-thermally broken (cold) aluminium window frame has no discernible reduction in thermal performance.

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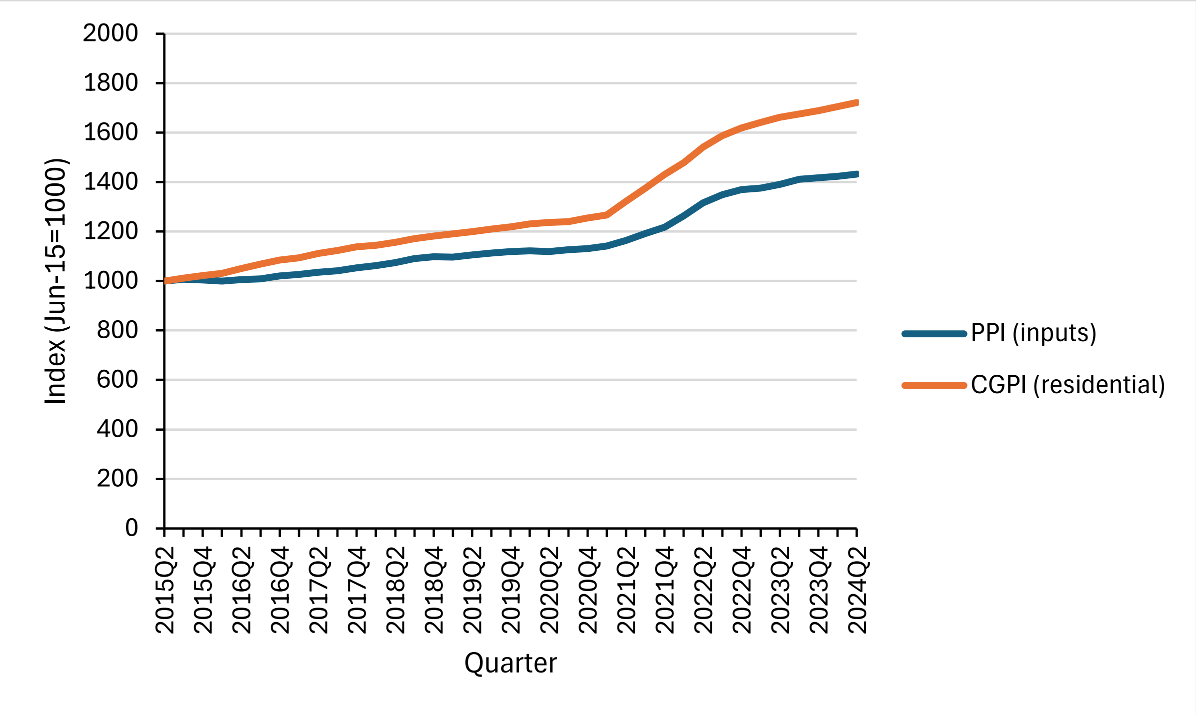
Appendix A: Economic context

The construction sector has been facing cost-increases over the past several years. COVID-related supply chain issues, high demand for construction products and higher staff input costs have all put pressure on material pricing in New Zealand (EBOSS, 2022). For example, the input costs for construction measured by the producers price index (PPI) (Statistics New Zealand, 2015) increased by 10% over the brief period between December 2021 and September 2022.

The capital goods price index (CGPI) for residential buildings aims to strip out quality changes (such as the change in insulation levels). Therefore, it is a useful measure to understand how build costs in the residential sector have changed without needing to account for the additional cost of higher insulation levels.

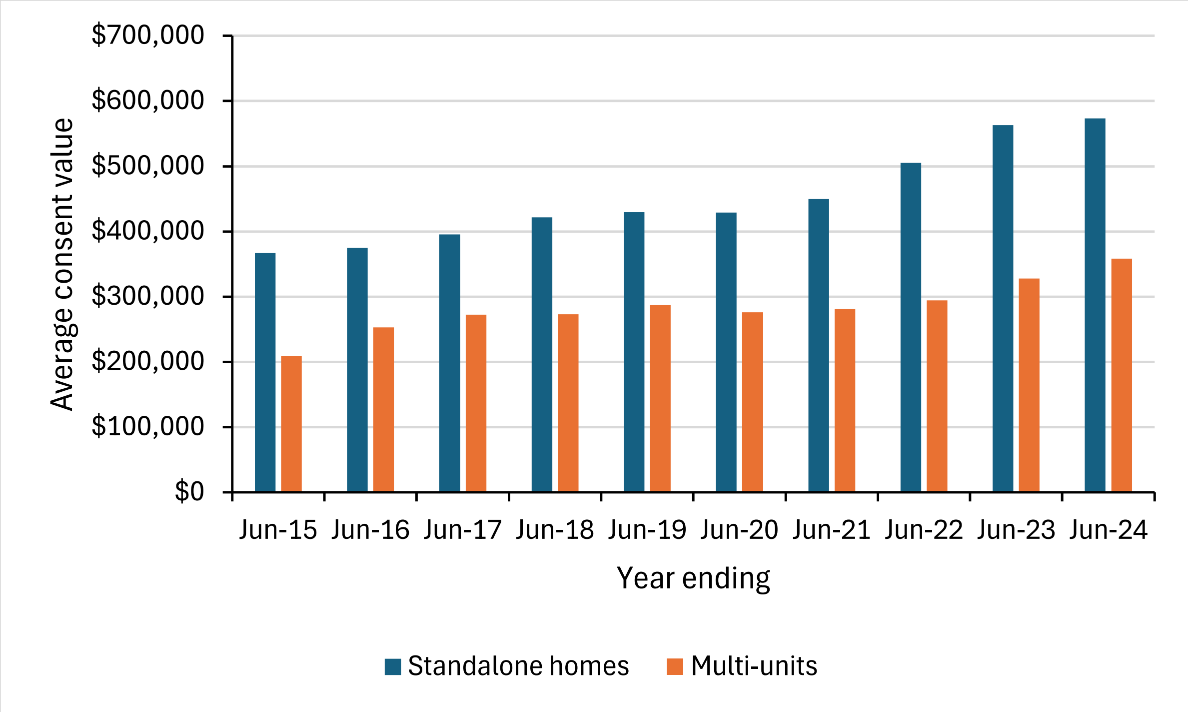
The CGPI has shown stronger levels of inflation since June 2015 than the PPI and showed more rapid increases in costs after the initial COVID-related lockdowns (Figure 58). It suggests that the cost to deliver a residential dwelling has increased by 30% since mid-2021, before accounting for the increased insulation costs.



Source: Stats NZ, BRANZ analysis.

Figure 58: Change in cost of construction

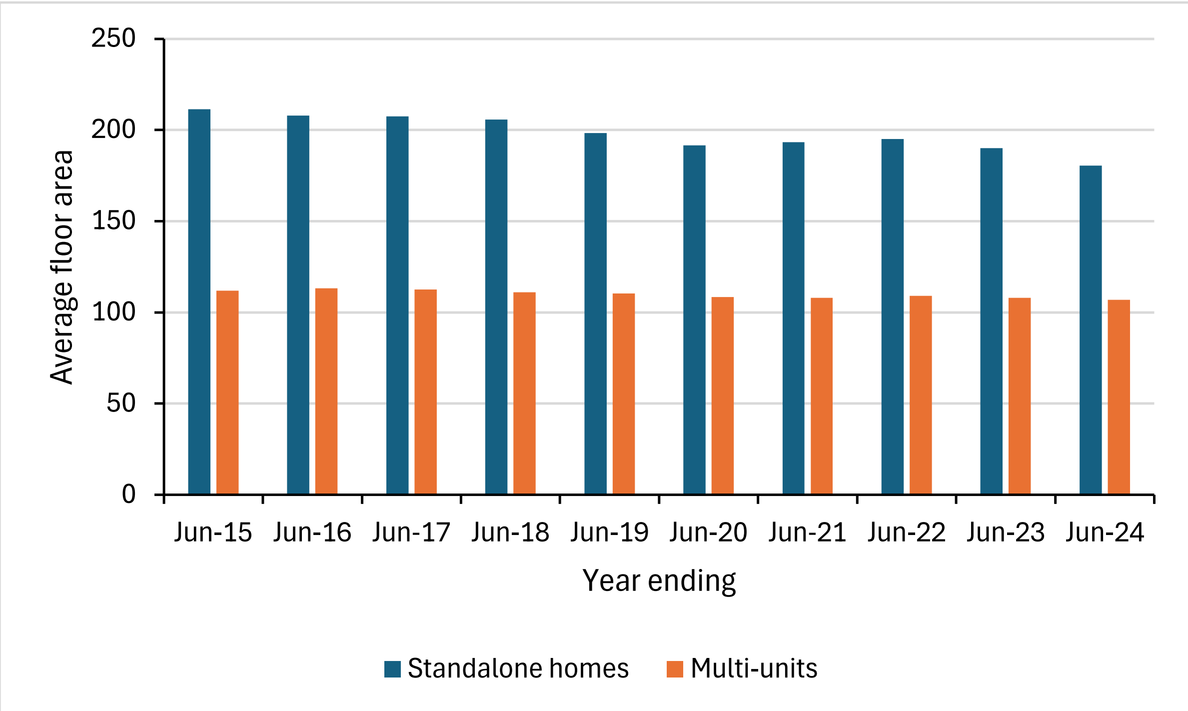
The average value of new dwelling consents has increased rapidly over the last few years (Figure 59). Between mid-2021 and mid-2024, the average value of new dwelling consents increased by 27% for both stand-alone homes and multi-unit dwellings.



Source: Stats NZ, BRANZ analysis. The average cost for multi-units is cost per unit.

Figure 59: Change in consent value for new dwellings

Seemingly, to offset some additional costs associated with higher construction prices, new dwellings are getting smaller (Figure 60). The average size of a stand-alone home in the year ending June 2021 was 193 m² and is now down to 181 m² (6.7% smaller). The change has not been as significant in multi-unit dwellings with a fall from 108 m² to 107 m² (1% smaller). It is worth noting that the saving associated with the smaller dwelling size could amount to $38,000 on average for a stand-alone home and about $3,350 for a multi-unit dwelling.



Source: Stats NZ, BRANZ analysis. The average cost for multi-units is cost per unit.

Figure 60: Change in floor area for new dwellings

Appendix B: Individual component results

Cost-benefit analyses were undertaken on each of the individual components across the four building typologies and six climate zones.

The analyses compared the marginal costs and benefits of each individual component against the specified component that would meet the H1/AS1 5th edition schedule method. NPVs were estimated for each individual component based on the following:

- Cost from quantity surveyor 1, standard electricity user, 0% real electricity escalation rate.
- Cost from quantity surveyor 1, low electricity user, 1.2% real electricity escalation rate.
- Cost from quantity surveyor 2, standard electricity user, 0% real electricity escalation rate.
- Cost from quantity surveyor 2, low electricity user, 1.2% real electricity escalation rate.

The following tables present both the lowest value (lower bound or LB) across the four NPVs estimated and the highest value (upper bound or UB). The lower bound was typically the quantity surveyor who provided the smallest difference in cost between the component that would meet the H1 5th edition amendment 1 schedule method and the alternatives. The results were driven by this cost difference between the different compliance methods, which could be significant at the component level.

We took the midpoint of the of the upper and lower bounds for each component at building typology level to determine which component was most cost-effective.[29] The most cost-effective component for ceiling insulation, wall insulation, floor insulation, slab insulation and windows has been highlighted in yellow. This can vary by building typology.

It is important to note that, in many instances, the lower bound of the most cost-effective component is negative. A positive NPV indicates that a component is more cost-effective than the current component that best meets the current H1/AS1 5th edition amendment 1 schedule method minimum requirement. A negative NPV suggests that it is less cost-effective, and a value of $0 indicates the component that currently meets the schedule method minimum requirements for each climate zone.

The analysis that follows in Table 39 to Table 44 suggests that the most cost-effective component may be highly dependent on the cost of construction for each of the individual components, which can vary from builder to builder.

[29] Defined as the component with the highest mid-point in NPV between the upper and lower bound.

Table 39: Zone 1 – individual component NPVs

	Construction	Single Storey		Double storey		Medium Density Dwellings		Apartment building	
	R-value	LB	UB	LB	UB	LB	UB	LB	UB
Wall R2.5 batt	R1.9	-$1,586	$145	-$2,242	$186	-$8,485	$242	-$15,651	$1,123
Wall R2.8 batt	R2.0	$0	$0	$0	$0	$0	$0	$0	$0
Wall R4.0 batt	R2.8	-$3,451	-$1,382	-$4,838	-$1,748	-$19,951	-$11,524	-$32,131	-$18,279
Wall R4.4 batt	R2.9	-$5,954	-$3,883	-$8,373	-$4,613	-$33,786	-$16,964	-$56,486	-$42,897
Roof R3.0 batt	R2.9	-$488	$1,074	-$266	$445	$16	$4,058	-$591	$3,614
Roof R3.3 batt	R3.2	$486	$2,666	$56	$1,956	$332	$13,713	$2,211	$12,288
Roof R3.4 batt	R3.3	-$1,147	$1,139	-$844	$820	-$3,659	$7,273	-$2,302	$3,708
Roof R3.6 batt	R3.5	$292	$3,040	-$9	$2,109	$86	$14,381	$1,383	$12,631
Roof R4.0 batt	R3.8	$192	$1,266	-$35	$1,011	-$33	$8,212	$989	$4,320
Roof R4.5 batt	R4.2	-$222	$1,441	-$245	$1,037	-$896	$8,344	-$226	$4,278
Roof R5.0 batt	R5.0	-$1,059	$2,556	-$698	$1,890	-$2,845	$12,678	-$2,524	$9,542
Roof R6.0 batt	R6.0	-$950	$1,306	-$590	$1,009	-$2,436	$7,007	-$2,386	$10,000
Roof R7.0 batt	R7.0	$0	$0	$0	$0	$0	$0	$0	$0
Roof R8.0 batt	R8.1	-$2,673	$500	-$1,530	$404	-$6,458	$2,108	-$7,045	$2,473
Timber floor R1.5 batt	R1.4	NA	NA	-$63	$55	-$3,434	-$312	NA	NA
Timber floor R1.8 batt	R.17	NA	NA	-$112	$52	-$321	-$212	NA	NA
Timber floor R2.0 batt	R1.9	NA	NA	-$156	-$69	-$684	-$151	NA	NA
Timber floor R2.6 batt	R2.5	NA	NA	$0	$0	$0	$0	NA	NA
Timber floor R2.8 batt	R2.6	NA	NA	-$96	$86	-$880	$47	NA	NA
Timber floor R3.0 batt	R2.8	NA	NA	-$54	$1	-$623	$91	NA	NA
Timber floor R3.2 batt	R3.0	NA	NA	$3	$543	$99	$149	NA	NA
Slab Uninsulated		$3,458	$4,586	$3,688	$4,133	$8,473	$11,932	NA	NA
Slab R1.0 edge insulation		-$1,355	$299	$1,756	$2,186	$3,096	$4,800	NA	NA
Slab R1.2 underslab insulation		$770	$2,134	$2,503	$3,066	$5,003	$9,636	NA	NA
Slab R2.4 underslab insulation		$0	$0	$2,148	$2,224	$4,012	$8,074	NA	NA
Slab R1.2 underslab + edge insulation		-$3,177	-$757	$358	$852	-$1,704	$2,953	NA	NA
Slab R2.4 underslab + edge insulation		-$4,025	-$2,830	$0	$0	-$2,742	$1,425	NA	NA
Slab 40mm1.0 slab topper insulation		-$11,407	-$9,643	-$2,021	-$149	$0	$0	NA	NA
Window aluminium glazing	R0.26	$2,356	$3,930	$2,634	$4,870	$19,023	$24,378	$93,056	$141,935
Window Aluminium low-E3 argon double glazing Ucog 1.1	R0.37	$1,913	$2,763	$2,379	$3,444	$14,110	$17,372	$83,810	$109,505
Window Thermally broken low-E3 argon double glazing Ucog 1.3	R0.46	$0	$0	$0	$0	$0	$0	$0	$0
Window Thermally broken low-E3 argon double glazing Ucog 1.1	R0.50	-$1,774	$183	-$2,236	$214	-$9,579	$776	-$61,254	$6,318

Note: The most cost-effective component for ceiling insulation, wall insulation, timber floor insulation, slab insulation, and windows has been highlighted in yellow.

Table 40: Zone 2 – individual component NPVs

	Construction	Single Storey		Double storey		Medium Density Dwellings		Apartment building	
	R-value	LB	UB	LB	UB	LB	UB	LB	UB
Wall R2.5 batt	R1.9	-$1,656	$46	-$2,354	$37	-$8,637	-$789	-$16,341	$100
Wall R2.8 batt	R2.0	$0	$0	$0	$0	$0	$0	$0	$0
Wall R4.0 batt	R2.8	-$2,709	-$539	-$3,660	-$394	-$16,840	-$7,570	-$24,798	-$9,028
Wall R4.4 batt	R2.9	-$5,082	-$2,861	-$7,006	-$3,009	-$29,801	-$12,722	-$47,433	-$30,720
Roof R3.0 batt	R2.9	-$2,037	-$274	-$1,387	-$522	-$3,716	$1,085	-$2,894	$1,669
Roof R3.3 batt	R3.2	-$813	$1,520	-$895	$1,033	-$2,850	$10,743	$223	$9,785
Roof R3.4 batt	R3.3	-$2,223	$80	-$1,635	$68	-$6,295	$4,871	-$3,860	$2,103
Roof R3.6 batt	R3.5	-$751	$2,084	-$774	$1,328	-$2,438	$11,854	-$266	$10,322
Roof R4.0 batt	R3.8	-$644	$465	-$650	$438	-$2,044	$6,428	-$314	$3,056
Roof R4.5 batt	R4.2	-$823	$800	-$690	$585	-$2,336	$6,910	-$1,121	$3,236
Roof R5.0 batt	R5.0	-$1,433	$2,047	-$992	$1,437	-$3,736	$11,134	-$2,999	$8,259
Roof R6.0 batt	R6.0	-$1,075	$996	-$698	$800	-$2,736	$6,285	-$2,486	$8,984
Roof R7.0 batt	R7.0	$0	$0	$0	$0	$0	$0	$0	$0
Roof R8.0 batt	R8.1	-$2,366	$636	-$1,340	$405	-$5,729	$2,409	-$6,374	$2,645
Timber floor R1.5 batt	R1.4	NA	NA	-$235	-$94	-$3,821	-$765	NA	NA
Timber floor R1.8 batt	R.17	NA	NA	-$234	-$53	-$731	-$287	NA	NA
Timber floor R2.0 batt	R1.9	NA	NA	-$247	-$144	-$981	-$370	NA	NA
Timber floor R2.6 batt	R2.5	NA	NA	$0	$0	$0	$0	NA	NA
Timber floor R2.8 batt	R2.6	NA	NA	-$84	$99	-$611	$103	NA	NA
Timber floor R3.0 batt	R2.8	NA	NA	-$25	$37	-$298	$224	NA	NA
Timber floor R3.2 batt	R3.0	NA	NA	$51	$573	$240	$342	NA	NA
Slab Uninsulated		$2,045	$3,239	$3,137	$3,397	$9,333	$13,619	NA	NA
Slab R1.0 edge insulation		-$2,548	-$647	$1,330	$1,718	$2,767	$8,285	NA	NA
Slab R1.2 underslab insulation		$423	$1,719	$2,275	$2,624	$8,509	$10,968	NA	NA
Slab R2.4 underslab insulation		$0	$0	$1,919	$2,096	$7,366	$10,241	NA	NA
Slab R1.2 underslab + edge insulation		-$3,271	-$1,891	$254	$643	$2,375	$4,390	NA	NA
Slab R2.4 underslab + edge insulation		-$3,804	-$3,492	$0	$0	$1,175	$3,717	NA	NA
Slab 40mm1.0 slab topper insulation		-$10,636	-$9,520	-$2,150	-$422	$0	$0	NA	NA
Window aluminium glazing	R0.26	$982	$2,866	$962	$3,456	$14,071	$18,884	$28,600	$78,358
Window Aluminium low-E3 argon double glazing Ucog 1.1	R0.37	$1,394	$2,397	$1,800	$2,967	$12,004	$14,746	$60,261	$83,243
Window Thermally broken low-E3 argon double glazing Ucog 1.3	R0.46	$0	$0	$0	$0	$0	$0	$0	$0
Window Thermally broken low-E3 argon double glazing Ucog 1.1	R0.50	-$1,589	$327	-$2,022	$371	-$8,875	$1,730	-$55,763	$13,733

Note: The most cost-effective component for ceiling insulation, wall insulation, timber floor insulation, slab insulation, and windows has been highlighted in yellow.

Table 41: Zone 3 – individual component NPVs

	Construction	Single Storey		Double storey		Medium Density Dwellings		Apartment building	
	R-value	LB	UB	LB	UB	LB	UB	LB	UB
Wall R2.5 batt	R1.9	-$1,648	$46	-$2,318	$55	-$8,637	-$789	-$16,341	$100
Wall R2.8 batt	R2.0	$0	$0	$0	$0	$0	$0	$0	$0
Wall R4.0 batt	R2.8	-$2,733	-$573	-$3,860	-$663	-$16,840	-$7,570	-$24,798	-$9,028
Wall R4.4 batt	R2.9	-$5,064	-$2,882	-$7,149	-$3,267	-$29,801	-$12,722	-$47,433	-$30,720
Roof R3.0 batt	R2.9	-$1,757	$40	-$1,102	-$236	-$3,716	$1,085	-$2,894	$1,669
Roof R3.3 batt	R3.2	-$593	$1,782	-$654	$1,280	-$2,850	$10,743	$223	$9,785
Roof R3.4 batt	R3.3	-$2,004	$327	-$1,406	$296	-$6,295	$4,871	-$3,860	$2,103
Roof R3.6 batt	R3.5	-$571	$2,295	-$577	$1,528	-$2,438	$11,854	-$266	$10,322
Roof R4.0 batt	R3.8	-$497	$637	-$489	$601	-$2,044	$6,428	-$314	$3,056
Roof R4.5 batt	R4.2	-$714	$926	-$572	$705	-$2,336	$6,910	-$1,121	$3,236
Roof R5.0 batt	R5.0	-$1,348	$2,140	-$899	$1,528	-$3,736	$11,134	-$2,999	$8,259
Roof R6.0 batt	R6.0	-$1,037	$1,036	-$655	$841	-$2,736	$6,285	-$2,486	$8,984
Roof R7.0 batt	R7.0	$0	$0	$0	$0	$0	$0	$0	$0
Roof R8.0 batt	R8.1	-$2,388	$605	-$1,366	$370	-$5,729	$2,409	-$6,374	$2,645
Timber floor R1.5 batt	R1.4	NA	NA	-$297	-$106	-$3,821	-$765	NA	NA
Timber floor R1.8 batt	R.17	NA	NA	-$258	-$61	-$731	-$287	NA	NA
Timber floor R2.0 batt	R1.9	NA	NA	-$266	-$151	-$981	-$370	NA	NA
Timber floor R2.6 batt	R2.5	NA	NA	$0	$0	$0	$0	NA	NA
Timber floor R2.8 batt	R2.6	NA	NA	-$84	$101	-$611	$103	NA	NA
Timber floor R3.0 batt	R2.8	NA	NA	-$48	$46	-$298	$224	NA	NA
Timber floor R3.2 batt	R3.0	NA	NA	$58	$563	$240	$342	NA	NA
Slab Uninsulated		$1,214	$2,740	$2,807	$3,301	$9,333	$13,619	NA	NA
Slab R1.0 edge insulation		-$3,195	-$1,038	$1,033	$1,564	$2,767	$8,285	NA	NA
Slab R1.2 underslab insulation		$234	$1,607	$2,176	$2,671	$8,509	$10,968	NA	NA
Slab R2.4 underslab insulation		$0	$0	$1,928	$2,089	$7,366	$10,241	NA	NA
Slab R1.2 underslab + edge insulation		-$3,317	-$1,976	$187	$670	$2,375	$4,390	NA	NA
Slab R2.4 underslab + edge insulation		-$3,723	-$3,415	$0	$0	$1,175	$3,717	NA	NA
Slab 40mm1.0 slab topper insulation		-$10,353	-$8,919	-$1,812	-$135	$0	$0	NA	NA
Window aluminium glazing	R0.26	$1,015	$3,102	$1,233	$3,953	$14,071	$18,884	$28,600	$78,358
Window Aluminium low-E3 argon double glazing Ucog 1.1	R0.37	$1,327	$2,439	$1,746	$3,071	$12,004	$14,746	$60,261	$83,243
Window Thermally broken low-E3 argon double glazing Ucog 1.3	R0.46	$0	$0	$0	$0	$0	$0	$0	$0
Window Thermally broken low-E3 argon double glazing Ucog 1.1	R0.50	-$1,615	$398	-$2,063	$446	-$8,875	$1,730	-$55,763	$13,733

Note: The most cost-effective component for ceiling insulation, wall insulation, timber floor insulation, slab insulation, and windows has been highlighted in yellow.

Table 42: Zone 4 – individual component NPVs

	Construction	Single Storey		Double storey		Medium Density Dwellings		Apartment building	
	R-value	LB	UB	LB	UB	LB	UB	LB	UB
Wall R2.5 batt	R1.9	-$1,850	-$103	-$6,911	-$2,456	-$9,453	-$1,374	-$18,470	-$2,607
Wall R2.8 batt	R2.0	$0	$0	$0	$0	$0	$0	$0	$0
Wall R4.0 batt	R2.8	-$1,910	$372	-$2,516	$1,082	-$13,335	-$3,535	-$14,132	$4,681
Wall R4.4 batt	R2.9	-$4,206	-$1,972	-$5,753	-$1,557	-$26,212	-$8,335	-$36,331	-$16,033
Roof R3.0 batt	R2.9	-$3,920	-$1,723	-$2,674	-$1,516	-$10,767	-$4,715	-$7,903	-$2,342
Roof R3.3 batt	R3.2	-$2,381	$458	-$1,960	$294	-$8,806	$6,238	-$4,014	$5,905
Roof R3.4 batt	R3.3	-$3,649	-$867	-$2,583	-$670	-$11,864	$323	-$7,938	-$1,617
Roof R3.6 batt	R3.5	$395	$2,193	$135	$914	$962	$8,331	$4,893	$6,959
Roof R4.0 batt	R3.8	-$1,661	-$329	-$1,342	-$102	-$5,876	$3,281	-$3,218	$272
Roof R4.5 batt	R4.2	-$1,592	$202	-$1,219	$173	-$5,197	$4,568	-$3,303	$1,460
Roof R5.0 batt	R5.0	-$1,994	$1,776	-$1,377	$1,138	-$5,843	$9,817	-$4,609	$6,554
Roof R6.0 batt	R6.0	-$1,315	$812	-$863	$673	-$3,655	$5,549	-$3,187	$8,018
Roof R7.0 batt	R7.0	$0	$0	$0	$0	$0	$0	$0	$0
Roof R8.0 batt	R8.1	-$2,243	$811	-$1,262	$514	-$5,188	$3,150	-$5,999	$3,186
Timber floor R1.5 batt	R1.4	NA	NA	-$549	-$315	-$4,382	-$1,585	NA	NA
Timber floor R1.8 batt	R.17	NA	NA	-$438	-$210	-$1,537	-$247	NA	NA
Timber floor R2.0 batt	R1.9	NA	NA	-$426	-$262	-$1,208	-$683	NA	NA
Timber floor R2.6 batt	R2.5	NA	NA	$0	$0	-$370	$404	NA	NA
Timber floor R2.8 batt	R2.6	NA	NA	-$96	$118	-$192	-$144	NA	NA
Timber floor R3.0 batt	R2.8	NA	NA	-$8	$94	$0	$0	NA	NA
Timber floor R3.2 batt	R3.0	NA	NA	$126	$671	$149	$882	NA	NA
Slab Uninsulated		-$1,066	$1,025	$2,127	$2,903	$8,202	$12,554	NA	NA
Slab R1.0 edge insulation		-$5,531	-$2,915	$364	$1,128	$1,725	$7,299	NA	NA
Slab R1.2 underslab insulation		-$294	$1,335	$2,022	$2,642	$8,303	$10,668	NA	NA
Slab R2.4 underslab insulation		$0	$0	$1,983	$2,095	$7,422	$10,160	NA	NA
Slab R1.2 underslab + edge insulation		-$3,862	-$2,436	$44	$551	$1,923	$4,177	NA	NA
Slab R2.4 underslab + edge insulation		-$3,754	-$3,544	$0	$0	$1,015	$3,729	NA	NA
Slab 40mm1.0 slab topper insulation		-$10,735	-$8,823	-$1,815	-$96	$0	$0	NA	NA
Window aluminium glazing	R0.26	-$145	$1,944	-$270	$2,511	$7,765	$14,068	-$25,320	$27,418
Window Aluminium low-E3 argon double glazing Ucog 1.1	R0.37	$967	$2,053	$1,317	$2,613	$10,150	$13,433	$45,874	$68,192
Window Thermally broken low-E3 argon double glazing Ucog 1.3	R0.46	$0	$0	$0	$0	$0	$0	$0	$0
Window Thermally broken low-E3 argon double glazing Ucog 1.1	R0.50	-$1,476	$556	-$1,916	$611	-$8,316	$2,357	-$51,291	$18,764

Note: The most cost-effective component for ceiling insulation, wall insulation, timber floor insulation, slab insulation, and windows has been highlighted in yellow.

Table 43: Zone 5 – individual component NPVs

	Construction	Single Storey		Double storey		Medium Density Dwellings		Apartment building	
	R-value	LB	UB	LB	UB	LB	UB	LB	UB
Wall R2.5 batt	R1.9	-$1,782	-$51	-$2,516	-$90	-$9,199	-$1,199	-$17,715	-$2,010
Wall R2.8 batt	R2.0	$0	$0	$0	$0	$0	$0	$0	$0
Wall R4.0 batt	R2.8	-$2,142	$114	-$2,909	$643	-$14,213	-$3,962	-$17,723	$671
Wall R4.4 batt	R2.9	-$4,420	-$2,245	-$6,128	-$2,027	-$26,966	-$8,194	-$39,834	-$20,304
Roof R3.0 batt	R2.9	-$3,465	-$1,154	-$2,305	-$1,083	-$9,393	-$3,525	-$7,017	-$1,183
Roof R3.3 batt	R3.2	-$1,970	$908	-$1,633	$642	-$7,668	$6,376	-$3,187	$6,813
Roof R3.4 batt	R3.3	-$3,295	-$455	-$2,306	-$362	-$10,845	$1,163	-$7,202	-$745
Roof R3.6 batt	R3.5	$703	$2,790	$387	$1,331	$2,397	$8,204	$5,686	$8,207
Roof R4.0 batt	R3.8	-$1,396	-$37	-$1,128	$125	-$5,164	$3,719	-$2,648	$900
Roof R4.5 batt	R4.2	-$1,398	$420	-$1,064	$342	-$4,672	$4,800	-$2,892	$1,929
Roof R5.0 batt	R5.0	-$1,863	$1,936	-$1,272	$1,261	-$5,489	$9,486	-$4,336	$6,898
Roof R6.0 batt	R6.0	-$1,269	$878	-$821	$727	-$3,517	$5,350	-$3,085	$8,167
Roof R7.0 batt	R7.0	$0	$0	$0	$0	$0	$0	$0	$0
Roof R8.0 batt	R8.1	-$2,333	$768	-$1,323	$479	-$5,446	$3,005	-$6,213	$3,089
Timber floor R1.5 batt	R1.4	NA	NA	-$713	-$295	-$4,607	-$1,498	NA	NA
Timber floor R1.8 batt	R.17	NA	NA	-$408	-$211	-$1,584	-$901	NA	NA
Timber floor R2.0 batt	R1.9	NA	NA	-$406	-$273	-$1,517	-$918	NA	NA
Timber floor R2.6 batt	R2.5	NA	NA	-$83	$21	-$520	-$371	NA	NA
Timber floor R2.8 batt	R2.6	NA	NA	-$101	$51	-$1,043	-$257	NA	NA
Timber floor R3.0 batt	R2.8	NA	NA	$0	$0	-$635	-$128	NA	NA
Timber floor R3.2 batt	R3.0	NA	NA	$54	$636	$0	$0	NA	NA
Slab Uninsulated		-$440	$1,731	$2,202	$3,077	$7,783	$12,718	NA	NA
Slab R1.0 edge insulation		-$4,625	-$2,084	$581	$1,367	$1,847	$7,640	NA	NA
Slab R1.2 underslab insulation		-$147	$1,500	$1,937	$2,635	$7,782	$10,579	NA	NA
Slab R2.4 underslab insulation		$0	$0	$1,864	$2,044	$6,831	$10,004	NA	NA
Slab R1.2 underslab + edge insulation		-$3,465	-$2,157	$82	$597	$1,548	$4,262	NA	NA
Slab R2.4 underslab + edge insulation		-$3,651	-$3,310	$0	$0	$517	$3,761	NA	NA
Slab 40mm1.0 slab topper insulation		-$10,663	-$8,573	-$1,827	-$110	$0	$0	NA	NA
Window aluminium glazing	R0.26	-$343	$3,872	-$506	$4,935	$6,339	$22,626	-$27,493	$95,056
Window Aluminium low-E3 argon double glazing Ucog 1.1	R0.37	$598	$3,740	$912	$4,769	$9,199	$20,737	$39,712	$118,860
Window Thermally broken low-E3 argon double glazing Ucog 1.3	R0.46	-$505	$1,535	-$549	$1,986	-$2,192	$8,530	-$17,314	$53,090
Window Thermally broken low-E3 argon double glazing Ucog 1.1	R0.50	$0	$0	$0	$0	$0	$0	$0	$0

Note: The most cost-effective component for ceiling insulation, wall insulation, timber floor insulation, slab insulation, and windows has been highlighted in yellow.

Table 44: Zone 6 – individual component NPVs

	Construction	Single Storey		Double storey		Medium Density Dwellings		Apartment building	
	R-value	LB	UB	LB	UB	LB	UB	LB	UB
Wall R2.5 batt	R1.9	-$2,104	-$194	-$2,943	-$444	-$10,368	-$1,545	-$20,684	-$3,388
Wall R2.8 batt	R2.0	$0	$0	$0	$0	$0	$0	$0	$0
Wall R4.0 batt	R2.8	-$589	$2,008	-$734	$2,952	-$8,257	$1,933	-$2,192	$17,169
Wall R4.4 batt	R2.9	-$2,718	-$425	-$3,761	$501	-$20,452	-$2,303	-$22,933	-$4,476
Roof R3.0 batt	R2.9	-$6,703	-$3,954	-$4,414	-$2,906	-$19,496	-$10,975	-$13,550	-$6,616
Roof R3.3 batt	R3.2	-$4,824	-$1,241	-$3,500	-$692	-$16,189	$1,395	-$8,791	$3,496
Roof R3.4 batt	R3.3	-$5,868	-$2,553	-$3,956	-$1,621	-$18,708	-$4,098	-$12,475	-$4,658
Roof R3.6 batt	R3.5	-$1,424	$3,602	-$917	$1,656	$528	$6,259	$2,217	$11,363
Roof R4.0 batt	R3.8	-$3,245	-$1,373	-$2,333	-$764	-$10,625	$447	-$6,455	-$1,785
Roof R4.5 batt	R4.2	-$2,783	-$543	-$1,977	-$311	-$8,723	$2,667	-$5,718	-$380
Roof R5.0 batt	R5.0	-$2,858	$1,284	-$1,935	$903	-$8,428	$8,247	-$6,355	$6,056
Roof R6.0 batt	R6.0	-$1,689	$693	-$1,107	$583	-$4,766	$5,100	-$3,906	$8,301
Roof R7.0 batt	R7.0	$0	$0	$0	$0	$0	$0	$0	$0
Roof R8.0 batt	R8.1	-$2,045	$1,085	-$1,147	$673	-$4,561	$4,001	-$5,614	$3,725
Timber floor R1.5 batt	R1.4	NA	NA	-$1,043	-$736	-$6,760	-$2,871	NA	NA
Timber floor R1.8 batt	R.17	NA	NA	-$849	-$548	-$2,848	-$1,925	NA	NA
Timber floor R2.0 batt	R1.9	NA	NA	-$740	-$544	-$2,550	-$1,755	NA	NA
Timber floor R2.6 batt	R2.5	NA	NA	-$174	-$79	-$923	-$697	NA	NA
Timber floor R2.8 batt	R2.6	NA	NA	-$157	$5	-$1,327	-$486	NA	NA
Timber floor R3.0 batt	R2.8	NA	NA	$0	$0	-$773	-$240	NA	NA
Timber floor R3.2 batt	R3.0	NA	NA	$102	$696	$0	$0	NA	NA
Slab Uninsulated		-$885	$1,141	$1,261	$3,068	$5,963	$10,169	NA	NA
Slab R1.0 edge insulation		-$4,806	-$2,616	-$270	$1,474	-$695	$5,295	NA	NA
Slab R1.2 underslab insulation		$3,040	$3,639	$2,172	$3,372	$7,790	$9,797	NA	NA
Slab R2.4 underslab insulation		$2,847	$4,281	$1,915	$3,456	$7,535	$9,784	NA	NA
Slab R1.2 underslab + edge insulation		$0	$0	$277	$1,535	$1,372	$3,667	NA	NA
Slab R2.4 underslab + edge insulation		-$762	$1,280	$1	$1,636	$1,050	$3,697	NA	NA
Slab 40mm1.0 slab topper insulation		-$7,778	-$3,591	$0	$0	$0	$0	NA	NA
Window aluminium glazing	R0.26	-$2,913	$1,573	-$4,002	$1,842	-$3,367	$12,011	-$135,583	-$7,377
Window Aluminium low-E3 argon double glazing Ucog 1.1	R0.37	-$501	$2,742	-$330	$3,608	$5,879	$16,411	$3,687	$81,104
Window Thermally broken low-E3 argon double glazing Ucog 1.3	R0.46	-$854	$1,249	-$881	$1,711	-$3,444	$7,489	-$26,490	$45,404
Window Thermally broken low-E3 argon double glazing Ucog 1.1	R0.50	$0	$0	$0	$0	$0	$0	$0	$0

Note: The most cost-effective component for ceiling insulation, wall insulation, timber floor insulation, slab insulation, and windows has been highlighted in yellow.

Appendix C: Hygrothermal results

The tables below present the VTT index results for each of the six climate zones for the wall options.

They include a sensitivity sweep of wall orientation, colour, insulation level and moisture generation rate inside the dwelling.

Results are presented for the internal surface (clear wall only) (Table 45) and interstitially at the line of the building underlay (Table 46).

Table 45: Wall internal surface for each climate zone (Auckland, Christchurch, Napier, Queenstown, Taupo, Wellington)

Auckland

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.1	0.1	0.1	0.1
	South Facing	0.1	0.1	0.1	0.1
Medium	North Facing	0.1	0.1	0.1	0.1
	South Facing	0.1	0.1	0.1	0.1
High	North Facing	0.1	0.1	0.1	0.1
	South Facing	0.1	0.1	0.1	0.1

Christchurch

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
Medium	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
High	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0

Napier

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
Medium	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
High	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0

Queenstown

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
Medium	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
High	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0

Taupo

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
Medium	North Facing	0.1	0.1	0.1	0.1
	South Facing	0.1	0.1	0.1	0.1
High	North Facing	0.1	0.1	0.1	0.1
	South Facing	0.1	0.1	0.1	0.1

Wellington

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
Medium	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
High	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0

Table 46: External underlay in walls mould index results for each climate zone (Auckland, Christchurch, Napier, Queenstown, Taupo, Wellington

Auckland

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.1	0.0	0.1
	South Facing	0.7	1.2	0.7	1.2
Medium	North Facing	0.0	0.2	0.0	0.1
	South Facing	0.9	1.5	0.9	1.5
High	North Facing	0.1	0.3	0.0	0.1
	South Facing	1.2	2.0	1.1	2.4

Christchurch

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.1
Medium	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.1	0.0	0.1
High	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.1	0.3	0.1	0.2

Napier

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
Medium	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.1	0.0	0.1
High	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.1	0.1	0.0	0.1

Queenstown

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
Medium	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.0	0.0	0.0	0.0
High	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.1	0.1	0.1	0.1

Taupo

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.1	0.0	0.0
	South Facing	0.2	0.4	0.1	0.4
Medium	North Facing	0.0	0.1	0.0	0.1
	South Facing	0.3	0.6	0.3	0.6
High	North Facing	0.0	0.3	0.0	0.1
	South Facing	0.5	0.9	0.4	0.8

Wellington

Moisture Load		R2.8 Dark	R2.8 Light	R4.0 Dark	R4.0 Light
Low	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.1	0.2	0.1	0.2
Medium	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.1	0.4	0.1	0.4
High	North Facing	0.0	0.0	0.0	0.0
	South Facing	0.3	0.6	0.2	0.6

Table 47 and Table 48 present the VTT index results for each of the six climate zones.

They include a sensitivity sweep of roof orientation, colour, insulation level and moisture generation rate inside the dwelling.

Table 47: Skillion roof mould index results for each climate zone (Auckland, Christchurch, Napier, Queenstown, Taupo, Wellington)

Auckland

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
	Low	North Facing	0.0	0.8	0.0	0.4
		South Facing	1.0	4.1	0.6	3.7
	Medium	North Facing	0.0	1.2	0.0	0.7
		South Facing	1.4	4.6	1.0	4.0
	High	North Facing	0.0	1.5	0.0	1.0
		South Facing	1.7	5.3	1.3	4.4

Christchurch

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
	Low	North Facing	0.0	0.2	0.0	0.1
		South Facing	0.4	2.1	0.3	1.7
	Medium	North Facing	0.0	0.3	0.0	0.2
		South Facing	0.9	2.8	0.5	2.2
	High	North Facing	0.0	0.6	0.0	0.3
		South Facing	1.3	3.6	0.8	2.7

Napier

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
	Low	North Facing	0.0	0.0	0.0	0.0
		South Facing	0.1	1.1	0.0	0.7
	Medium	North Facing	0.0	0.1	0.0	0.0
		South Facing	0.2	1.4	0.1	1.1
	High	North Facing	0.0	0.1	0.0	0.0
		South Facing	0.3	1.9	0.1	1.3

Queenstown

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
	Low	North Facing	0.0	0.2	0.0	0.1
		South Facing	0.4	2.3	0.3	1.5
	Medium	North Facing	0.0	0.3	0.0	0.2
		South Facing	0.9	3.6	0.4	2.0
	High	North Facing	0.0	0.6	0.0	0.3
		South Facing	1.3	5.1	0.8	4.8

Taupo

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
	Low	North Facing	0.0	0.9	0.0	0.4
		South Facing	0.8	3.0	0.4	2.5
	Medium	North Facing	0.0	1.3	0.0	0.9
		South Facing	1.2	3.7	0.8	3.0
	High	North Facing	0.1	1.6	0.0	1.2
		South Facing	1.5	5.3	1.1	3.5

Wellington

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
	Low	North Facing	0.0	0.6	0.0	0.3
		South Facing	0.8	3.1	0.4	2.7
	Medium	North Facing	0.0	1.2	0.0	0.5
		South Facing	1.3	3.7	0.8	3.2
	High	North Facing	0.0	1.6	0.0	1.0
		South Facing	1.6	4.2	1.2	3.6

Table 48: Pitched roof mould index results for each climate zone (Auckland, Christchurch, Napier, Queenstown, Taupo, Wellington)

Auckland

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
Low		North Facing	0.0	0.5	0.0	0.4
		South Facing	0.7	3.9	0.4	3.5
Medium		North Facing	0.0	0.8	0.0	0.8
		South Facing	1.0	4.3	0.6	3.8
High		North Facing	0.0	1.1	0.0	1.2
		South Facing	1.3	5.3	0.8	4.1

Christchurch

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
Low		North Facing	0.0	0.1	0.0	0.1
		South Facing	0.3	1.6	0.2	1.4
Medium		North Facing	0.0	0.2	0.0	0.2
		South Facing	0.4	2.1	0.3	1.7
High		North Facing	0.0	0.3	0.0	0.3
		South Facing	0.7	2.7	0.4	2.0

Napier

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
Low		North Facing	0.0	0.0	0.0	0.0
		South Facing	0.0	0.6	0.0	0.4
Medium		North Facing	0.0	0.0	0.0	0.0
		South Facing	0.1	1.0	0.0	0.7
High		North Facing	0.0	0.1	0.0	0.0
		South Facing	0.1	1.3	0.1	1.0

Queenstown

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
	Low	North Facing	0.0	0.1	0.0	0.1
		South Facing	0.3	5.3	0.2	1.3
	Medium	North Facing	0.0	0.2	0.0	0.2
		South Facing	0.5	5.3	0.3	5.2
	High	North Facing	0.0	0.3	0.0	0.3
		South Facing	2.0	5.3	0.4	5.3

Taupo

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
	Low	North Facing	0.0	0.6	0.0	0.5
		South Facing	0.4	2.5	0.3	2.1
	Medium	North Facing	0.0	1.0	0.0	1.0
		South Facing	0.8	3.0	0.4	2.5
	High	North Facing	0.0	1.2	0.0	1.3
		South Facing	1.1	3.6	0.6	2.9

Wellington

Moisture Load		Insulation	R2.9		R6.6	
		Roof colour	Dark	Light	Dark	Light
	Low	North Facing	0.0	0.3	0.0	0.3
		South Facing	0.4	2.6	0.3	2.2
	Medium	North Facing	0.0	0.6	0.0	0.7
		South Facing	0.7	3.1	0.4	2.6
	High	North Facing	0.0	1.0	0.0	1.2
		South Facing	1.1	3.6	0.6	3.0

Appendix D: HEEP-based internal gains schedules

Loads

In previous work (Sullivan et al., 2021), loads derived from HEEP data were adjusted according to plausible improvements in appliance energy efficiency that could be identified.

To apply these loads to different zones, equipment loads were broken up into miscellaneous loads and major appliances that could be readily assigned to specific zones. Thus, the six types of load to be applied are:

- miscellaneous equipment
- specific appliances
- lighting
- people
- hot water
- cold water and evaporation losses.

The equipment and lighting loads also need to be scaled – larger houses and households will tend to use more energy, and this needs to be accounted for. At the same time, it is not necessarily a simple direct relationship – a 200 m² house does not use twice the energy as a 100 m² house, and a four-person household will probably not use twice the energy as a two-person household. Equations to scale the loads were derived from the HEERA model from HEEP and other data on fridge size and energy use as appropriate. Sensible gains from people were assumed to be 75 W during the day, reduced by 30% overnight following CIBSE TM59.

Miscellaneous equipment loads (kWh/yr)

Living zones[1]	$595*f_{L1}$	$f_{L1} = 0.393896 + 0.122415N + 0.002007A$ Where N = number of occupants, A = floor area
Kitchen	$324*f_{L1}$	
Study/office[2]	$129*f_{L1}$	
Bedroom	129	Load not varied by occupancy or area[3]
Corridors	0	Assumed to have no significant miscellaneous appliance loads
Bathrooms	0	

[1] Load to be divided across all living zones.
[2] No good information on study/office loads. For simplicity, as bedrooms and studies are often interchangeable, it was assumed they had the same load as a bedroom.
[3] Adding a bedroom is already adding more floor area and occupancy, so scaling them again would be double counting.

Specific equipment loads (kWh/yr)

# people in household		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Fridge/freezer	Assume one in kitchen, second in garage or laundry absent specific information	265	265	343	420	498	575	575
Range[1]	Range loads in kitchen	260	417	575	733	890	1,048	1,205
Laundry[2]	Combined washing + dryer load	110	187	264	341	418	495	572
	Washing machine only (to be sustainable!)	27	46	65	84	103	122	141
Heated towel rail	Assume 1 per bathroom (70 W for 4 hours in the morning and 4 hours in the evening)							
Hot water cylinder	Assume standard 100 W constant load to selected zone or nothing if instant gas							

[1] Assumed 20% latent, 18% lost to factors such as extract ventilation.
[2] Assumed 60% lost, 4% latent due to most of the energy being vented (Wilson et al., 2014).

Lighting loads (W/m²)

# people in household	1	2	3	4	5	6	7
Living/kitchen	0.56	0.83	1.10	1.36	1.63	1.89	2.16
Kitchen	0.90	1.33	1.75	2.18	2.60	3.03	3.46
Living	0.46	0.68	0.90	1.12	1.33	1.55	1.77
Bedroom	0.16	0.23	0.30	0.37	0.45	0.52	0.59
Study/office	0.16	0.23	0.30	0.37	0.45	0.52	0.59
Other	0.22	0.32	0.42	0.52	0.63	0.73	0.83

Hot water

Hot water loads are broken up into four sources:

- Shower/bath use – assumed 52 L/day/person based on measurements of average New Zealand usage (Heinrich, 2010; Whittaker et al., 2022) @ 40°C.
- Other hot water use – 20 + 2.5L/person @ 60°C.
- Pipe losses – estimated as a function of occupancy, insulation and distribution system.
- Storage losses – estimated as a function of cylinder volume, assumed 60°C.

For simplicity, the formulae in the WHAT HO! spreadsheet were implemented in the EnergyPlus model via EMS programs. This allows us to simply alter things like occupancy assumptions by changing a single input rather than having to recalculate all the hot water use. Following SAP 10.2,[30] it is assumed only around 25% of the shower and other hot water heat is converted into sensible gains while 80% of pipe and storage losses become sensible gains. Shower gains are divided among the bathrooms in the house. Storage losses are assigned to wherever the hot water cylinder is. In the absence of better information, pipe losses were distributed across the zones using hot water and the corridor and hot water cylinder zones. Other hot water uses were distributed assuming 50% is used in the kitchen, 40% in the laundry and 10% in the bathroom(s).

Cold water and evaporation losses

SAP 10.2 assigns -40W/person of heat losses as a result of heat absorbed by cold water or evaporation. Unfortunately, both SAP and PHPP are single-zone models and thus provide little guidance as to how to distribute these loads by zone. The cold water losses are primarily discussed with regards to toilet cisterns[31] so we allocate -20W/person across the toilet zones. Evaporation is assumed to primarily occur in the bathrooms (wet towels) and the kitchen (drying dishes) and so the -20W/person evaporation losses are distributed over these zones. To apply negative internal gains in the model, we utilise the OtherEquipment object in EnergyPlus.

Schedules

The schedules (Figure 61 to Figure 65) were derived from a range of sources – miscellaneous equipment, range and lighting schedules from previous work using HEEP data and laundry appliance schedules from United States data and residential modelling guidance (Wilson et al., 2014). Occupancy schedules and distributions were based on a combination of New Zealand and United States time use surveys (Khajehzadeh, 2017; Mitra et al., 2020), attempting to scale them such that the overall occupancy would be in line with how many hours people would be expected to be in those rooms. It is acknowledged these are all necessarily approximate and in real households can vary widely.

[30] https://files.bregroup.com/SAP/SAP%2010.2%20-%2021-04-2022.pdf

[31] https://passipedia.org/planning/calculating_energy_efficiency/phpp_-_the_passive_house_planning_package/internal_heat_gains_in_relation_to_living_area

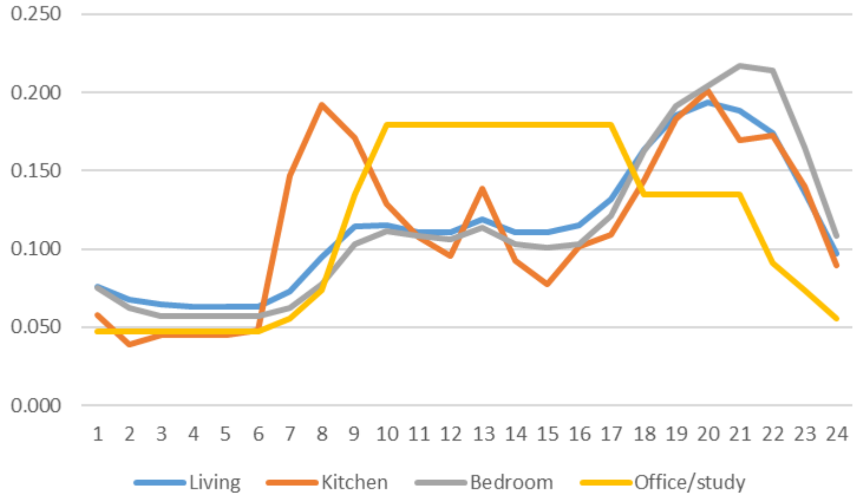


Figure 61: Miscellaneous equipment schedules for different zones scaled for kWh/yr loads

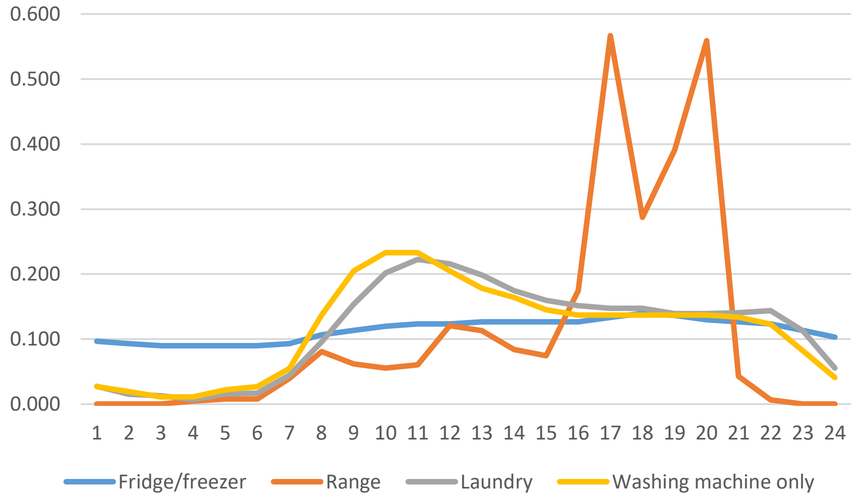


Figure 62: Specific appliance schedules not scaled for kWh/yr loads

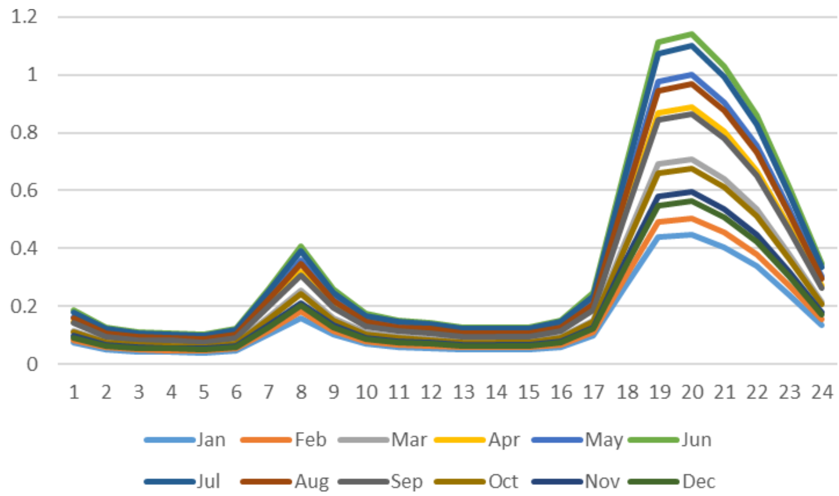


Figure 63: Lighting schedule[32]

[32] The overall schedule derived from HEEP data was varied between different months so that the overall lighting load would vary appropriately over the year in line with the plot of monthly average lighting power in the HEEP report (Isaacs et al., 2010). In reality, the lighting hours would also vary during the year. However given that the lighting load is now less than 10% of the overall internal load of the house it was decided that level of detail wouldn't be necessary.

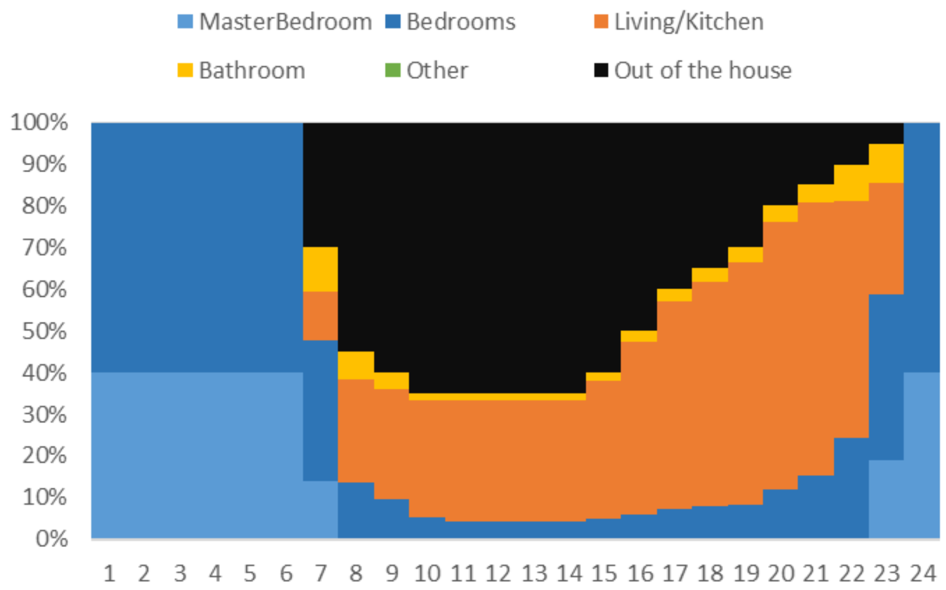


Figure 64: Occupancy distribution in the four-bedroom house (assumed five occupants)

The hot water schedule was applied based on observed water use schedules in recent New Zealand work (Whittaker et al., 2022) (Figure 65). No attempt was made to disaggregate hot water uses here as the different uses broadly followed the same pattern, and testing indicated that heating and cooling loads were relatively insensitive to schedule assumptions here. This schedule was applied to the hot water loads (showers, other and pipe losses) as well as the evaporation losses on the assumption that evaporation and water use would be linked. The storage and cold water losses were left with constant schedules for simplicity.

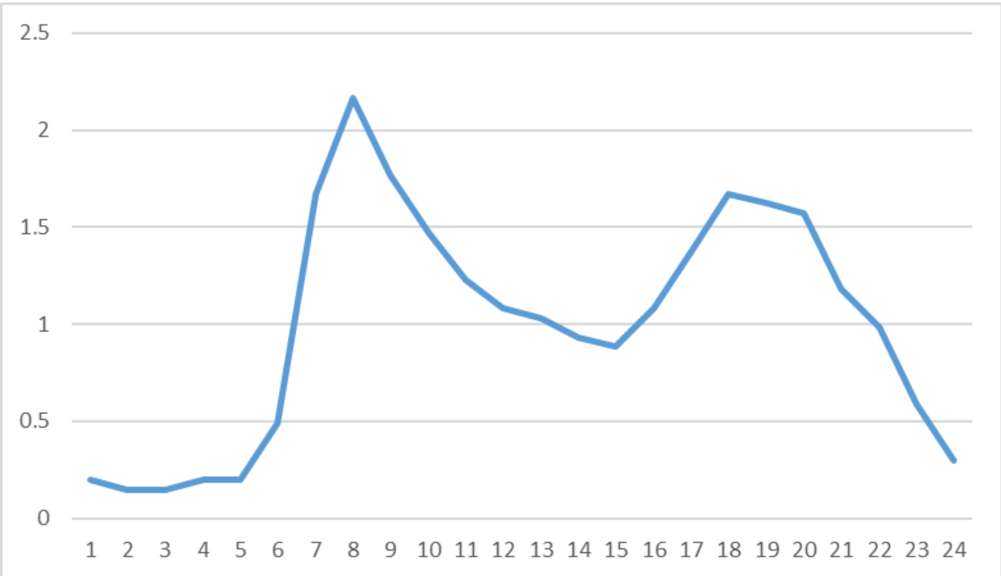


Figure 65: Hot water use schedule

Appendix E: Sensitivity analysis 1

Main model comparisons

Model estimates are, ultimately, a product of their assumptions. Often there is no single objectively correct choice to make, and there are a range of assumptions that could defensibly be used and would produce different answers.

One of the classic examples of this is heating schedules. H1/VM1 assumes 24/7 space conditioning in all rooms. This may be effective for assessing the heating efficiency of the house, but in the New Zealand context, it is likely an overestimate of the actual heating use and costs. Historically, New Zealand households have tended to only heat spaces they are using, and heating bedrooms overnight is uncommon, though this may vary depending on if the house has young children for example (Burrough et al., 2015; Isaacs et al., 2010). Cooling/air-conditioning is also not common. A more realistic schedule might have no cooling, no heating in the corridors and no heating overnight, which would result in significantly lower energy use and thus lower benefits from increased insulation.

At the same time, it may be argued that doing this fails to value overheating mitigation or warmer bedrooms. Applying cooling, for example, can be a way of assigning a dollar value to overheating in the house and incorporating it into the cost-benefit analysis. This may be argued to be desirable when assessing the benefits of insulation changes even if it is not strictly speaking the most accurate depiction of the actual energy savings of a typical New Zealand household. There is no correct answer here – only different arguments that modellers and those interpreting the results should be aware of.

To illustrate some of this uncertainty and the potential impact of such model assumptions, the various H1-compliant and lower-cost models were rerun using different assumptions:

- **Dark window frames:** In the main analysis, we assumed the window frames would be white (80% reflectance) in order to minimise cooling loads and focus on heating efficiency. Window frames, however, are commonly both white and black, and darker frames may present significantly higher heat gains, affecting the differences between aluminium and thermally broken frames. The window frame reflectance was reduced to 10%.
- **No mixing:** In the initial modelling, we applied some simple air mixing between zones, assuming that doors would be opened for cross-ventilation and airflow when it was hot. That being said, interzonal air mixing is optional in H1/VM1. Moreover, the overheating analysis (Q4) suggested that, in some situations, the lack of directionality in these simple mixing assumptions could result in some zones having significantly lower cooling loads than otherwise. Theoretically, this should not have a significant impact on overall energy use across the house when all zones are being conditioned identically. However, it is worth checking, so to examine the potential effect of this assumption, the interzonal air mixing through open doors was removed.
- **Heating only during occupied hours:** As a slightly more realistic schedule than H1/VM1's 24/7 heating, the heating schedules were altered to only condition spaces during occupied hours. Thus, the living spaces were only conditioned during the day, and intermittently occupied spaces like corridors and bathrooms were not conditioned. Bedrooms continue to be conditioned day and night. This is likely still more heating (and cooling) than many households would use, but it was felt to be important to still assign value to, for example, night-time bedroom temperatures.
- **Low ventilation + airtightness:** The main analysis assumed high levels of ventilation from opening all windows and doors in order to minimise cooling loads. However people may not do this. The analysis also assumed 0.5 ACH baseline fresh air/infiltration following H1/VM1. Modern houses have becoming increasingly air tight and, without opening windows, may not get that much fresh air (McNeil & Rupp, 2018). Lower levels of ventilation and infiltration would increase

cooling loads and decrease heating loads, which may change the relative performance and energy savings of the insulation options. To illustrate this, we lowered the ventilation rate to a significantly lower 5 ACH in the more heavily ventilated zones such as living spaces and 1 ACH elsewhere and lowered the infiltration rate to 0.1 ACH.[33]

- **Lower soil conductivity:** H1/AS1 5th edition changed the assumed soil properties in the modelling of concrete slabs to a conductivity of 2.0 W/m.K and volumetric heat capacity of 2.0 x 10^6 J/m^{3}K. This is significantly higher than values that have historically been used – conductivity of 1.2 W/m.K (Trethowen, 2000) and heat capacity of 1.2x10^6 J/m^{3}K (NZS 4214:2016 *Methods of determining the total thermal resistance of parts of buildings* – clay soil). In reality, soil properties may vary widely between sites and may be a significant source of uncertainty in concrete slab performance. To show the effect of this, we ran the models using the old ground properties as well as setting the water table depth to 10 m instead of 2 m to reduce heat loss.
- **Combined:** To examine the potential overall impact of these assumptions together, the assumptions that produced lower energy differences were combined. This included lower soil conductivity (with the exception of the single-storey Queenstown comparison), removal of air mixing, heating only during occupied hours, darker window frames in the colder climate zones, reducing the ventilation rate and reducing the infiltration rate to 0.35 ACH (to still meet minimum NZS 4303:1990 fresh air requirements).

Results

In terms of overall energy use, the effects of the assumptions do vary between houses and climates (Figure 66 to Figure 69). However, we can observe some general patterns:

- Swapping to dark window frames has effects varying from a 5% decrease in overall energy use to a ~30% increase. Increases are observed in the warmer climates, and decreases are observed in the cooler heating-dominated climates. The largest increases are observed in the reference models as the window size is increased.
- Removing interzonal air mixing has negligible effects on overall energy use – mostly in the 0–2% range. We see larger effects on the reference models, especially if they do not have shading – a result of how the assumption affects cooling loads more than heating.
- Reducing heating to just occupied hours reduces energy use by ~10–30%, varying between houses (with the exception of the apartments, which are minimally affected because their small living spaces and limited bathroom/corridor area means the schedule changes did not change a lot).
- Lower ventilation and infiltration reduces heating use by as much as 30–60% in this instance, while increasing cooling use by ~50–200%. The overall impact of this depends on the climate and the heating/cooling balance. The much higher cooling loads in the reference models with their high window areas means that they also tend more towards increases.
- Adjusting the soil properties reduced energy use by ~1–25%. Effects mainly varied based on the house design – the single-storey house with the most slab area showed the largest impact, while differences were minor in the medium-density house.

[33] While this may be a realistic estimate of infiltration in many modern homes (McNeil et al., 2015), it would not meet minimum fresh air requirements and more fresh air should be provided by either opening windows or mechanical ventilation.

Single Storey		Delivered Total (kWh/m2)												
		M1	M2	M3	M4	M5	M6	M7						
Climate	Label	Baseline	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings
Zone 1 - Auckland	H1 4th ed schedule	10.9	11.1	10.9	8.1	9.3	9.6	8.2	102%	100%	74%	85%	88%	75%
Zone 1 - Auckland	H1 5th ed schedule	5.9	5.9	5.9	4.1	5.0	4.9	4.6	100%	100%	70%	85%	84%	79%
Zone 1 - Auckland	H1 5th ed reference	7.8	8.3	7.6	6.0	7.9	7.1	7.4	106%	98%	78%	102%	91%	95%
Zone 1 - Auckland	H1 5th ed reference w.out eav	9.2	10.4	8.9	7.6	10.3	8.7	9.7	113%	97%	82%	111%	95%	106%
Zone 1 - Auckland	H1 5th ed calculation	7.7	7.8	7.7	5.5	6.4	6.6	5.8	101%	100%	71%	84%	86%	76%
Zone 1 - Auckland	H1 5th ed modelling	9.9	9.9	9.9	7.0	7.7	7.8	6.5	100%	100%	70%	78%	78%	65%
Zone 1 - Auckland	Cost effective (Q3)	10.8	11.0	10.8	7.9	8.8	8.7	7.5	101%	100%	73%	82%	81%	70%
Zone 1 - Auckland	Alt. compliant cost effective	6.7	6.8	6.7	4.7	5.5	5.5	5.0	101%	100%	70%	82%	82%	74%
Zone 2 - Napier	H1 4th ed schedule	19.3	19.1	19.5	13.9	15.0	16.9	12.8	99%	101%	72%	78%	88%	66%
Zone 2 - Napier	H1 5th ed schedule	11.4	11.1	11.6	7.9	7.9	9.7	7.2	98%	102%	69%	70%	85%	63%
Zone 2 - Napier	H1 5th ed reference	13.4	13.6	13.6	9.8	11.3	12.0	10.2	102%	101%	73%	84%	89%	76%
Zone 2 - Napier	H1 5th ed reference w.out eav	14.6	15.7	14.7	11.2	13.5	13.4	12.4	108%	101%	77%	93%	92%	85%
Zone 2 - Napier	H1 5th ed calculation	14.2	13.9	14.4	9.9	10.3	12.4	9.1	98%	101%	70%	73%	87%	64%
Zone 2 - Napier	H1 5th ed modelling	14.7	14.3	14.9	10.1	10.1	11.0	7.9	97%	101%	69%	69%	75%	54%
Zone 2 - Napier	Cost effective (Q3)	19.6	19.3	19.8	14.0	14.9	15.8	11.8	99%	101%	71%	76%	80%	60%
Zone 2 - Napier	Alt. compliant cost effective	12.8	12.5	13.0	8.9	9.0	10.7	7.8	98%	102%	69%	70%	83%	61%
Zone 3 - Wellington	H1 4th ed schedule	21.2	20.6	21.4	14.9	15.8	17.9	12.6	97%	101%	71%	75%	84%	60%
Zone 3 - Wellington	H1 5th ed schedule	13.2	12.8	13.3	8.9	8.3	10.8	6.9	97%	101%	67%	63%	82%	53%
Zone 3 - Wellington	H1 5th ed reference	14.1	13.9	14.3	9.8	10.7	12.0	9.5	98%	101%	70%	76%	85%	67%
Zone 3 - Wellington	H1 5th ed reference w.out eav	14.1	14.3	14.3	10.0	11.9	12.2	11.2	101%	101%	71%	84%	86%	79%
Zone 3 - Wellington	H1 5th ed calculation	16.1	15.4	16.2	10.9	10.9	13.5	9.0	96%	101%	68%	68%	84%	56%
Zone 3 - Wellington	H1 5th ed modelling	15.0	14.4	15.2	10.2	9.8	12.0	7.8	96%	101%	68%	65%	80%	52%
Zone 3 - Wellington	Cost effective (Q3)	22.4	21.7	22.5	15.8	16.6	17.1	11.9	97%	101%	71%	74%	76%	53%
Zone 3 - Wellington	Alt. compliant cost effective	15.0	14.4	15.2	10.2	9.8	12.0	7.8	96%	101%	68%	65%	80%	52%
Zone 4 - Taupo	H1 4th ed schedule	32.9	32.0	33.1	23.5	23.7	28.1	18.9	97%	101%	71%	72%	85%	58%
Zone 4 - Taupo	H1 5th ed schedule	23.3	22.5	23.5	16.2	14.8	19.7	12.4	97%	101%	69%	63%	85%	53%
Zone 4 - Taupo	H1 5th ed reference	24.5	24.0	24.8	17.3	17.2	21.2	14.9	98%	101%	71%	70%	86%	61%
Zone 4 - Taupo	H1 5th ed reference w.out eav	24.3	24.2	24.5	17.4	18.2	21.3	16.4	100%	101%	71%	75%	88%	67%
Zone 4 - Taupo	H1 5th ed calculation	27.0	26.2	27.1	18.8	18.0	23.2	14.8	97%	101%	70%	67%	86%	55%
Zone 4 - Taupo	H1 5th ed modelling	25.5	24.4	25.6	17.9	16.7	21.7	14.0	96%	101%	70%	66%	85%	55%
Zone 4 - Taupo	Cost effective (Q3)	29.8	28.7	29.9	20.9	20.4	25.0	16.0	96%	101%	70%	68%	84%	54%
Zone 4 - Taupo	Alt. compliant cost effective	26.0	24.9	26.2	18.2	17.1	21.5	13.6	96%	101%	70%	66%	82%	52%
Zone 5 - Christchurch	H1 4th ed schedule	36.8	35.9	37.0	26.7	26.7	32.0	21.6	97%	101%	73%	72%	87%	59%
Zone 5 - Christchurch	H1 5th ed schedule	26.0	25.3	26.2	18.4	16.6	22.4	14.1	97%	101%	70%	64%	86%	54%
Zone 5 - Christchurch	H1 5th ed reference	27.2	26.6	27.4	19.4	19.0	23.8	16.5	98%	101%	71%	70%	88%	61%
Zone 5 - Christchurch	H1 5th ed reference w.out eav	26.9	26.6	27.2	19.3	19.7	23.7	17.6	99%	101%	72%	73%	88%	66%
Zone 5 - Christchurch	H1 5th ed calculation	28.9	27.9	29.1	20.7	19.2	25.1	16.3	96%	101%	71%	66%	87%	56%
Zone 5 - Christchurch	H1 5th ed modelling	28.1	27.1	28.3	20.0	18.5	24.4	15.6	96%	101%	71%	66%	87%	55%
Zone 5 - Christchurch	Cost effective (Q3)	33.4	32.3	33.6	23.8	23.2	28.6	18.5	97%	101%	71%	69%	86%	55%
Zone 5 - Christchurch	Alt. compliant cost effective	28.1	27.1	28.3	20.0	18.5	24.4	15.6	96%	101%	71%	66%	87%	55%
Zone 6 - Queenstown	H1 4th ed schedule	50.8	49.3	51.1	36.8	37.3	44.0	33.5	97%	101%	72%	73%	87%	66%
Zone 6 - Queenstown	H1 5th ed schedule	38.0	36.8	38.3	27.2	24.7	30.5	23.8	97%	101%	72%	65%	80%	63%
Zone 6 - Queenstown	H1 5th ed reference	38.7	37.5	39.2	27.8	26.8	31.7	24.7	97%	101%	72%	69%	82%	64%
Zone 6 - Queenstown	H1 5th ed reference w.out eav	37.7	36.8	38.1	27.0	26.9	31.1	24.1	98%	101%	72%	71%	83%	64%
Zone 6 - Queenstown	H1 5th ed calculation	38.7	37.5	38.9	27.6	25.7	33.3	24.3	97%	101%	71%	66%	86%	63%
Zone 6 - Queenstown	H1 5th ed modelling	38.7	37.5	38.9	27.6	25.7	33.3	24.3	97%	101%	71%	66%	86%	63%
Zone 6 - Queenstown	Cost effective (Q3)	40.6	39.0	40.8	29.0	27.6	35.2	25.7	96%	101%	71%	68%	87%	63%
Zone 6 - Queenstown	Alt. compliant cost effective	35.7	34.1	36.0	25.5	23.1	30.5	22.2	95%	101%	71%	65%	85%	62%

Figure 66: Single-storey house – sensitivity analysis on resulting total delivered energy use for the different construction sets

Double Storey		Delivered Total (kWh/m2)												
		M1	M2	M3	M4	M5	M6	M7						
Climate	Label	Baseline	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings
Zone 1 - Auckland	H1 4th ed schedule	11.8	12.3	11.5	9.9	9.7	11.4	10.1	105%	98%	84%	82%	97%	86%
Zone 1 - Auckland	H1 5th ed schedule	6.7	6.8	6.5	5.7	5.1	6.4	5.9	102%	97%	85%	77%	95%	88%
Zone 1 - Auckland	H1 5th ed reference	11.7	13.1	11.2	10.6	11.5	11.6	12.0	112%	96%	91%	98%	99%	102%
Zone 1 - Auckland	H1 5th ed reference w.out eav	12.9	14.8	12.4	11.8	13.3	12.8	13.7	115%	96%	91%	103%	99%	106%
Zone 1 - Auckland	H1 5th ed calculation	8.9	9.2	8.6	7.4	7.1	8.6	7.7	104%	97%	84%	81%	97%	87%
Zone 1 - Auckland	H1 5th ed modelling	12.4	13.0	12.1	10.4	10.3	11.9	10.5	104%	98%	84%	83%	96%	85%
Zone 1 - Auckland	Cost effective (Q3)	11.5	12.0	11.2	9.6	9.5	11.0	9.9	105%	97%	84%	83%	96%	86%
Zone 1 - Auckland	Alt. compliant cost effective	8.2	8.6	8.0	6.9	6.6	7.9	7.2	104%	97%	84%	80%	96%	88%
Zone 2 - Napier	H1 4th ed schedule	20.1	20.4	20.0	16.5	15.3	19.4	15.7	102%	100%	82%	76%	97%	78%
Zone 2 - Napier	H1 5th ed schedule	12.3	12.2	12.3	10.1	8.0	11.7	9.3	99%	100%	82%	65%	95%	76%
Zone 2 - Napier	H1 5th ed reference	18.5	19.9	18.3	16.0	15.6	18.1	16.3	108%	99%	86%	84%	98%	88%
Zone 2 - Napier	H1 5th ed reference w.out eav	19.8	21.8	19.5	17.2	17.5	19.5	18.0	110%	98%	87%	88%	98%	91%
Zone 2 - Napier	H1 5th ed calculation	15.6	15.7	15.6	12.8	11.1	15.1	12.1	100%	100%	82%	71%	97%	78%
Zone 2 - Napier	H1 5th ed modelling	21.0	21.4	20.9	17.1	16.1	20.0	16.2	102%	100%	82%	77%	95%	77%
Zone 2 - Napier	Cost effective (Q3)	16.3	16.3	16.3	13.2	11.5	15.3	12.2	100%	100%	81%	71%	94%	75%
Zone 2 - Napier	Alt. compliant cost effective	14.6	14.7	14.6	12.0	10.2	14.1	11.3	100%	100%	82%	70%	96%	77%
Zone 3 - Wellington	H1 4th ed schedule	19.9	19.5	19.9	16.1	14.6	18.8	14.7	98%	100%	81%	73%	95%	74%
Zone 3 - Wellington	H1 5th ed schedule	12.4	11.9	12.4	10.0	7.4	11.5	8.5	96%	100%	81%	60%	93%	69%
Zone 3 - Wellington	H1 5th ed reference	16.2	16.7	16.2	13.6	13.1	15.6	13.7	103%	100%	84%	81%	96%	84%
Zone 3 - Wellington	H1 5th ed reference w.out eav	16.5	17.3	16.5	13.9	14.2	15.9	14.7	105%	100%	84%	86%	96%	89%
Zone 3 - Wellington	H1 5th ed calculation	15.6	15.1	15.6	12.5	10.5	14.9	11.3	97%	100%	80%	67%	96%	72%
Zone 3 - Wellington	H1 5th ed modelling	18.4	18.1	18.5	14.9	13.3	17.0	13.3	98%	100%	81%	72%	92%	72%
Zone 3 - Wellington	Cost effective (Q3)	19.5	19.2	19.6	15.8	14.3	18.1	14.2	98%	100%	81%	73%	93%	73%
Zone 3 - Wellington	Alt. compliant cost effective	14.8	14.3	14.9	11.9	9.7	14.0	10.6	96%	100%	81%	66%	94%	71%
Zone 4 - Taupo	H1 4th ed schedule	32.5	31.9	32.5	26.6	23.0	31.0	23.3	98%	100%	82%	71%	95%	72%
Zone 4 - Taupo	H1 5th ed schedule	22.8	22.1	22.8	18.8	14.0	21.6	15.7	97%	100%	83%	61%	95%	69%
Zone 4 - Taupo	H1 5th ed reference	27.6	27.9	27.5	23.1	20.1	26.7	21.1	101%	100%	84%	73%	97%	76%
Zone 4 - Taupo	H1 5th ed reference w.out eav	28.2	28.8	28.1	23.7	21.4	27.3	22.2	102%	99%	84%	76%	97%	79%
Zone 4 - Taupo	H1 5th ed calculation	27.6	26.8	27.6	22.6	18.5	26.6	19.7	97%	100%	82%	67%	96%	71%
Zone 4 - Taupo	H1 5th ed modelling	30.2	29.3	30.2	24.6	20.6	28.0	20.7	97%	100%	81%	68%	93%	68%
Zone 4 - Taupo	Cost effective (Q3)	29.2	28.3	29.2	23.9	19.7	27.1	20.0	97%	100%	82%	68%	93%	68%
Zone 4 - Taupo	Alt. compliant cost effective	25.1	24.2	25.1	20.7	16.2	23.9	17.6	97%	100%	83%	65%	95%	70%
Zone 5 - Christchurch	H1 4th ed schedule	35.8	35.4	35.9	29.5	25.8	34.4	26.2	99%	100%	82%	72%	96%	73%
Zone 5 - Christchurch	H1 5th ed schedule	24.7	24.1	24.8	20.4	15.3	23.5	17.2	98%	100%	83%	62%	95%	70%
Zone 5 - Christchurch	H1 5th ed reference	30.1	30.6	30.0	25.3	22.0	29.2	23.2	102%	100%	84%	73%	97%	77%
Zone 5 - Christchurch	H1 5th ed reference w.out eav	30.8	31.6	30.7	26.0	23.2	29.9	24.3	103%	100%	85%	76%	97%	79%
Zone 5 - Christchurch	H1 5th ed calculation	26.4	25.7	26.5	21.7	17.1	25.3	18.6	97%	100%	82%	65%	96%	70%
Zone 5 - Christchurch	H1 5th ed modelling	33.3	32.5	33.4	27.2	23.1	31.2	23.3	98%	100%	82%	69%	94%	70%
Zone 5 - Christchurch	Cost effective (Q3)	32.3	31.5	32.4	26.5	22.2	30.2	22.6	98%	100%	82%	69%	94%	70%
Zone 5 - Christchurch	Alt. compliant cost effective	27.6	27.0	27.7	22.9	18.2	26.7	19.9	98%	100%	83%	66%	97%	72%
Zone 6 - Queenstown	H1 4th ed schedule	48.2	47.2	48.3	39.8	34.8	46.2	34.7	98%	100%	83%	72%	96%	72%
Zone 6 - Queenstown	H1 5th ed schedule	34.6	33.7	34.6	28.8	22.0	33.5	24.2	98%	100%	83%	64%	97%	70%
Zone 6 - Queenstown	H1 5th ed reference	39.2	39.2	39.2	33.0	28.2	38.2	30.5	100%	100%	84%	72%	97%	78%
Zone 6 - Queenstown	H1 5th ed reference w.out eav	39.8	40.1	39.8	33.6	29.4	38.8	31.9	101%	100%	84%	74%	98%	80%
Zone 6 - Queenstown	H1 5th ed calculation	36.5	35.2	36.5	30.1	23.9	34.9	25.0	96%	100%	83%	65%	96%	69%
Zone 6 - Queenstown	H1 5th ed modelling	42.5	41.2	42.6	35.1	29.3	40.8	29.8	97%	100%	83%	69%	96%	70%
Zone 6 - Queenstown	Cost effective (Q3)	36.2	34.9	36.2	29.9	23.6	34.6	24.8	96%	100%	83%	65%	96%	69%

Figure 67: Double-storey house – sensitivity analysis on resulting total delivered energy use for the different construction sets

Medium Density		Delivered Total (kWh/m2)												
		M1	M2	M3	M4	M5	M6	M7						
Climate	Label	Baseline	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings
Zone 1 - Auckland	H1 4th ed schedule	8.5	8.9	8.6	7.7	7.2	8.4	8.3	104%	100%	91%	85%	98%	98%
Zone 1 - Auckland	H1 5th ed schedule	4.3	4.4	4.4	3.9	3.9	4.2	4.6	102%	101%	90%	90%	97%	107%
Zone 1 - Auckland	H1 5th ed reference	8.4	9.8	8.0	8.0	9.5	8.3	10.0	117%	96%	96%	113%	99%	120%
Zone 1 - Auckland	H1 5th ed reference w.out eav	10.6	13.0	9.9	10.4	13.2	10.7	13.6	122%	93%	98%	124%	101%	128%
Zone 1 - Auckland	H1 5th ed calculation	5.7	5.9	5.8	5.2	4.9	5.6	5.8	104%	101%	90%	86%	98%	102%
Zone 1 - Auckland	H1 5th ed modelling	8.5	8.8	8.6	7.7	7.2	8.2	8.2	103%	100%	90%	84%	97%	97%
Zone 1 - Auckland	Cost effective (Q3)	7.8	8.1	7.8	7.0	6.6	7.5	7.7	104%	101%	90%	85%	97%	99%
Zone 1 - Auckland	Alt. compliant cost effective	5.3	5.6	5.4	4.8	4.7	5.2	5.5	104%	101%	90%	88%	98%	104%
Zone 2 - Napier	H1 4th ed schedule	14.6	14.5	14.8	13.0	10.6	14.3	12.5	99%	101%	89%	73%	98%	86%
Zone 2 - Napier	H1 5th ed schedule	8.2	8.0	8.4	7.2	5.1	7.9	6.8	98%	102%	88%	63%	97%	83%
Zone 2 - Napier	H1 5th ed reference	12.4	13.6	12.4	11.4	11.2	12.2	12.6	110%	100%	92%	91%	99%	102%
Zone 2 - Napier	H1 5th ed reference w.out eav	14.2	16.4	13.8	13.3	14.6	14.1	15.8	116%	97%	94%	103%	100%	111%
Zone 2 - Napier	H1 5th ed calculation	10.4	10.2	10.6	9.2	6.9	10.2	8.8	98%	102%	89%	67%	98%	85%
Zone 2 - Napier	H1 5th ed modelling	14.6	14.5	14.8	13.0	10.5	14.1	12.3	99%	101%	89%	72%	96%	84%
Zone 2 - Napier	Cost effective (Q3)	13.4	13.3	13.6	11.9	9.6	12.9	11.4	99%	102%	89%	72%	96%	85%
Zone 2 - Napier	Alt. compliant cost effective	9.7	9.5	9.9	8.7	6.5	9.6	8.3	98%	102%	89%	66%	98%	85%
Zone 3 - Wellington	H1 4th ed schedule	15.0	14.5	15.2	13.4	10.2	14.6	12.1	96%	101%	89%	68%	97%	80%
Zone 3 - Wellington	H1 5th ed schedule	8.7	8.2	8.7	7.6	4.5	8.3	6.3	95%	101%	87%	52%	96%	72%
Zone 3 - Wellington	H1 5th ed reference	10.8	11.0	11.0	9.6	8.8	10.5	11.1	102%	102%	89%	82%	97%	103%
Zone 3 - Wellington	H1 5th ed reference w.out eav	10.6	11.6	10.6	9.6	10.6	10.4	13.6	110%	100%	91%	100%	98%	128%
Zone 3 - Wellington	H1 5th ed calculation	11.0	10.3	11.1	9.7	6.4	10.7	8.4	94%	101%	88%	59%	98%	76%
Zone 3 - Wellington	H1 5th ed modelling	11.6	10.9	11.7	10.2	6.8	10.9	8.5	94%	101%	88%	59%	94%	73%
Zone 3 - Wellington	Cost effective (Q3)	14.1	13.6	14.3	12.5	9.4	13.4	11.0	96%	101%	89%	66%	95%	78%
Zone 3 - Wellington	Alt. compliant cost effective	10.4	9.7	10.5	9.2	6.0	10.1	7.9	94%	101%	88%	58%	97%	76%
Zone 4 - Taupo	H1 4th ed schedule	24.0	23.3	24.1	21.7	15.7	23.5	18.7	97%	100%	90%	65%	98%	78%
Zone 4 - Taupo	H1 5th ed schedule	16.2	15.5	16.2	14.6	8.7	15.7	11.7	96%	100%	90%	54%	97%	72%
Zone 4 - Taupo	H1 5th ed reference	19.6	19.7	19.7	17.8	13.8	19.2	17.3	101%	100%	90%	71%	98%	88%
Zone 4 - Taupo	H1 5th ed reference w.out eav	19.8	20.6	19.6	18.1	15.3	19.5	19.3	104%	99%	91%	77%	98%	97%
Zone 4 - Taupo	H1 5th ed calculation	19.1	18.4	19.1	17.2	11.0	18.6	14.1	96%	100%	90%	58%	97%	74%
Zone 4 - Taupo	H1 5th ed modelling	21.0	20.0	21.1	18.9	12.8	20.5	15.7	95%	100%	90%	61%	98%	75%
Zone 4 - Taupo	Cost effective (Q3)	21.1	20.1	21.2	19.0	12.8	20.1	15.4	95%	100%	90%	61%	95%	73%
Zone 4 - Taupo	Alt. compliant cost effective	18.8	17.9	18.9	17.0	11.0	18.5	14.1	95%	100%	90%	59%	98%	75%
Zone 5 - Christchurch	H1 4th ed schedule	27.1	26.3	27.3	24.6	17.8	26.6	21.1	97%	101%	91%	66%	98%	78%
Zone 5 - Christchurch	H1 5th ed schedule	17.9	17.3	18.0	16.2	9.6	17.4	13.0	97%	101%	90%	54%	98%	73%
Zone 5 - Christchurch	H1 5th ed reference	21.2	21.4	21.4	19.3	14.8	20.9	18.6	101%	101%	91%	70%	98%	88%
Zone 5 - Christchurch	H1 5th ed reference w.out eav	21.5	22.6	21.4	19.8	16.5	21.3	21.0	105%	100%	92%	76%	99%	98%
Zone 5 - Christchurch	H1 5th ed calculation	21.4	20.8	21.6	19.4	12.5	21.1	16.0	97%	101%	91%	58%	98%	75%
Zone 5 - Christchurch	H1 5th ed modelling	23.0	22.1	23.2	20.9	14.0	22.7	17.4	96%	101%	91%	61%	98%	75%
Zone 5 - Christchurch	Cost effective (Q3)	23.7	22.7	23.9	21.5	14.5	22.8	17.5	96%	101%	90%	61%	96%	74%
Zone 5 - Christchurch	Alt. compliant cost effective	20.1	19.2	20.3	18.2	11.5	19.8	14.9	95%	101%	91%	57%	98%	74%
Zone 6 - Queenstown	H1 4th ed schedule	37.2	35.8	37.4	34.0	24.8	36.5	28.8	96%	101%	91%	67%	98%	78%
Zone 6 - Queenstown	H1 5th ed schedule	25.6	24.6	25.7	23.4	14.2	25.0	18.6	96%	101%	91%	55%	98%	73%
Zone 6 - Queenstown	H1 5th ed reference	29.2	28.9	29.4	26.7	19.8	28.6	24.4	99%	101%	92%	68%	98%	84%
Zone 6 - Queenstown	H1 5th ed reference w.out eav	28.9	29.4	28.8	26.6	20.9	28.4	26.2	102%	100%	92%	72%	98%	91%
Zone 6 - Queenstown	H1 5th ed calculation	29.9	28.9	30.1	27.4	17.9	29.5	22.5	97%	101%	92%	60%	98%	75%
Zone 6 - Queenstown	H1 5th ed modelling	30.3	29.3	30.4	27.7	18.2	29.6	22.6	97%	101%	92%	60%	98%	75%
Zone 6 - Queenstown	Cost effective (Q3)	32.3	30.8	32.5	29.6	20.1	31.6	24.2	95%	101%	92%	62%	98%	75%
Zone 6 - Queenstown	Alt. compliant cost effective	28.3	26.9	28.5	25.9	16.7	27.9	21.0	95%	101%	91%	59%	98%	74%

Figure 68: Medium-density house – sensitivity analysis on resulting total delivered energy use for the different construction sets

Apartment		Delivered Total (kWh/m2)										
		M1	M2	M3	M4	M5	M6					
Climate	Label	Baseline	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Combined lower savings	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Combined lower savings
Zone 1 - Auckland	H1 4th ed schedule	11.5	12.4	11.4	11.6	11.3	12.0	108%	99%	101%	98%	104%
Zone 1 - Auckland	H1 5th ed schedule	6.8	7.3	6.8	6.9	7.0	7.4	107%	100%	101%	103%	108%
Zone 1 - Auckland	H1 5th ed reference	4.9	5.0	5.0	5.0	4.7	5.2	102%	102%	101%	95%	106%
Zone 1 - Auckland	H1 5th ed reference w.out eav	4.9	5.2	5.1	4.9	5.4	5.7	105%	103%	100%	110%	115%
Zone 1 - Auckland	H1 5th ed calculation	4.9	5.1	4.9	4.9	5.3	5.6	106%	101%	101%	108%	114%
Zone 1 - Auckland	H1 5th ed modelling	4.5	4.6	4.6	4.6	4.4	4.9	102%	102%	101%	98%	108%
Zone 1 - Auckland	Cost effective (Q3)	11.4	12.2	11.3	11.5	11.2	11.8	108%	99%	101%	98%	104%
Zone 2 - Napier	H1 4th ed schedule	19.3	20.1	19.3	19.3	18.3	19.4	104%	100%	100%	95%	101%
Zone 2 - Napier	H1 5th ed schedule	12.3	12.7	12.4	12.4	11.6	12.5	103%	101%	100%	94%	101%
Zone 2 - Napier	H1 5th ed reference	9.9	9.9	10.0	10.0	8.7	9.8	100%	101%	101%	88%	99%
Zone 2 - Napier	H1 5th ed reference w.out eav	9.6	9.6	9.8	9.6	9.0	9.8	101%	102%	100%	94%	103%
Zone 2 - Napier	H1 5th ed calculation	9.3	9.5	9.4	9.3	8.7	9.5	102%	101%	101%	94%	102%
Zone 2 - Napier	H1 5th ed modelling	9.2	9.2	9.4	9.3	8.1	9.1	100%	102%	101%	88%	99%
Zone 2 - Napier	Cost effective (Q3)	14.3	15.0	14.3	14.3	13.4	14.4	105%	100%	100%	94%	101%
Zone 3 - Wellington	H1 4th ed schedule	19.1	19.2	19.1	19.2	17.7	19.0	101%	100%	100%	93%	100%
Zone 3 - Wellington	H1 5th ed schedule	11.5	11.5	11.5	11.6	10.3	11.4	100%	101%	101%	90%	99%
Zone 3 - Wellington	H1 5th ed reference	9.7	9.5	9.8	9.8	8.0	9.3	98%	101%	101%	83%	96%
Zone 3 - Wellington	H1 5th ed reference w.out eav	8.9	8.7	9.0	8.9	7.7	8.7	98%	101%	100%	86%	98%
Zone 3 - Wellington	H1 5th ed calculation	8.3	8.3	8.4	8.4	7.2	8.3	100%	101%	101%	87%	99%
Zone 3 - Wellington	H1 5th ed modelling	8.3	8.3	8.4	8.4	7.2	8.3	100%	101%	101%	87%	99%
Zone 3 - Wellington	Cost effective (Q3)	13.8	13.9	13.9	13.9	12.5	13.7	100%	100%	101%	90%	99%
Zone 4 - Taupo	H1 4th ed schedule	30.2	30.2	30.2	30.4	27.8	29.7	100%	100%	101%	92%	98%
Zone 4 - Taupo	H1 5th ed schedule	20.5	20.4	20.6	20.7	18.2	20.0	99%	100%	101%	89%	98%
Zone 4 - Taupo	H1 5th ed reference	18.0	17.6	18.1	18.3	15.3	17.4	98%	100%	101%	85%	96%
Zone 4 - Taupo	H1 5th ed reference w.out eav	17.0	16.6	17.1	17.1	14.7	16.5	98%	101%	101%	87%	97%
Zone 4 - Taupo	H1 5th ed calculation	16.1	15.9	16.2	16.2	13.8	15.6	99%	101%	101%	86%	97%
Zone 4 - Taupo	H1 5th ed modelling	16.1	15.9	16.2	16.2	13.8	15.6	99%	101%	101%	86%	97%
Zone 4 - Taupo	Cost effective (Q3)	23.5	23.5	23.6	23.7	21.1	23.0	100%	100%	101%	90%	98%
Zone 5 - Christchurch	H1 4th ed schedule	33.3	33.2	33.3	33.5	30.6	32.8	100%	100%	101%	92%	98%
Zone 5 - Christchurch	H1 5th ed schedule	21.9	21.8	22.0	22.2	19.4	21.4	99%	100%	101%	88%	97%
Zone 5 - Christchurch	H1 5th ed reference	19.5	19.1	19.6	19.7	16.6	18.7	98%	101%	101%	85%	96%
Zone 5 - Christchurch	H1 5th ed reference w.out eav	18.6	18.3	18.8	18.8	16.1	18.0	98%	101%	101%	86%	97%
Zone 5 - Christchurch	H1 5th ed calculation	18.2	18.1	18.3	18.4	15.7	17.6	99%	101%	101%	86%	97%
Zone 5 - Christchurch	H1 5th ed modelling	18.2	18.1	18.3	18.4	15.7	17.6	99%	101%	101%	86%	97%
Zone 5 - Christchurch	Cost effective (Q3)	26.1	26.0	26.2	26.3	23.4	25.5	100%	100%	101%	90%	98%
Zone 6 - Queenstown	H1 4th ed schedule	44.1	43.8	44.1	44.4	40.6	43.3	99%	100%	101%	92%	98%
Zone 6 - Queenstown	H1 5th ed schedule	30.2	29.9	30.3	30.5	26.9	29.4	99%	100%	101%	89%	97%
Zone 6 - Queenstown	H1 5th ed reference	27.4	26.8	27.5	27.8	23.7	26.5	98%	100%	101%	86%	96%
Zone 6 - Queenstown	H1 5th ed reference w.out eav	26.0	25.4	26.1	26.3	22.6	25.1	98%	100%	101%	87%	97%
Zone 6 - Queenstown	H1 5th ed calculation	25.4	25.1	25.5	25.8	22.1	24.6	99%	100%	101%	87%	97%
Zone 6 - Queenstown	H1 5th ed modelling	25.4	25.1	25.5	25.8	22.1	24.6	99%	100%	101%	87%	97%
Zone 6 - Queenstown	Cost effective (Q3)	33.5	33.1	33.6	33.9	30.1	32.7	99%	100%	101%	90%	98%

Figure 69: Apartment building – sensitivity analysis on resulting total delivered energy use for the different construction sets

Total energy use, however, is not actually what determines the results of the cost-benefit analysis. To understand how these model assumptions might affect that, we instead want to look at how they affect the calculated *differences* between models – specifically, the difference in energy use compared to our baseline H1/AS1 5th edition schedule method model. The impacts here vary somewhat idiosyncratically from the effects on overall energy use (Figure 70 to Figure 73). Looking at the difference in modelled energy use compared to that of the H1/AS1 5th edition schedule model (the key comparison used for the cost-benefit analysis), we see a variety of changes:

- **Dark window frames**: First, using dark window frames could significantly affect the differences in energy use for some of the lower-cost models in the warmer climates – the extra energy use they need increases by ~10–20%, particularly in Auckland. This is due to aluminium window frames letting in more heat and increasing cooling use more compared to thermally broken ones. At the same time, we also see the opposite effect in colder climates where increased heat gain through aluminium frames can help mitigate heat loss. Second, using dark window frames would have significantly increased the extra energy needed in the reference model(s) by around 20–80% and made compliance much easier. We tried to avoid taking advantage of this in the main analysis, but it would be entirely valid and illustrates how impactful this factor can be for compliance.

- **No mixing:** Despite disabling mixing having minor effects at most on overall energy use, the differences between models occasionally change more significantly. The houses see minimal impact with the exception of the lowest-cost modelling method option for the single-storey house in Queenstown, which has the difference between it and the schedule method model drop by ~12%. In this case, it seems to be due to the differences being very small overall, so small changes can produce large relative effects.
- **Heating only during occupied hours:** Reducing the heating schedules produces significant reductions in the differences between the models and thus the energy savings from insulation which varying from ~10–30% depending on the model and climate zone.
- **Low ventilation + airtightness:** Reducing ventilation significantly increases the extra energy needed in the reference models in the order of +30–200% due to the increased cooling, which would make compliance much easier and allow significantly lower insulation levels to comply, again highlighting why we tried to minimise our ability to exploit this with aggressive ventilation assumptions in the main analysis. Reducing ventilation tends to reduce the differences between the schedule method model and alternatives in the order of 5–20%, though this can vary significantly. For example, in the single-storey house in Queenstown, the reduction in ventilation makes the differences larger. These variations appear to relate to how much the overall difference between models stem from heating differences or cooling differences and depends on the specifics of the situation. Overall, a general tendency to reducing the observed savings/costs of insulation changes but with a lot of complex interactions.
- **Lower soil conductivity:** Reducing soil conductivity increases the differences with the reference models (because cooling use is higher). Comparing the different H1-compliant options, reducing soil conductivity has a range of effects depending on the model. The largest effects are seen in the single-storey model with the largest slab. It mostly shows reductions in the differences in the order of 5–60% as a result of the reduced slab heat loss. One exception here is the single-storey house in Queenstown where the various lower-cost options have their energy cost relative to the current schedule method model increase significantly instead. The key difference here is that the schedule method model in Queenstown also had edge insulation. The reduction in soil conductivity and core slab heat loss is resulting in an increase to the heat losses through the slab edge to the outdoor air, which increases the effect of edge insulation. These effects can be seen in the double-storey house too, which also used edge insulation in the schedule method model. Effects are smaller on the multi-storey houses as the slab has less of an effect on overall energy use.
- **Combined:** Attempting to combine the assumptions did not always have the intended effect. In many cases, it appears that interactions meant that the difference between models with the combined assumptions was not always smaller than the difference with a single assumption change. This was also partly because the assumptions did not affect all the model differences the same way and so combinations that reduce the differences with one model may not do the same to another. As a result, for illustrating the impact of the model assumptions on the cost-benefit analysis, we simply selected the option that produced the smallest energy saving/cost for each model.

Single Storey		Difference relative to H1 5th ed												
Climate	H1 5th ed reference	Baseline	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings
Zone 1 - Auckland	H1 4th ed schedule	5.1	5.2	5.0	4.0	4.3	4.6	3.6	104%	99%	79%	86%	91%	71%
Zone 1 - Auckland	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 1 - Auckland	H1 5th ed reference	1.9	2.4	1.7	1.9	2.9	2.1	2.8	125%	90%	101%	152%	111%	146%
Zone 1 - Auckland	H1 5th ed reference w.out eav	3.3	4.5	3.0	3.5	5.3	3.8	5.1	135%	90%	104%	158%	114%	154%
Zone 1 - Auckland	H1 5th ed calculation	1.8	1.9	1.8	1.3	1.4	1.7	1.2	104%	100%	75%	80%	93%	68%
Zone 1 - Auckland	H1 5th ed modelling	4.1	4.1	4.0	2.9	2.7	2.8	1.9	100%	100%	71%	67%	69%	46%
Zone 1 - Auckland	Cost effective (Q3)	5.0	5.1	4.9	3.8	3.8	3.8	2.9	102%	99%	76%	77%	76%	59%
Zone 1 - Auckland	Alt. compliant cost effective	0.8	0.9	0.8	0.6	0.5	0.5	0.4	108%	99%	72%	57%	66%	44%
Zone 2 - Napier	H1 4th ed schedule	7.9	7.9	7.9	6.0	7.1	7.2	5.6	101%	100%	76%	90%	91%	71%
Zone 2 - Napier	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 2 - Napier	H1 5th ed reference	2.0	2.4	2.0	2.0	3.3	2.2	3.1	123%	100%	99%	166%	111%	153%
Zone 2 - Napier	H1 5th ed reference w.out eav	3.2	4.5	3.1	3.3	5.6	3.7	5.3	143%	98%	105%	177%	115%	166%
Zone 2 - Napier	H1 5th ed calculation	2.8	2.8	2.8	2.1	2.4	2.7	1.9	99%	100%	73%	84%	94%	69%
Zone 2 - Napier	H1 5th ed modelling	3.3	3.1	3.3	2.2	2.2	1.3	0.7	96%	100%	68%	67%	40%	22%
Zone 2 - Napier	Cost effective (Q3)	8.2	8.2	8.2	6.1	7.0	6.0	4.6	100%	100%	75%	86%	74%	56%
Zone 2 - Napier	Alt. compliant cost effective	1.4	1.4	1.4	1.0	1.0	0.9	0.6	96%	101%	73%	73%	66%	45%
Zone 3 - Wellington	H1 4th ed schedule	8.0	7.8	8.0	6.1	7.5	7.1	5.7	98%	100%	76%	94%	89%	71%
Zone 3 - Wellington	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 3 - Wellington	H1 5th ed reference	0.9	1.1	1.0	1.0	2.4	1.2	2.6	122%	107%	104%	260%	126%	278%
Zone 3 - Wellington	H1 5th ed reference w.out eav	0.9	1.6	1.0	1.2	3.6	1.4	4.3	171%	109%	126%	387%	153%	461%
Zone 3 - Wellington	H1 5th ed calculation	2.9	2.6	2.9	2.1	2.6	2.7	2.0	92%	101%	72%	89%	94%	71%
Zone 3 - Wellington	H1 5th ed modelling	1.8	1.6	1.8	1.4	1.5	1.2	0.9	88%	101%	76%	84%	65%	50%
Zone 3 - Wellington	Cost effective (Q3)	9.2	8.9	9.2	6.9	8.3	6.3	5.0	98%	100%	76%	91%	68%	54%
Zone 3 - Wellington	Alt. compliant cost effective	1.8	1.6	1.8	1.4	1.5	1.2	0.9	88%	101%	76%	84%	65%	50%
Zone 4 - Taupo	H1 4th ed schedule	9.6	9.4	9.7	7.3	8.9	8.4	6.6	98%	100%	76%	92%	88%	68%
Zone 4 - Taupo	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 4 - Taupo	H1 5th ed reference	1.2	1.4	1.3	1.1	2.5	1.5	2.5	116%	107%	92%	205%	123%	210%
Zone 4 - Taupo	H1 5th ed reference w.out eav	1.0	1.6	1.0	1.2	3.4	1.6	4.0	166%	103%	117%	343%	157%	406%
Zone 4 - Taupo	H1 5th ed calculation	3.7	3.7	3.7	2.6	3.2	3.5	2.5	99%	100%	71%	87%	94%	67%
Zone 4 - Taupo	H1 5th ed modelling	2.1	1.8	2.1	1.7	1.9	2.0	1.6	86%	99%	78%	90%	94%	76%
Zone 4 - Taupo	Cost effective (Q3)	6.5	6.1	6.5	4.7	5.6	5.3	3.7	94%	100%	72%	87%	82%	57%
Zone 4 - Taupo	Alt. compliant cost effective	2.7	2.4	2.7	2.0	2.3	1.8	1.2	87%	100%	75%	84%	64%	44%
Zone 5 - Christchurch	H1 4th ed schedule	10.8	10.5	10.8	8.4	10.0	9.6	7.5	98%	100%	77%	93%	89%	69%
Zone 5 - Christchurch	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 5 - Christchurch	H1 5th ed reference	1.1	1.2	1.2	1.0	2.3	1.4	2.3	111%	108%	91%	208%	125%	207%
Zone 5 - Christchurch	H1 5th ed reference w.out eav	0.8	1.3	1.0	0.9	3.0	1.4	3.5	154%	115%	112%	364%	166%	420%
Zone 5 - Christchurch	H1 5th ed calculation	2.9	2.6	2.9	2.3	2.6	2.7	2.1	89%	99%	80%	88%	95%	73%
Zone 5 - Christchurch	H1 5th ed modelling	2.1	1.8	2.1	1.6	1.9	2.0	1.4	85%	100%	77%	91%	97%	70%
Zone 5 - Christchurch	Cost effective (Q3)	7.3	7.0	7.3	5.5	6.5	6.2	4.4	95%	100%	74%	89%	84%	60%
Zone 5 - Christchurch	Alt. compliant cost effective	2.1	1.8	2.1	1.6	1.9	2.0	1.4	85%	100%	77%	91%	97%	70%
Zone 6 - Queenstown	H1 4th ed schedule	12.8	12.5	12.8	9.6	12.7	13.5	9.7	98%	100%	75%	99%	105%	75%
Zone 6 - Queenstown	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 6 - Queenstown	H1 5th ed reference	0.7	0.7	0.9	0.6	2.1	1.2	0.9	103%	120%	81%	297%	167%	127%
Zone 6 - Queenstown	H1 5th ed reference w.out eav	-0.3	0.0	-0.2	-0.2	2.3	0.6	0.3	-3%	55%	59%	-655%	-175%	-87%
Zone 6 - Queenstown	H1 5th ed calculation	0.6	0.7	0.6	0.4	1.0	2.8	0.5	117%	88%	64%	159%	443%	74%
Zone 6 - Queenstown	H1 5th ed modelling	0.6	0.7	0.6	0.4	1.0	2.8	0.5	117%	88%	64%	159%	443%	74%
Zone 6 - Queenstown	Cost effective (Q3)	2.6	2.2	2.5	1.8	2.9	4.7	1.9	85%	97%	71%	112%	182%	74%
Zone 6 - Queenstown	Alt. compliant cost effective	-2.3	-2.7	-2.4	-1.7	-1.5	0.0	-1.6	116%	103%	73%	67%	0%	68%

Figure 70: Single-storey house – sensitivity analysis on resulting differences in delivered energy use for the different construction sets

Double Storey		Difference relative to H1 5th ed													
Climate	H1 5th ed reference	Baseline	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings
Zone 1 - Auckland	H1 4th ed schedule	5.1	5.5	5.0	4.3	4.6	5.0	4.2	109%	98%	84%	90%	99%	83%
Zone 1 - Auckland	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 1 - Auckland	H1 5th ed reference	5.0	6.2	4.7	4.9	6.3	5.2	6.1	126%	94%	98%	128%	104%	122%
Zone 1 - Auckland	H1 5th ed reference w.out eav	6.2	8.0	5.8	6.1	8.2	6.4	7.8	130%	95%	99%	132%	104%	126%
Zone 1 - Auckland	H1 5th ed calculation	2.1	2.4	2.1	1.8	2.0	2.2	1.8	111%	99%	82%	94%	102%	86%
Zone 1 - Auckland	H1 5th ed modelling	5.7	6.1	5.6	4.7	5.1	5.5	4.7	108%	98%	82%	90%	96%	82%
Zone 1 - Auckland	Cost effective (Q3)	4.7	5.2	4.6	3.9	4.3	4.5	4.0	109%	98%	84%	92%	96%	85%
Zone 1 - Auckland	Alt. compliant cost effective	1.5	1.7	1.5	1.2	1.4	1.5	1.3	115%	98%	82%	95%	100%	88%
Zone 2 - Napier	H1 4th ed schedule	7.8	8.2	7.7	6.4	7.2	7.7	6.4	106%	99%	82%	93%	98%	82%
Zone 2 - Napier	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 2 - Napier	H1 5th ed reference	6.2	7.7	6.0	5.9	7.6	6.4	7.0	124%	96%	94%	122%	103%	113%
Zone 2 - Napier	H1 5th ed reference w.out eav	7.5	9.6	7.2	7.1	9.4	7.7	8.7	128%	96%	95%	126%	103%	116%
Zone 2 - Napier	H1 5th ed calculation	3.3	3.5	3.3	2.7	3.1	3.4	2.8	105%	99%	81%	94%	103%	85%
Zone 2 - Napier	H1 5th ed modelling	8.7	9.1	8.6	7.0	8.1	8.3	6.9	105%	99%	81%	93%	95%	79%
Zone 2 - Napier	Cost effective (Q3)	4.0	4.1	4.0	3.1	3.4	3.5	2.9	103%	100%	78%	86%	89%	72%
Zone 2 - Napier	Alt. compliant cost effective	2.3	2.5	2.3	1.9	2.2	2.3	2.0	106%	99%	81%	94%	100%	84%
Zone 3 - Wellington	H1 4th ed schedule	7.5	7.6	7.5	6.1	7.2	7.3	6.2	101%	100%	82%	96%	98%	83%
Zone 3 - Wellington	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 3 - Wellington	H1 5th ed reference	3.9	4.8	3.8	3.6	5.6	4.1	5.2	124%	98%	93%	146%	106%	134%
Zone 3 - Wellington	H1 5th ed reference w.out eav	4.2	5.4	4.1	3.9	6.8	4.4	6.2	130%	98%	94%	163%	106%	149%
Zone 3 - Wellington	H1 5th ed calculation	3.2	3.1	3.2	2.6	3.1	3.4	2.8	97%	100%	79%	95%	105%	86%
Zone 3 - Wellington	H1 5th ed modelling	6.1	6.2	6.1	4.9	5.9	5.5	4.8	102%	100%	81%	96%	90%	79%
Zone 3 - Wellington	Cost effective (Q3)	7.2	7.3	7.2	5.8	6.9	6.6	5.7	102%	100%	81%	96%	92%	79%
Zone 3 - Wellington	Alt. compliant cost effective	2.5	2.3	2.5	2.0	2.3	2.5	2.1	95%	100%	80%	96%	100%	84%
Zone 4 - Taupo	H1 4th ed schedule	9.7	9.7	9.6	7.8	9.0	9.4	7.6	101%	100%	81%	93%	97%	79%
Zone 4 - Taupo	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 4 - Taupo	H1 5th ed reference	4.8	5.8	4.7	4.3	6.2	5.1	5.4	119%	97%	88%	128%	105%	112%
Zone 4 - Taupo	H1 5th ed reference w.out eav	5.4	6.7	5.2	4.8	7.4	5.7	6.5	124%	97%	89%	138%	105%	121%
Zone 4 - Taupo	H1 5th ed calculation	4.8	4.6	4.8	3.8	4.5	5.0	4.0	97%	100%	79%	94%	105%	84%
Zone 4 - Taupo	H1 5th ed modelling	7.4	7.1	7.4	5.8	6.6	6.4	5.0	97%	100%	78%	89%	86%	68%
Zone 4 - Taupo	Cost effective (Q3)	6.4	6.2	6.4	5.0	5.8	5.5	4.3	97%	100%	79%	90%	85%	68%
Zone 4 - Taupo	Alt. compliant cost effective	2.3	2.1	2.3	1.8	2.2	2.3	1.9	93%	99%	82%	98%	101%	85%
Zone 5 - Christchurch	H1 4th ed schedule	11.1	11.3	11.1	9.1	10.4	10.9	9.0	101%	100%	82%	94%	98%	81%
Zone 5 - Christchurch	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 5 - Christchurch	H1 5th ed reference	5.4	6.4	5.3	4.9	6.7	5.7	5.9	120%	98%	92%	124%	106%	111%
Zone 5 - Christchurch	H1 5th ed reference w.out eav	6.1	7.5	5.9	5.6	7.9	6.4	7.0	123%	98%	92%	131%	105%	116%
Zone 5 - Christchurch	H1 5th ed calculation	1.7	1.6	1.7	1.3	1.8	1.8	1.4	92%	99%	74%	105%	106%	79%
Zone 5 - Christchurch	H1 5th ed modelling	8.6	8.4	8.6	6.8	7.8	7.7	6.0	98%	100%	79%	90%	89%	70%
Zone 5 - Christchurch	Cost effective (Q3)	7.6	7.4	7.6	6.1	6.9	6.7	5.3	97%	100%	80%	91%	88%	70%
Zone 5 - Christchurch	Alt. compliant cost effective	2.9	2.8	2.9	2.5	2.8	3.2	2.6	97%	99%	83%	97%	109%	90%
Zone 6 - Queenstown	H1 4th ed schedule	13.7	13.5	13.7	11.1	12.9	12.7	10.5	98%	100%	81%	94%	93%	77%
Zone 6 - Queenstown	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 6 - Queenstown	H1 5th ed reference	4.6	5.5	4.5	4.3	6.2	4.7	6.3	119%	98%	92%	134%	102%	137%
Zone 6 - Queenstown	H1 5th ed reference w.out eav	5.2	6.4	5.1	4.8	7.5	5.3	7.7	122%	98%	93%	143%	102%	149%
Zone 6 - Queenstown	H1 5th ed calculation	1.9	1.4	1.9	1.4	1.9	1.4	0.8	75%	99%	72%	102%	74%	41%
Zone 6 - Queenstown	H1 5th ed modelling	8.0	7.5	8.0	6.4	7.3	7.3	5.6	94%	100%	80%	92%	92%	71%
Zone 6 - Queenstown	Cost effective (Q3)	1.6	1.2	1.6	1.2	1.7	1.1	0.6	71%	99%	71%	103%	70%	37%

Figure 71: Double-storey house – sensitivity analysis on resulting differences in delivered energy use for the different construction sets

Medium Density		Difference relative to H1 5th ed													
Climate	H1 5th ed reference	Baseline	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Lower soil conductivity	Combined lower savings
Zone 1 - Auckland	H1 4th ed schedule	4.2	4.5	4.2	3.9	3.4	4.2	3.7	106%	99%	92%	80%	99%	88%
Zone 1 - Auckland	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 1 - Auckland	H1 5th ed reference	4.1	5.4	3.7	4.2	5.6	4.1	5.4	133%	91%	102%	138%	102%	133%
Zone 1 - Auckland	H1 5th ed reference w.out eav	6.3	8.6	5.5	6.5	9.3	6.5	9.0	136%	88%	104%	148%	103%	143%
Zone 1 - Auckland	H1 5th ed calculation	1.4	1.6	1.4	1.3	1.1	1.5	1.3	110%	100%	91%	76%	102%	88%
Zone 1 - Auckland	H1 5th ed modelling	4.2	4.4	4.2	3.8	3.3	4.1	3.7	105%	100%	91%	78%	97%	87%
Zone 1 - Auckland	Cost effective (Q3)	3.5	3.7	3.4	3.2	2.8	3.3	3.1	107%	100%	91%	80%	97%	89%
Zone 1 - Auckland	Alt. compliant cost effective	1.0	1.2	1.0	1.0	0.9	1.1	1.0	114%	100%	92%	81%	102%	91%
Zone 2 - Napier	H1 4th ed schedule	6.4	6.5	6.4	5.8	5.5	6.3	5.7	102%	100%	90%	85%	99%	89%
Zone 2 - Napier	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 2 - Napier	H1 5th ed reference	4.2	5.6	4.0	4.2	6.1	4.3	5.8	134%	95%	99%	145%	102%	137%
Zone 2 - Napier	H1 5th ed reference w.out eav	6.0	8.5	5.5	6.1	9.5	6.2	9.0	141%	91%	102%	158%	103%	149%
Zone 2 - Napier	H1 5th ed calculation	2.2	2.2	2.2	2.0	1.8	2.3	2.0	99%	100%	91%	82%	103%	91%
Zone 2 - Napier	H1 5th ed modelling	6.4	6.5	6.4	5.8	5.4	6.1	5.5	101%	100%	90%	84%	95%	86%
Zone 2 - Napier	Cost effective (Q3)	5.2	5.3	5.2	4.7	4.5	5.0	4.6	102%	100%	90%	86%	95%	88%
Zone 2 - Napier	Alt. compliant cost effective	1.6	1.6	1.6	1.4	1.4	1.6	1.5	99%	100%	91%	87%	104%	94%
Zone 3 - Wellington	H1 4th ed schedule	6.4	6.3	6.5	5.8	5.7	6.3	5.8	98%	101%	91%	89%	99%	91%
Zone 3 - Wellington	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 3 - Wellington	H1 5th ed reference	2.1	2.8	2.2	2.1	4.3	2.2	4.8	130%	105%	97%	203%	103%	226%
Zone 3 - Wellington	H1 5th ed reference w.out eav	1.9	3.4	1.9	2.0	6.1	2.1	7.3	175%	99%	105%	313%	107%	375%
Zone 3 - Wellington	H1 5th ed calculation	2.3	2.1	2.3	2.1	1.9	2.4	2.1	90%	101%	91%	84%	103%	90%
Zone 3 - Wellington	H1 5th ed modelling	2.9	2.7	2.9	2.6	2.3	2.6	2.2	91%	101%	90%	81%	88%	76%
Zone 3 - Wellington	Cost effective (Q3)	5.5	5.3	5.5	4.9	4.9	5.1	4.8	98%	101%	90%	90%	93%	87%
Zone 3 - Wellington	Alt. compliant cost effective	1.7	1.5	1.8	1.6	1.5	1.8	1.6	87%	101%	91%	86%	105%	93%
Zone 4 - Taupo	H1 4th ed schedule	7.9	7.7	7.9	7.1	7.0	7.8	7.0	98%	100%	91%	89%	99%	89%
Zone 4 - Taupo	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 4 - Taupo	H1 5th ed reference	3.5	4.2	3.4	3.2	5.2	3.5	5.6	122%	100%	92%	150%	102%	163%
Zone 4 - Taupo	H1 5th ed reference w.out eav	3.7	5.1	3.4	3.6	6.6	3.8	7.6	139%	93%	97%	181%	104%	208%
Zone 4 - Taupo	H1 5th ed calculation	2.9	2.9	2.9	2.6	2.4	2.9	2.4	99%	100%	91%	82%	99%	84%
Zone 4 - Taupo	H1 5th ed modelling	4.8	4.5	4.8	4.4	4.1	4.8	4.0	93%	100%	91%	85%	99%	84%
Zone 4 - Taupo	Cost effective (Q3)	4.9	4.6	4.9	4.4	4.1	4.4	3.7	93%	101%	90%	84%	90%	76%
Zone 4 - Taupo	Alt. compliant cost effective	2.6	2.4	2.6	2.4	2.3	2.7	2.4	90%	100%	92%	89%	105%	91%
Zone 5 - Christchurch	H1 4th ed schedule	9.2	9.0	9.3	8.4	8.2	9.1	8.1	98%	100%	91%	89%	99%	88%
Zone 5 - Christchurch	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 5 - Christchurch	H1 5th ed reference	3.3	4.1	3.4	3.2	5.2	3.4	5.6	123%	100%	94%	156%	102%	169%
Zone 5 - Christchurch	H1 5th ed reference w.out eav	3.6	5.4	3.4	3.6	6.9	3.8	8.0	148%	94%	99%	190%	105%	221%
Zone 5 - Christchurch	H1 5th ed calculation	3.5	3.5	3.5	3.2	2.9	3.6	3.0	99%	100%	91%	82%	103%	86%
Zone 5 - Christchurch	H1 5th ed modelling	5.1	4.8	5.2	4.7	4.4	5.2	4.4	93%	100%	91%	86%	102%	86%
Zone 5 - Christchurch	Cost effective (Q3)	5.8	5.5	5.9	5.3	4.9	5.3	4.5	94%	100%	90%	84%	91%	76%
Zone 5 - Christchurch	Alt. compliant cost effective	2.2	1.9	2.2	2.0	1.9	2.4	1.9	86%	100%	91%	87%	106%	86%
Zone 6 - Queenstown	H1 4th ed schedule	11.6	11.2	11.6	10.6	10.6	11.5	10.2	97%	100%	91%	91%	99%	88%
Zone 6 - Queenstown	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Zone 6 - Queenstown	H1 5th ed reference	3.6	4.3	3.7	3.3	5.7	3.7	5.8	119%	102%	92%	157%	102%	161%
Zone 6 - Queenstown	H1 5th ed reference w.out eav	3.3	4.8	3.1	3.2	6.7	3.5	7.5	145%	95%	98%	205%	106%	230%
Zone 6 - Queenstown	H1 5th ed calculation	4.4	4.3	4.4	4.0	3.7	4.5	3.9	99%	100%	92%	86%	104%	89%
Zone 6 - Queenstown	H1 5th ed modelling	4.7	4.7	4.7	4.3	4.0	4.7	4.0	99%	100%	92%	85%	99%	85%
Zone 6 - Queenstown	Cost effective (Q3)	6.7	6.2	6.7	6.2	5.9	6.7	5.6	92%	100%	92%	88%	99%	83%
Zone 6 - Queenstown	Alt. compliant cost effective	2.8	2.3	2.8	2.5	2.5	3.0	2.3	82%	100%	91%	91%	107%	84%

Figure 72: Medium-density house – sensitivity analysis on resulting differences in delivered energy use for the different construction sets

Apartment		Difference relative to H1 5th ed										
Climate	H1 5th ed reference	Baseline	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Combined lower savings	Dark window frames	No mixing	Heating only during occupied hours	Low ventilation + airtightness	Combined lower savings
Zone 1 - Auckland	H1 4th ed schedule	4.7	5.1	4.6	4.7	4.3	4.6	108%	98%	100%	92%	98%
Zone 1 - Auckland	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-
Zone 1 - Auckland	H1 5th ed reference	-1.9	-2.3	-1.8	-1.9	-2.3	-2.2	121%	96%	101%	122%	115%
Zone 1 - Auckland	H1 5th ed reference w.out eav	-1.9	-2.1	-1.7	-1.9	-1.6	-1.7	113%	93%	103%	84%	89%
Zone 1 - Auckland	H1 5th ed calculation	-1.9	-2.1	-1.9	-1.9	-1.7	-1.8	111%	98%	100%	88%	94%
Zone 1 - Auckland	H1 5th ed modelling	-2.3	-2.7	-2.2	-2.3	-2.5	-2.5	116%	96%	101%	111%	108%
Zone 1 - Auckland	Cost effective (Q3)	4.6	5.0	4.5	4.6	4.2	4.5	109%	97%	100%	92%	98%
Zone 2 - Napier	H1 4th ed schedule	6.9	7.4	6.9	6.9	6.7	6.9	107%	99%	100%	97%	100%
Zone 2 - Napier	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-
Zone 2 - Napier	H1 5th ed reference	-2.4	-2.8	-2.3	-2.4	-2.9	-2.7	118%	97%	100%	120%	113%
Zone 2 - Napier	H1 5th ed reference w.out eav	-2.7	-3.1	-2.6	-2.8	-2.6	-2.7	111%	96%	103%	94%	97%
Zone 2 - Napier	H1 5th ed calculation	-3.0	-3.2	-3.0	-3.0	-2.9	-3.0	107%	99%	100%	96%	99%
Zone 2 - Napier	H1 5th ed modelling	-3.1	-3.5	-3.0	-3.1	-3.5	-3.3	113%	98%	100%	112%	108%
Zone 2 - Napier	Cost effective (Q3)	2.0	2.3	2.0	2.0	1.8	1.9	118%	99%	100%	89%	99%
Zone 3 - Wellington	H1 4th ed schedule	7.6	7.7	7.6	7.6	7.5	7.6	101%	100%	100%	98%	100%
Zone 3 - Wellington	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-
Zone 3 - Wellington	H1 5th ed reference	-1.8	-2.0	-1.8	-1.8	-2.2	-2.1	114%	100%	100%	127%	117%
Zone 3 - Wellington	H1 5th ed reference w.out eav	-2.6	-2.8	-2.6	-2.6	-2.6	-2.7	109%	99%	102%	101%	103%
Zone 3 - Wellington	H1 5th ed calculation	-3.1	-3.1	-3.1	-3.1	-3.0	-3.1	101%	100%	101%	97%	99%
Zone 3 - Wellington	H1 5th ed modelling	-3.1	-3.1	-3.1	-3.1	-3.0	-3.1	101%	100%	101%	97%	99%
Zone 3 - Wellington	Cost effective (Q3)	2.3	2.4	2.3	2.4	2.2	2.3	102%	100%	100%	93%	99%
Zone 4 - Taupo	H1 4th ed schedule	9.7	9.9	9.6	9.7	9.6	9.7	102%	100%	100%	99%	100%
Zone 4 - Taupo	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-
Zone 4 - Taupo	H1 5th ed reference	-2.5	-2.8	-2.4	-2.4	-2.8	-2.7	112%	99%	98%	115%	108%
Zone 4 - Taupo	H1 5th ed reference w.out eav	-3.5	-3.7	-3.5	-3.6	-3.5	-3.6	107%	99%	102%	99%	102%
Zone 4 - Taupo	H1 5th ed calculation	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	101%	100%	101%	98%	100%
Zone 4 - Taupo	H1 5th ed modelling	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	101%	100%	101%	98%	100%
Zone 4 - Taupo	Cost effective (Q3)	3.0	3.1	3.0	3.0	2.9	3.0	102%	100%	100%	97%	100%
Zone 5 - Christchurch	H1 4th ed schedule	11.3	11.4	11.3	11.3	11.2	11.3	101%	100%	100%	99%	100%
Zone 5 - Christchurch	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-
Zone 5 - Christchurch	H1 5th ed reference	-2.5	-2.7	-2.4	-2.4	-2.8	-2.6	110%	99%	99%	114%	107%
Zone 5 - Christchurch	H1 5th ed reference w.out eav	-3.3	-3.5	-3.3	-3.3	-3.3	-3.4	107%	99%	101%	100%	101%
Zone 5 - Christchurch	H1 5th ed calculation	-3.7	-3.8	-3.7	-3.7	-3.7	-3.7	101%	100%	100%	99%	100%
Zone 5 - Christchurch	H1 5th ed modelling	-3.7	-3.8	-3.7	-3.7	-3.7	-3.7	101%	100%	100%	99%	100%
Zone 5 - Christchurch	Cost effective (Q3)	4.1	4.1	4.1	4.1	4.0	4.1	100%	100%	100%	97%	99%
Zone 6 - Queenstown	H1 4th ed schedule	13.9	13.9	13.9	13.9	13.7	13.9	100%	100%	100%	99%	100%
Zone 6 - Queenstown	H1 5th ed schedule	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-
Zone 6 - Queenstown	H1 5th ed reference	-2.7	-3.0	-2.7	-2.7	-3.2	-3.0	111%	100%	98%	116%	107%
Zone 6 - Queenstown	H1 5th ed reference w.out eav	-4.2	-4.5	-4.1	-4.2	-4.2	-4.3	107%	99%	101%	102%	103%
Zone 6 - Queenstown	H1 5th ed calculation	-4.8	-4.8	-4.8	-4.8	-4.8	-4.8	100%	100%	100%	100%	100%
Zone 6 - Queenstown	H1 5th ed modelling	-4.8	-4.8	-4.8	-4.8	-4.8	-4.8	100%	100%	100%	100%	100%
Zone 6 - Queenstown	Cost effective (Q3)	3.3	3.2	3.3	3.3	3.2	3.3	97%	100%	100%	96%	99%

Figure 73: Apartment building – sensitivity analysis on resulting differences in delivered energy use for the different construction sets

Individual constructions

Additionally, to examine the uncertainty in results and how conclusions regarding the cost-effectiveness of individual construction choices might change, the individual construction simulations were rerun under different assumptions.

The following scenarios were run:

- **Adjusted heating and ventilation down:** The heating/cooling schedules were adjusted to only be applied to the living spaces during the day and the bedrooms day and night with no conditioning to the bathrooms and corridors. Ventilation was reduced to 5 ACH in spaces with strong ventilation potential and 1 ACH elsewhere along with reducing infiltration to 0.1 ACH to reflect a more airtight modern house and removing interzonal air mixing. These assumption changes should reduce heating use and present more cooling-focused results, which make insulation appear less useful.
- **Windows only – dark window frames:** The window frame reflectance was reduced from 80% to 10% in order to see how that would affect the relative effectiveness of the window options.

- **Concrete slab only – ground conductivity reduced:** The soil properties were adjusted down to the pre-H1/AS1 5th edition values of a conductivity of 1.2 W/m.K (Trethowen, 2000) and heat capacity of 1.2×10^6 J/m^{3}K (NZS 4214:2016 clay soil). In reality, soil properties may vary widely between sites and may be a significant source of uncertainty in concrete slab performance. Additionally, the water table depth was set to 10 m instead of 2 m to reduce heat loss.

Results

Heating and ventilation assumptions

Figure 74 to Figure 77 reflect the results for Auckland.

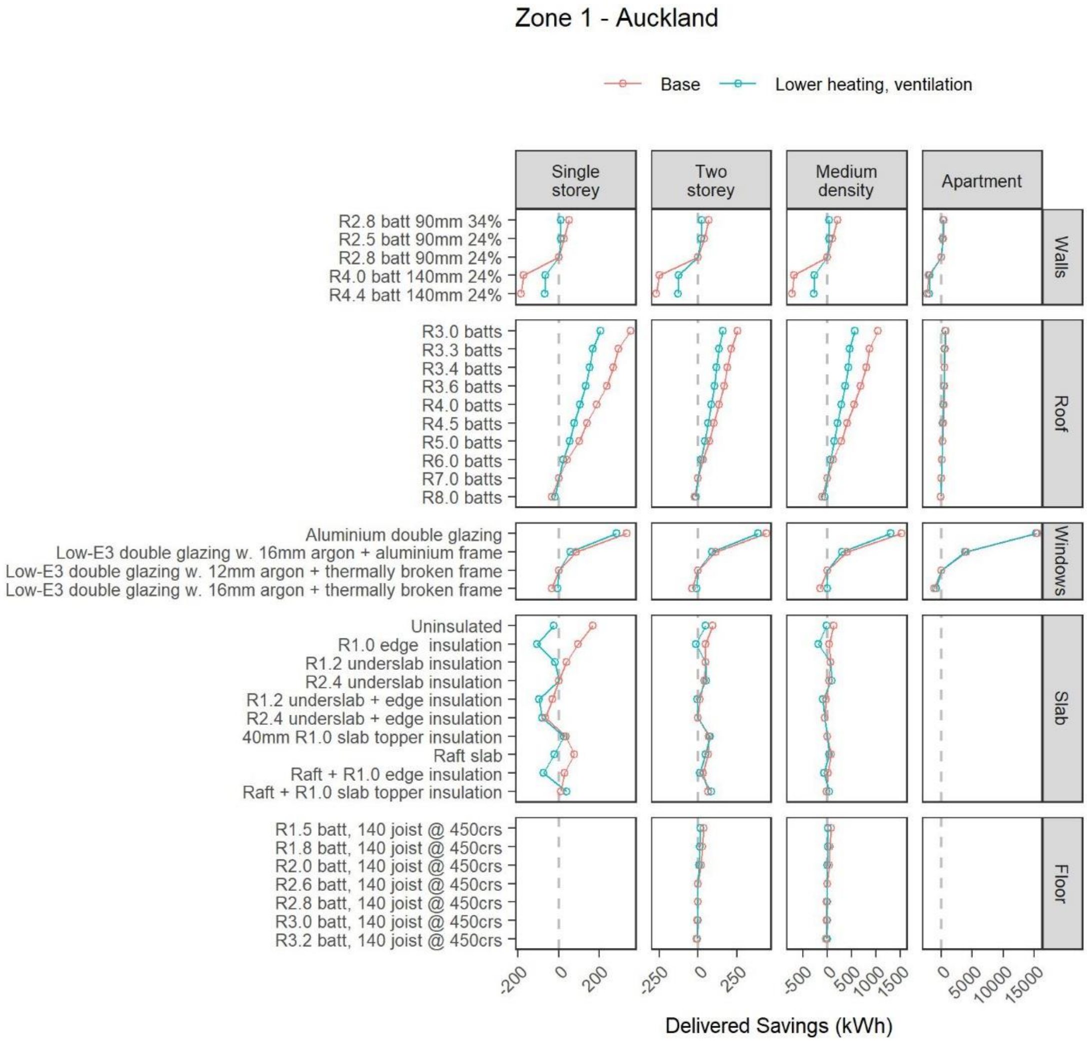


Figure 74: Sensitivity analysis (Auckland) – effect of adjusting heating schedules and ventilation assumptions on delivered energy 'savings' for different constructions (the difference in energy use compared to the baseline 5th edition schedule method constructions)[34]

[34] As calculated, negative numbers mean a decrease in energy use. Savings and positive numbers mean an increase in energy use.

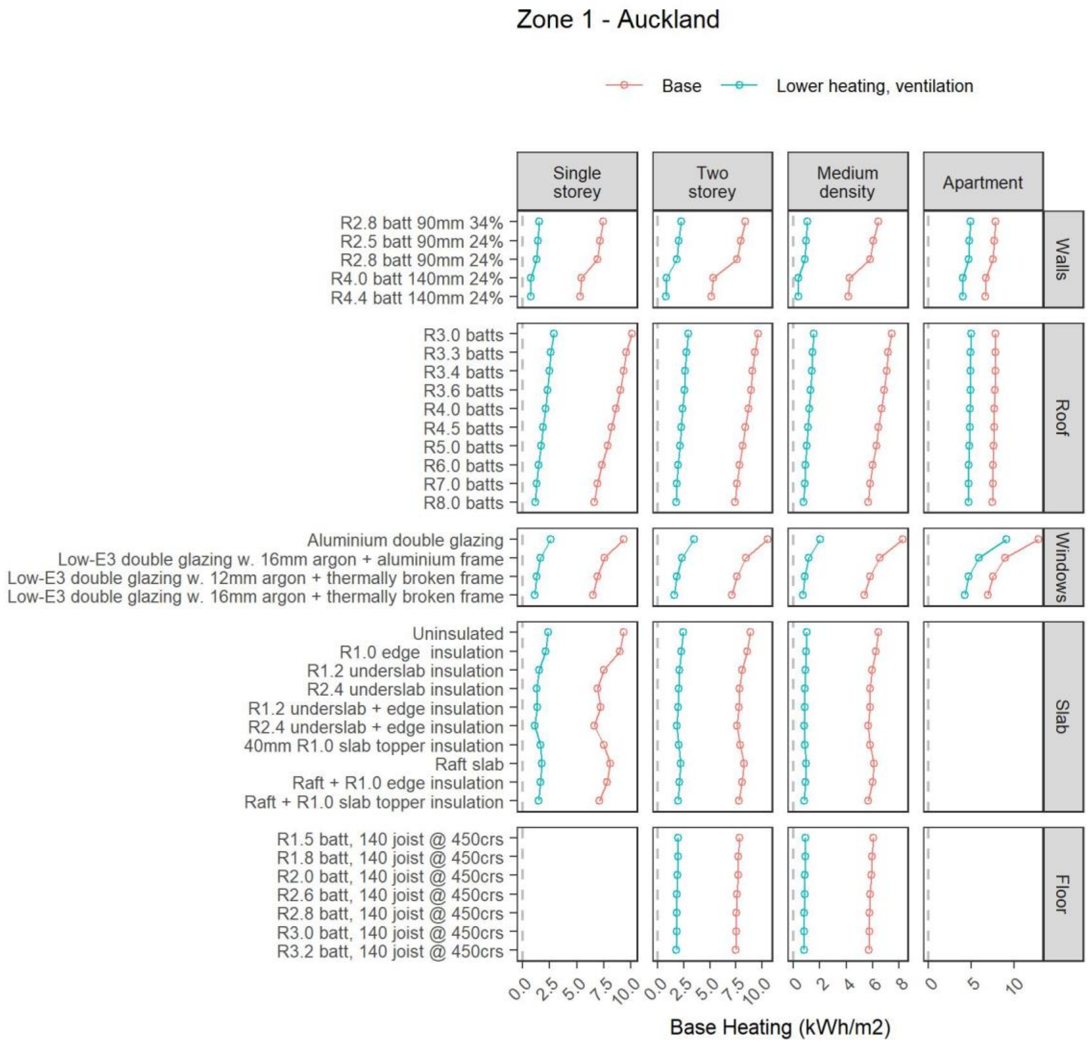


Figure 75: Sensitivity analysis (Auckland) – effect of adjusting heating schedules and ventilation assumptions on modelled heating use for different constructions

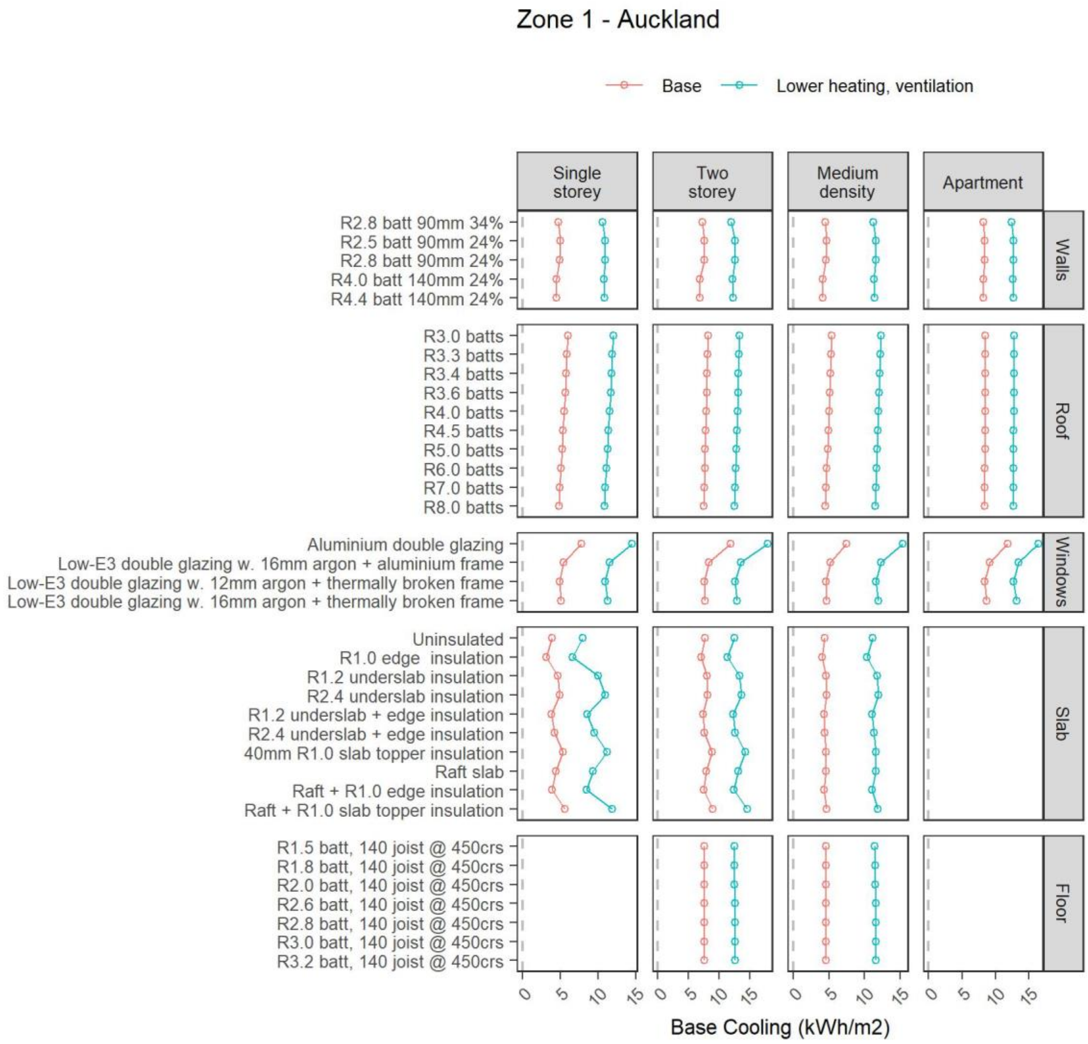


Figure 76: Sensitivity analysis (Auckland) – effect of adjusting heating schedules and ventilation assumptions on modelled cooling use for different constructions

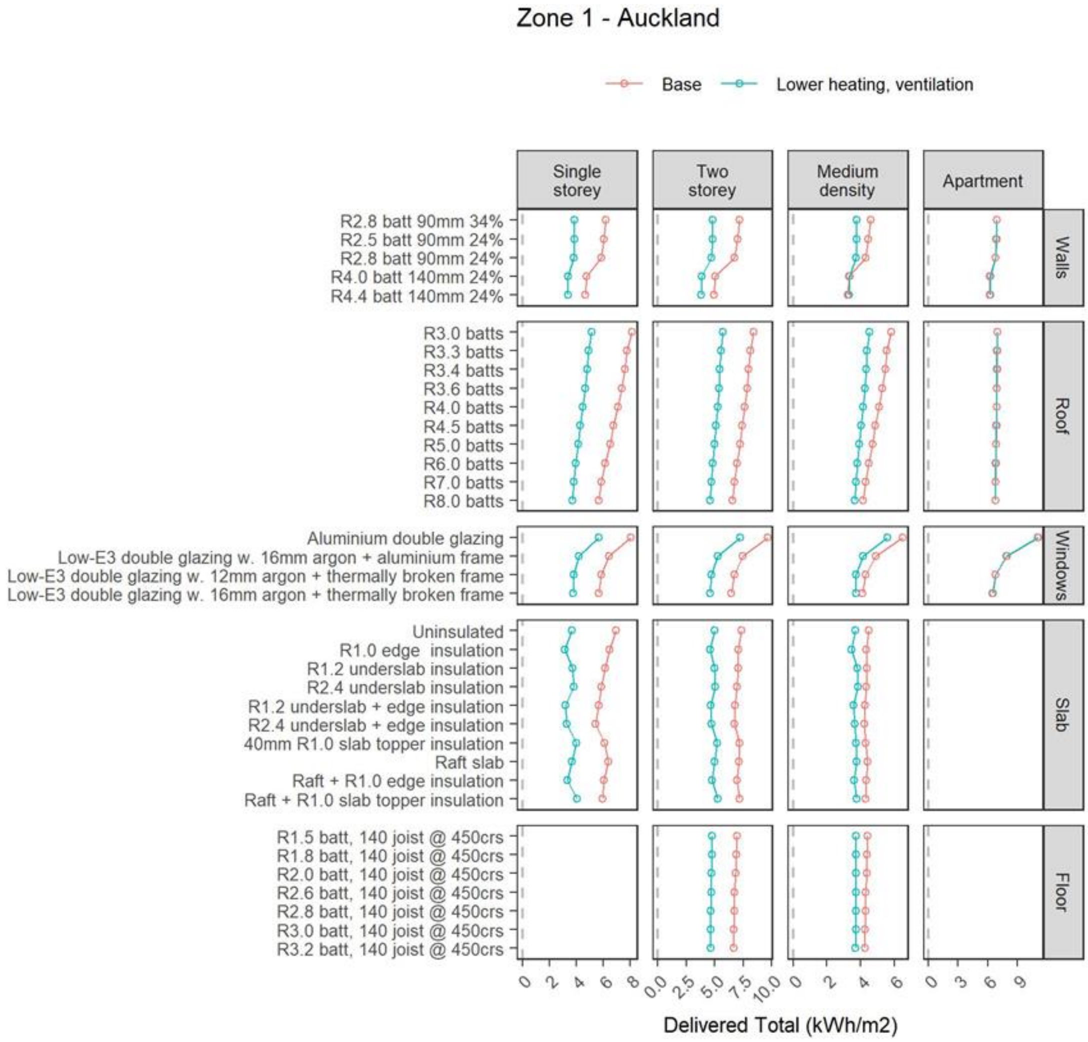


Figure 77: Sensitivity analysis (Auckland) – effect of adjusting heating schedules and ventilation assumptions on delivered energy use for different constructions

As expected, reducing heating and ventilation significantly lowers heating use and significantly increases cooling use by a factor of two depending on the model and climate. Mostly, this results in a significant decrease in overall energy use, though the apartment building is minimally changed. This is because the effect of changing the heating schedules is much less there due to its zoning meaning that the living spaces are not large and there are not significant corridor/bathroom areas to not be conditioned. In this case, the heating reductions and cooling increases are to an extent cancelled out. In terms of the key effects on the savings from insulation, the overall effect is that the energy savings from insulation – and thus its value – are reduced. The main exception here is the concrete slabs where the shift towards a more cooling dominated heat balance changes slab performance and makes edge insulation appear better by providing cooling savings in climates like Auckland.

Window frame reflectance

Figure 78 to Figure 81 reflect the results. Using dark window frames resulted in a small reduction to modelled heating use and a significant increase to modelled cooling use. However, these effects appear to cancel out with the total energy use, not changing significantly. Correspondingly, energy savings/costs from using different windows also changed little. In warmer climates, the aluminium double glazing (under the H1/AS1 4th edition) would have worse relative performance if the frames were dark though the differences are small. In the opposite direction, black frames may have better overall performance in colder climates and the increased heat gains may mean that the additional heating energy caused by the use of aluminium frames instead of thermally broken may be reduced.

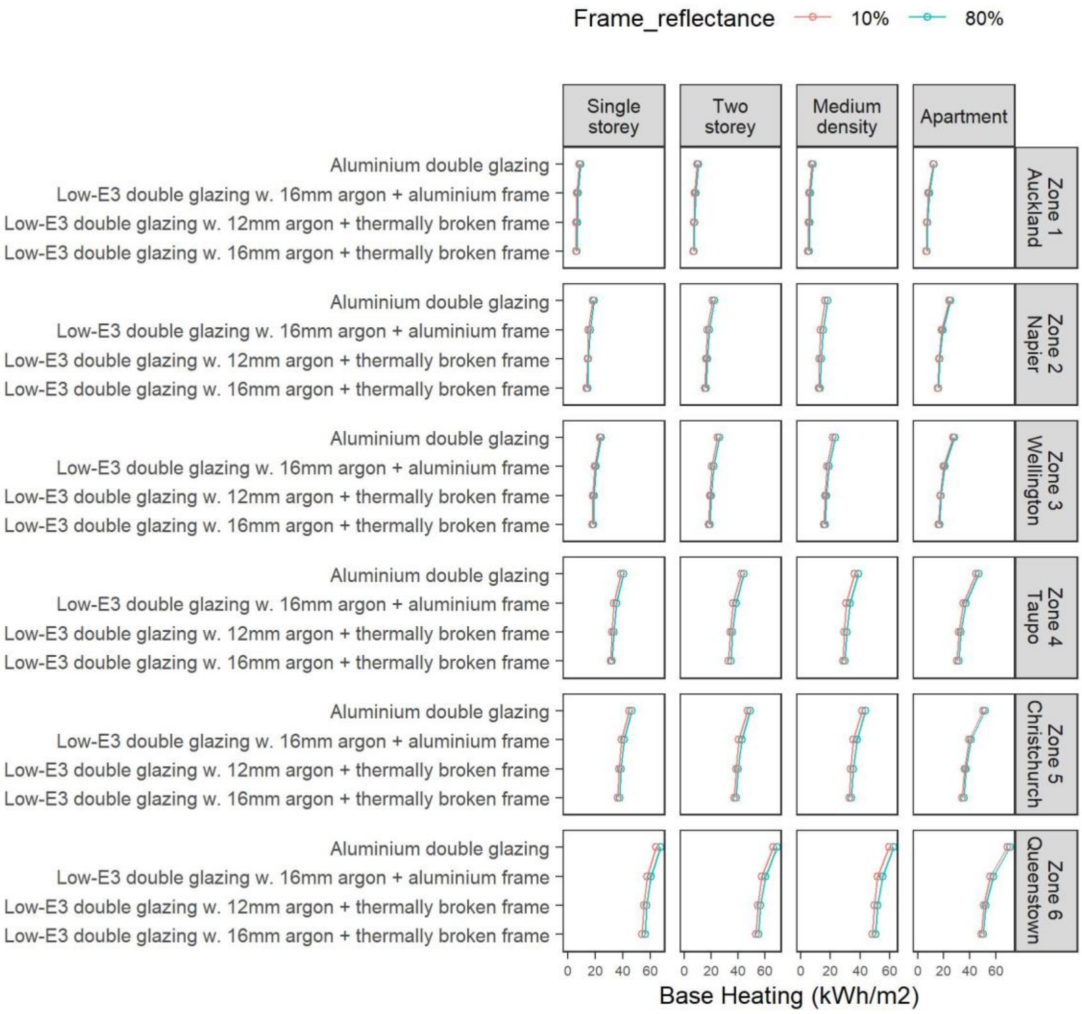


Figure 78: Effect of frame reflectance on modelled heating use for different windows

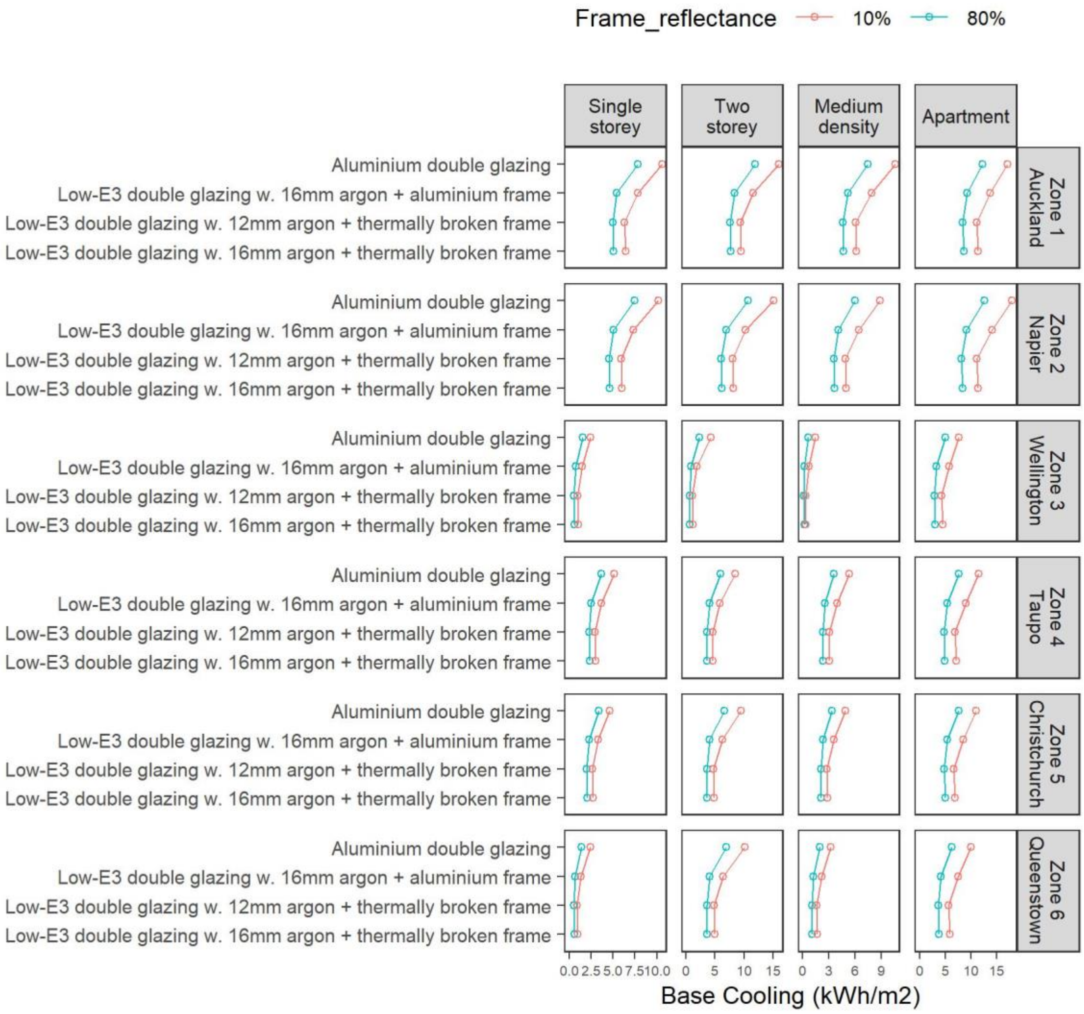


Figure 79: Effect of frame reflectance on modelled cooling use for different windows

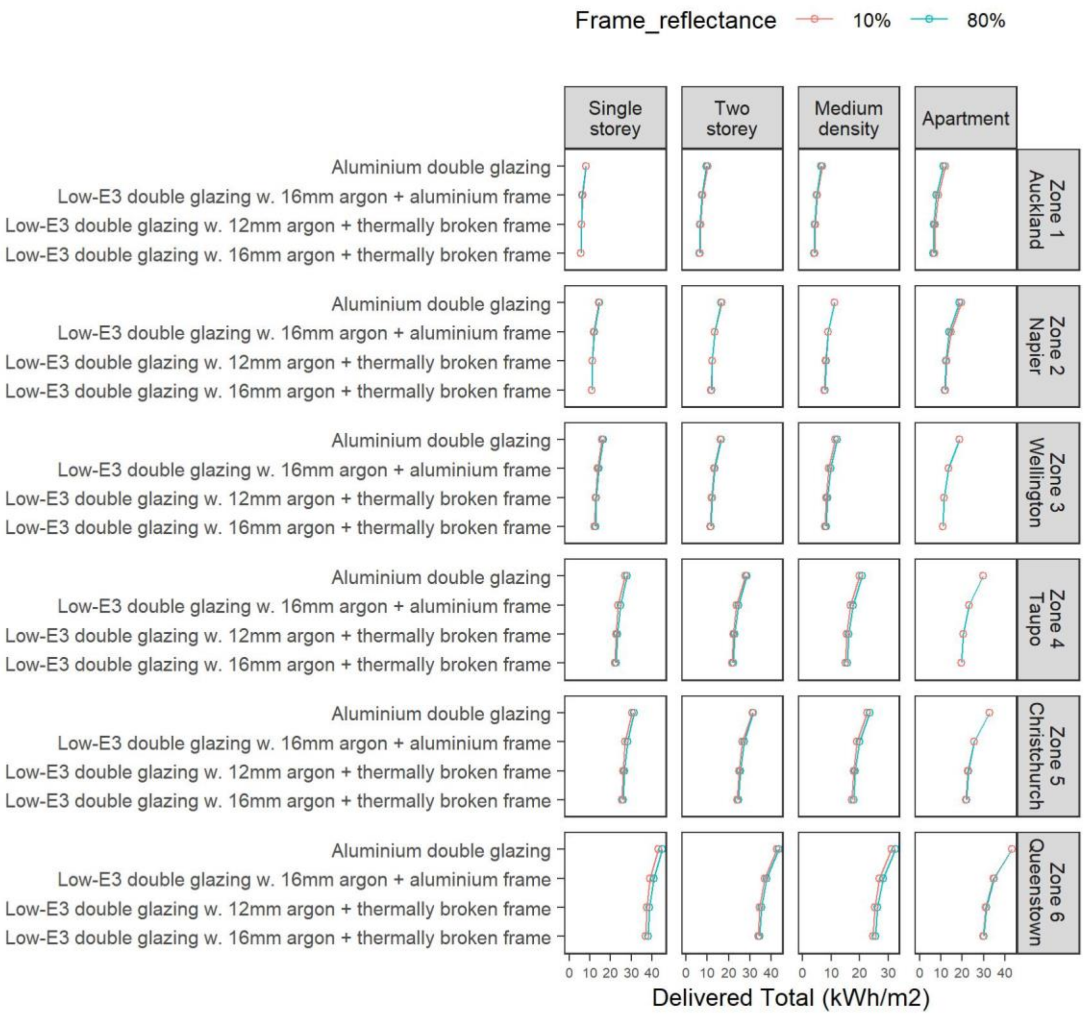


Figure 80: Effect of frame reflectance on total energy use for different windows

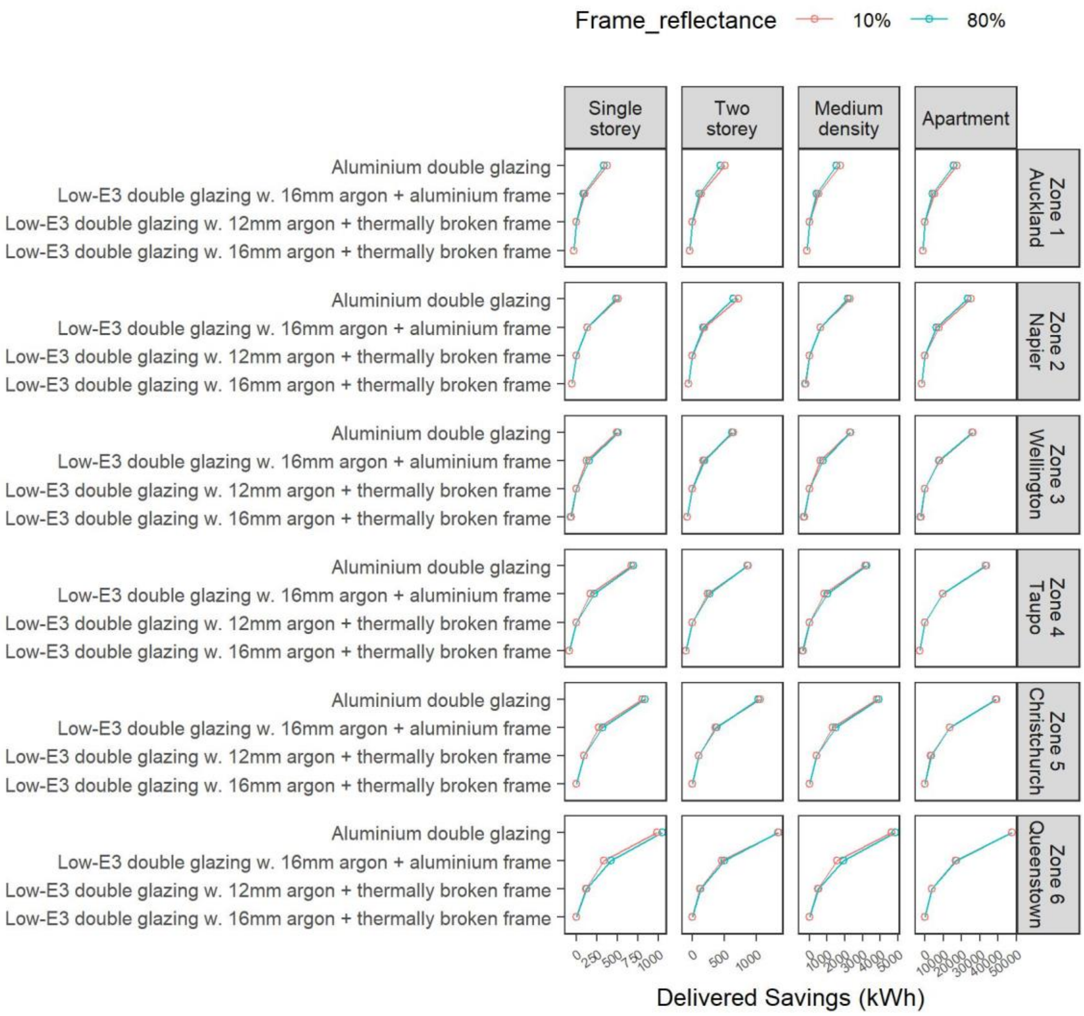


Figure 81: Effect of frame reflectance on the delivered energy 'savings' for different windows (the difference in energy use compared to the baseline 5th edition schedule method constructions)

Concrete slab ground properties

Figure 82 to Figure 85 reflect the results. The effect of reducing soil conductivity and heat loss is to, unsurprisingly, significantly reduce heating use and increase cooling use. The reduced ground heat transfer also reduces the effect of slab insulation overall – in some cases approximately halving the impact on energy use relative to H1's defaults. The exception to this is slab edge insulation, which becomes more effective at lower ground conductivities. This is because the slab edge losses are mostly to the outdoor air rather than to the ground and reducing the heat flow to the ground increases the heat flow through that bridge.

In general, the changes to default ground assumptions in H1 5th edition have significantly increased the salience of underslab insulation, and the relative cost-effectiveness of slab insulation may vary a lot depending on the local ground conditions.

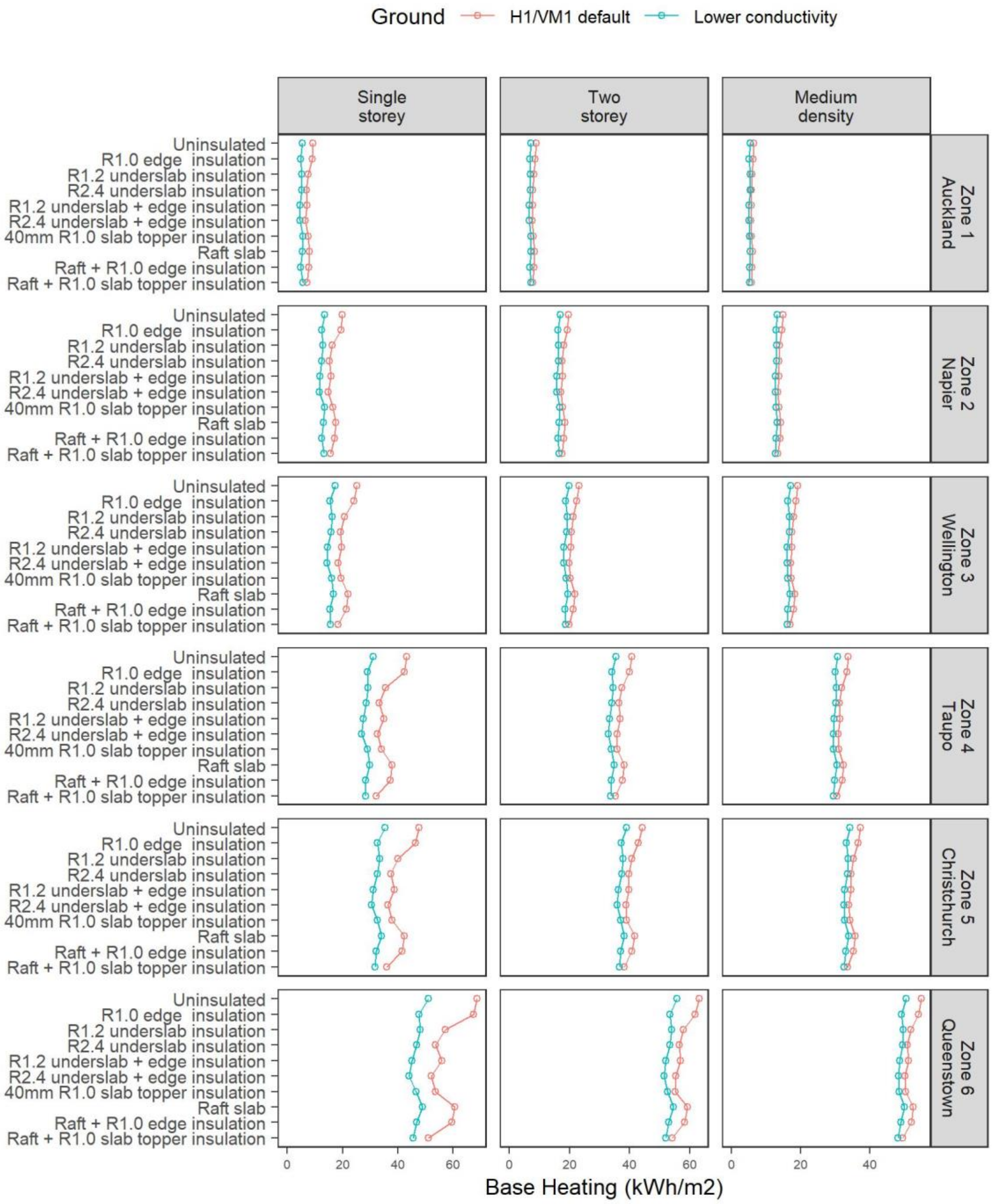


Figure 82: Effect of ground assumptions on modelled heating use for different slabs

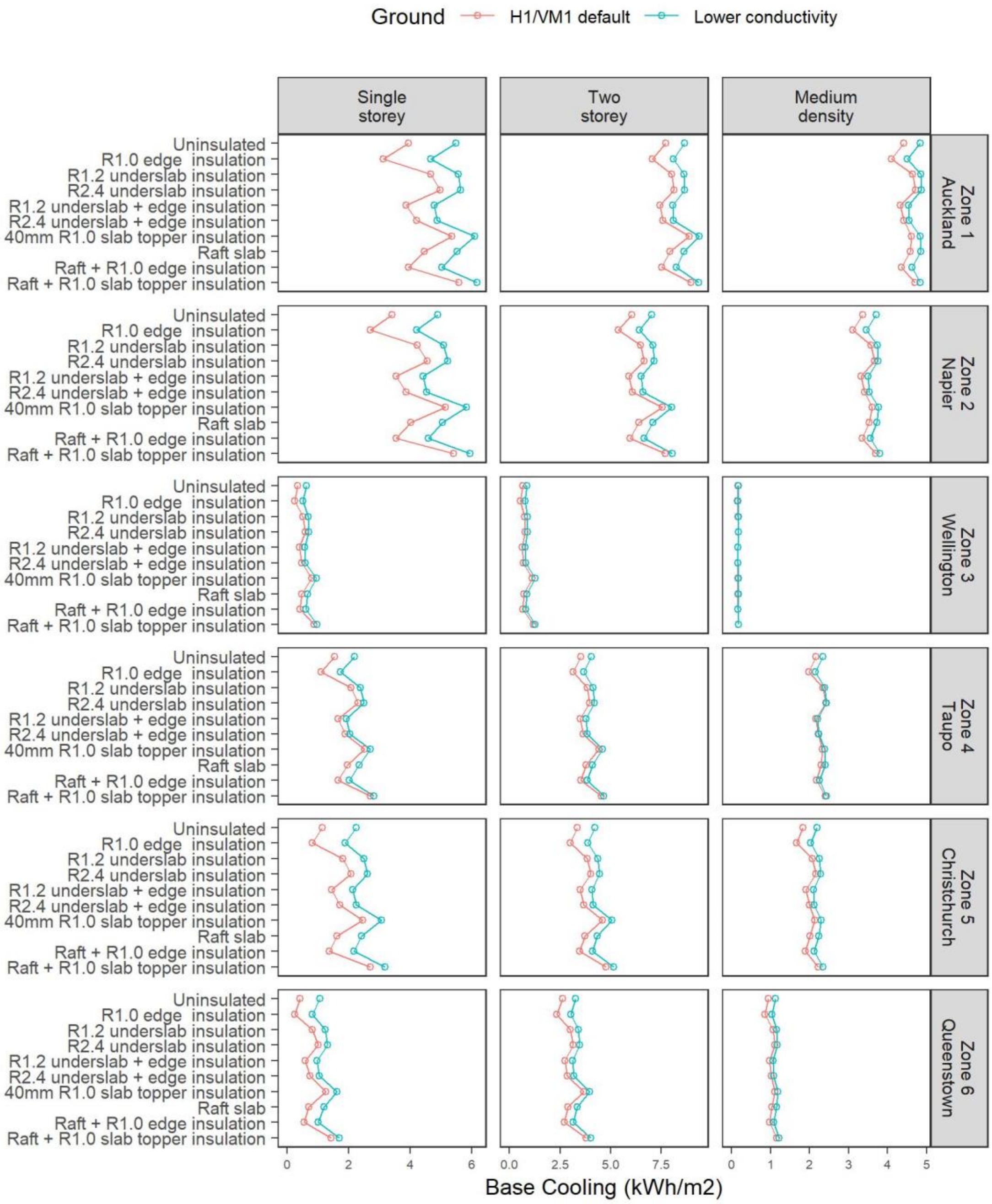


Figure 83: Effect of ground assumptions on modelled cooling use for different slabs

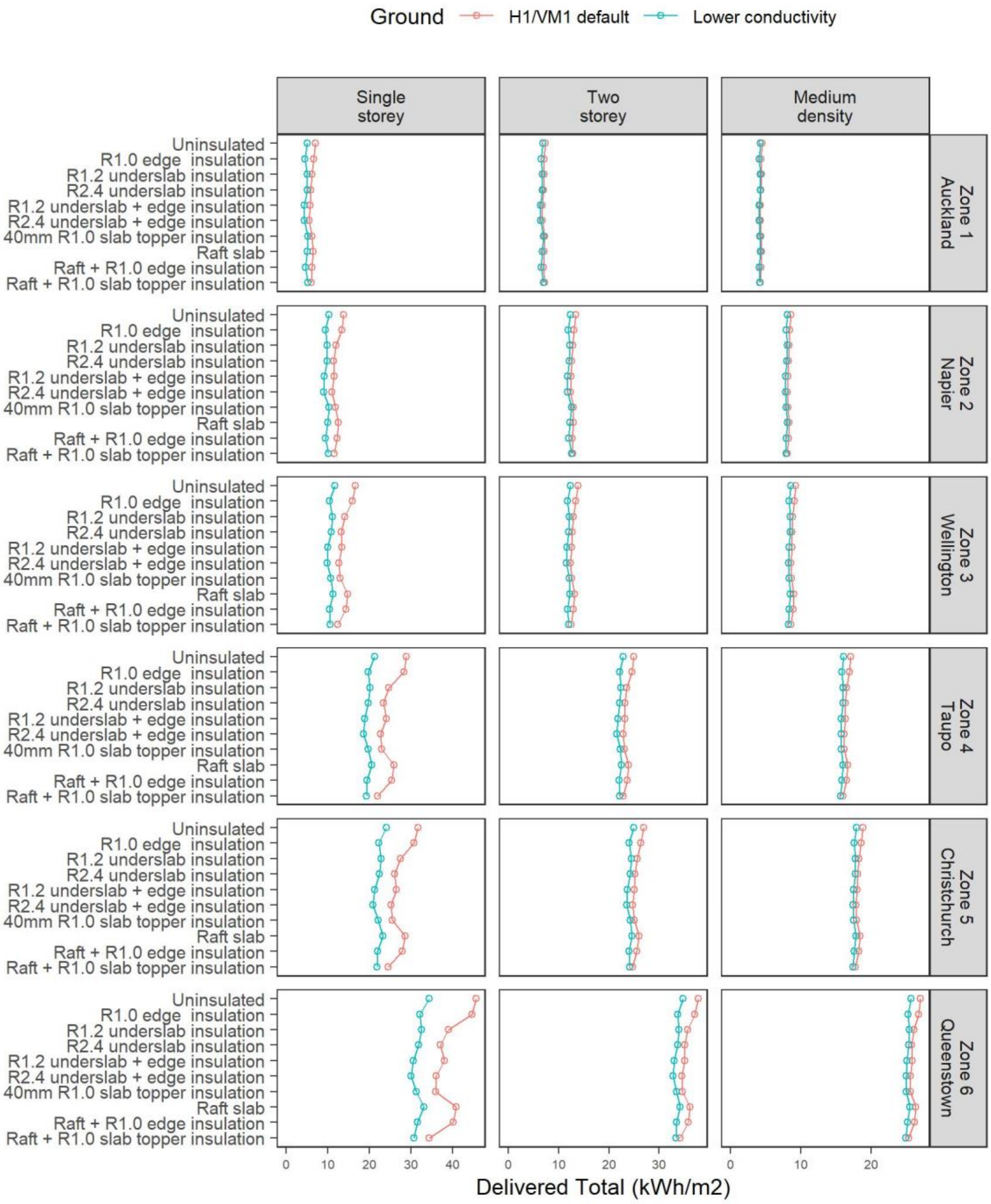


Figure 84: Effect of ground assumptions on total heating and cooling use for different slabs

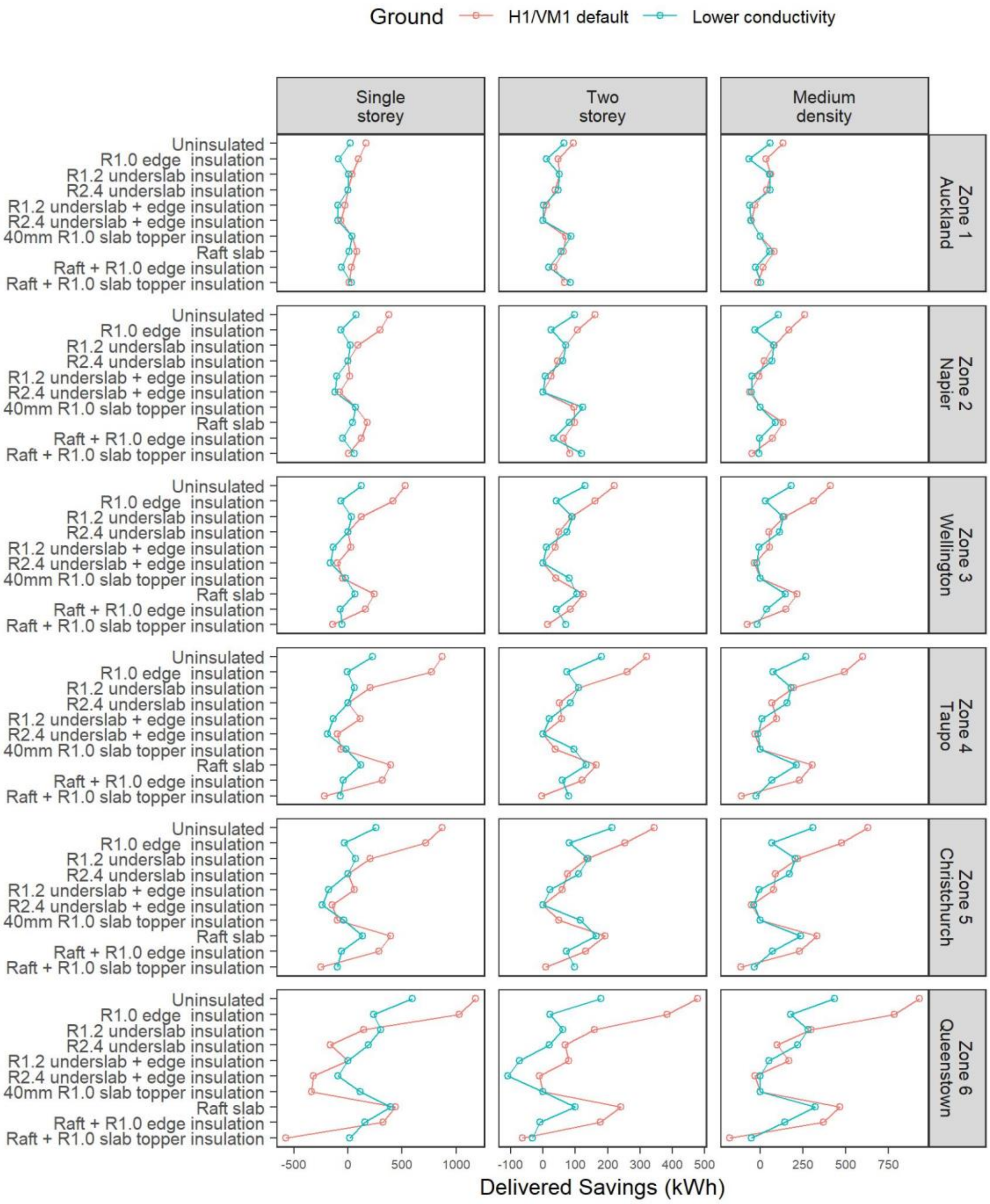


Figure 85: Effect of ground assumptions on the delivered energy 'savings' for different slabs (the difference in energy use compared to the baseline 5th edition schedule method constructions)

Appendix F: Additional Q4 overheating figures

More detailed breakdowns of effects of model assumptions

Daytime overheating

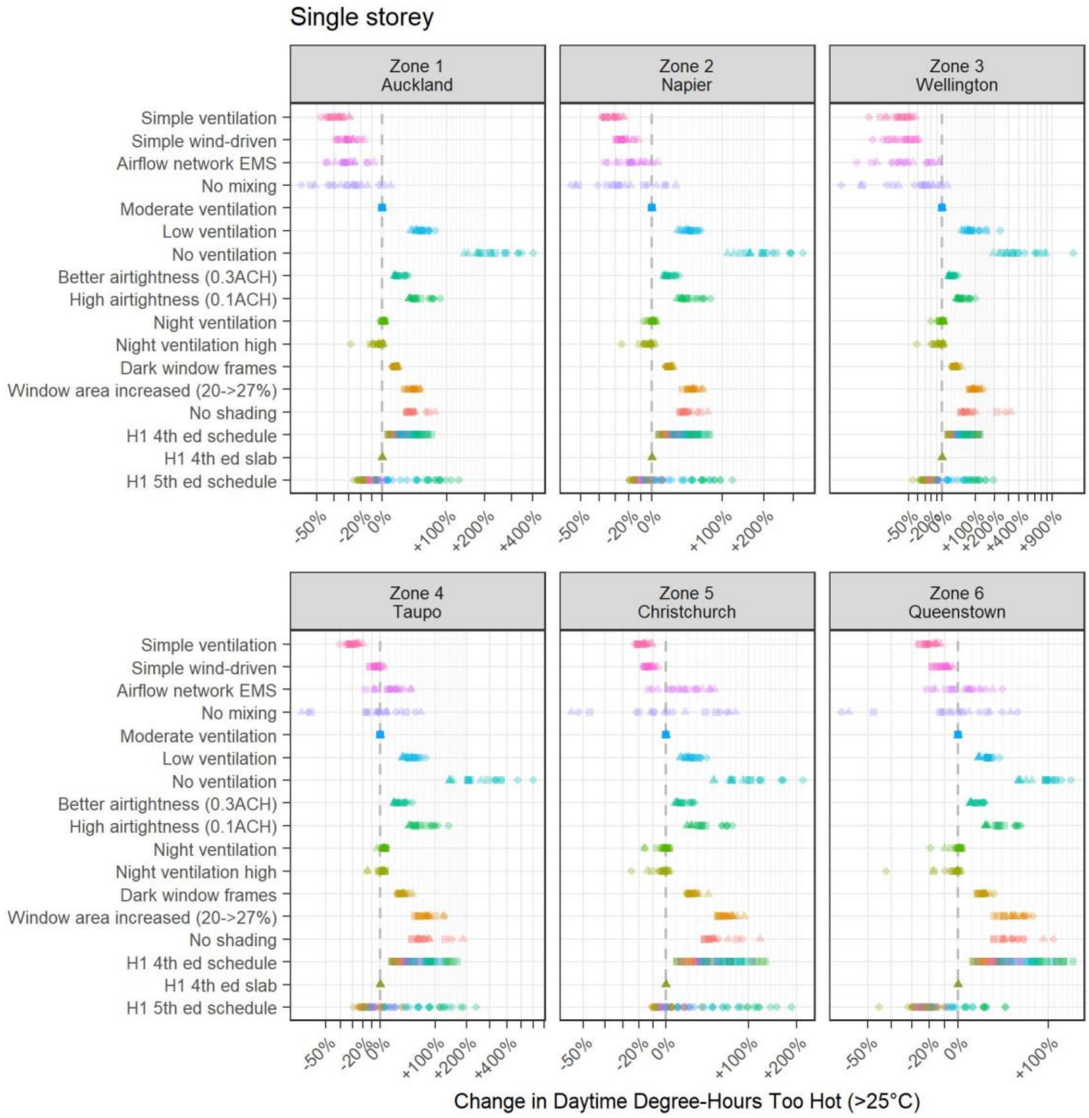


Figure 86: Relative change in daytime overheating in the single-storey house as a result of different factors

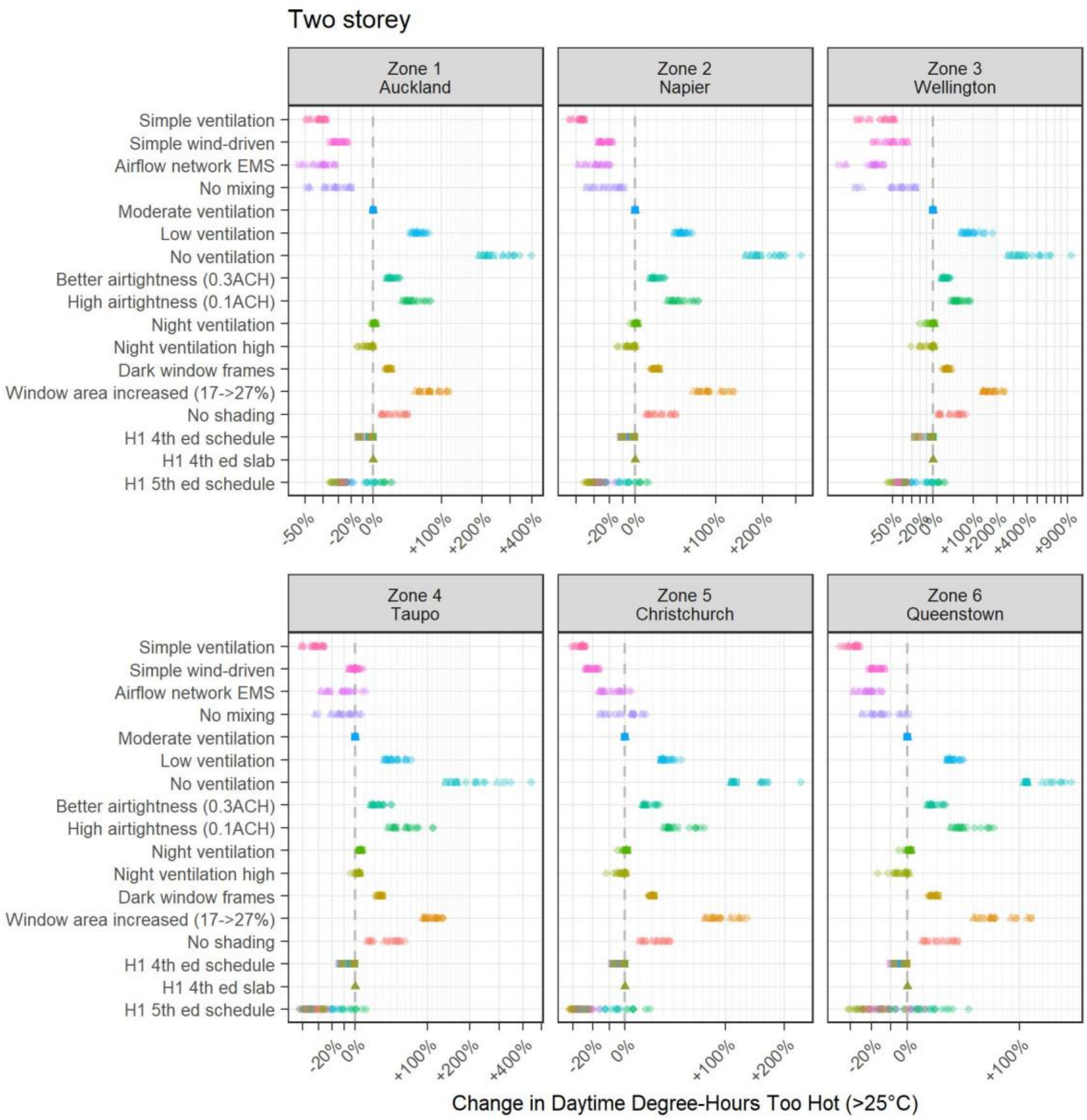


Figure 87: Relative change in daytime overheating in the two-storey house as a result of different factors

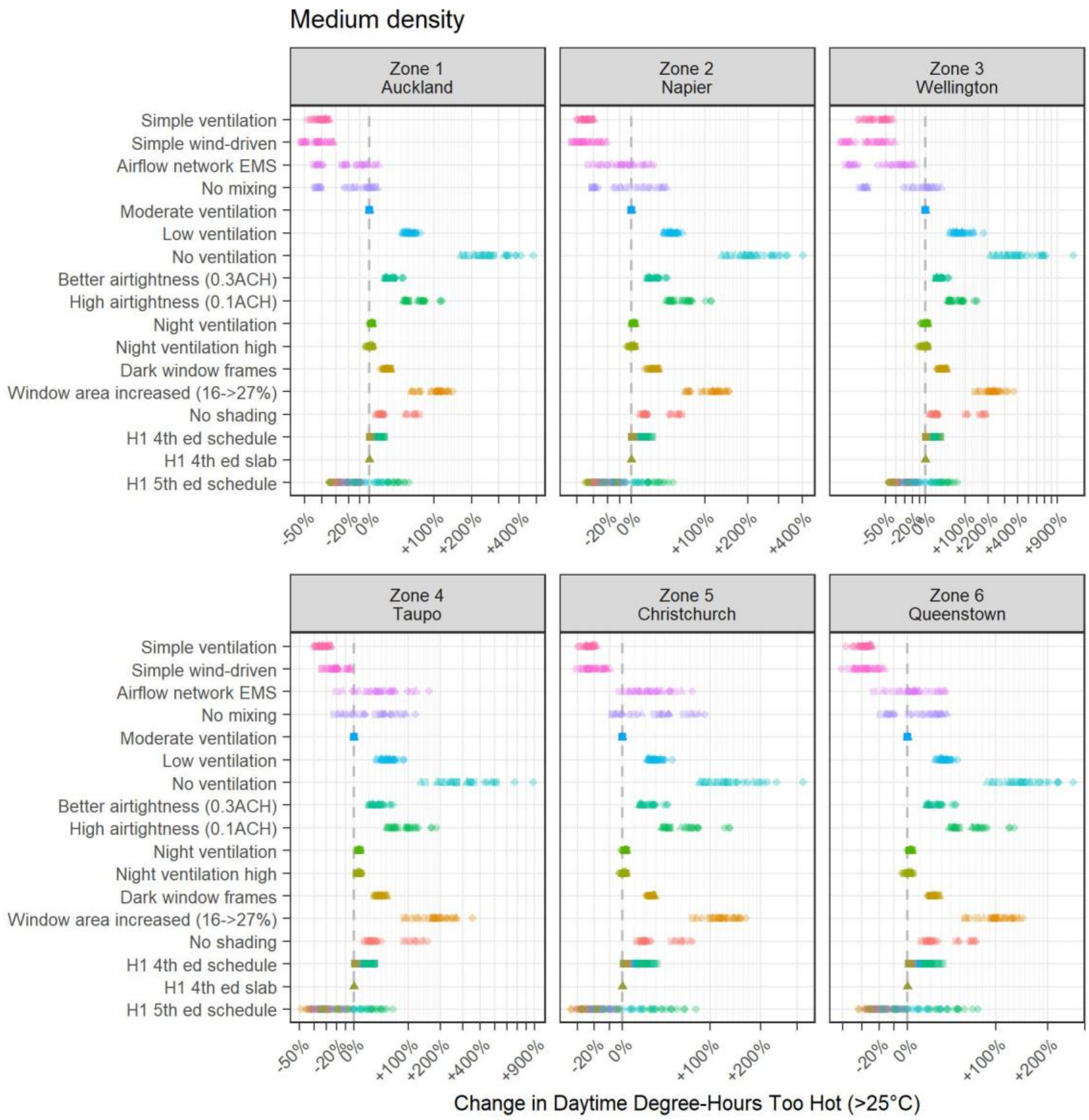


Figure 88: Relative change in daytime overheating in the medium-density house as a result of different factors

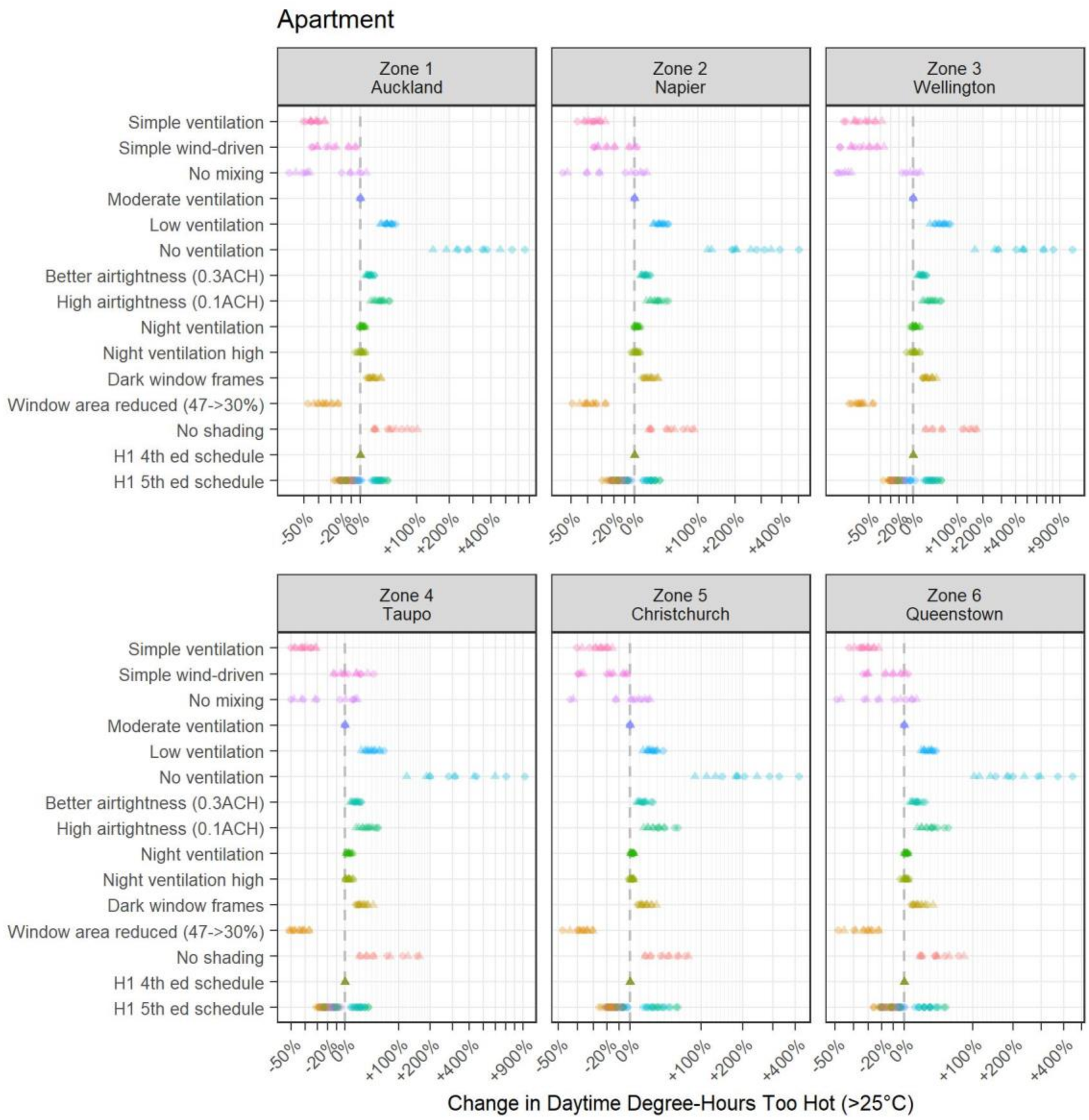


Figure 89: Relative change in daytime overheating in the apartments as a result of different factors

Night-time overheating

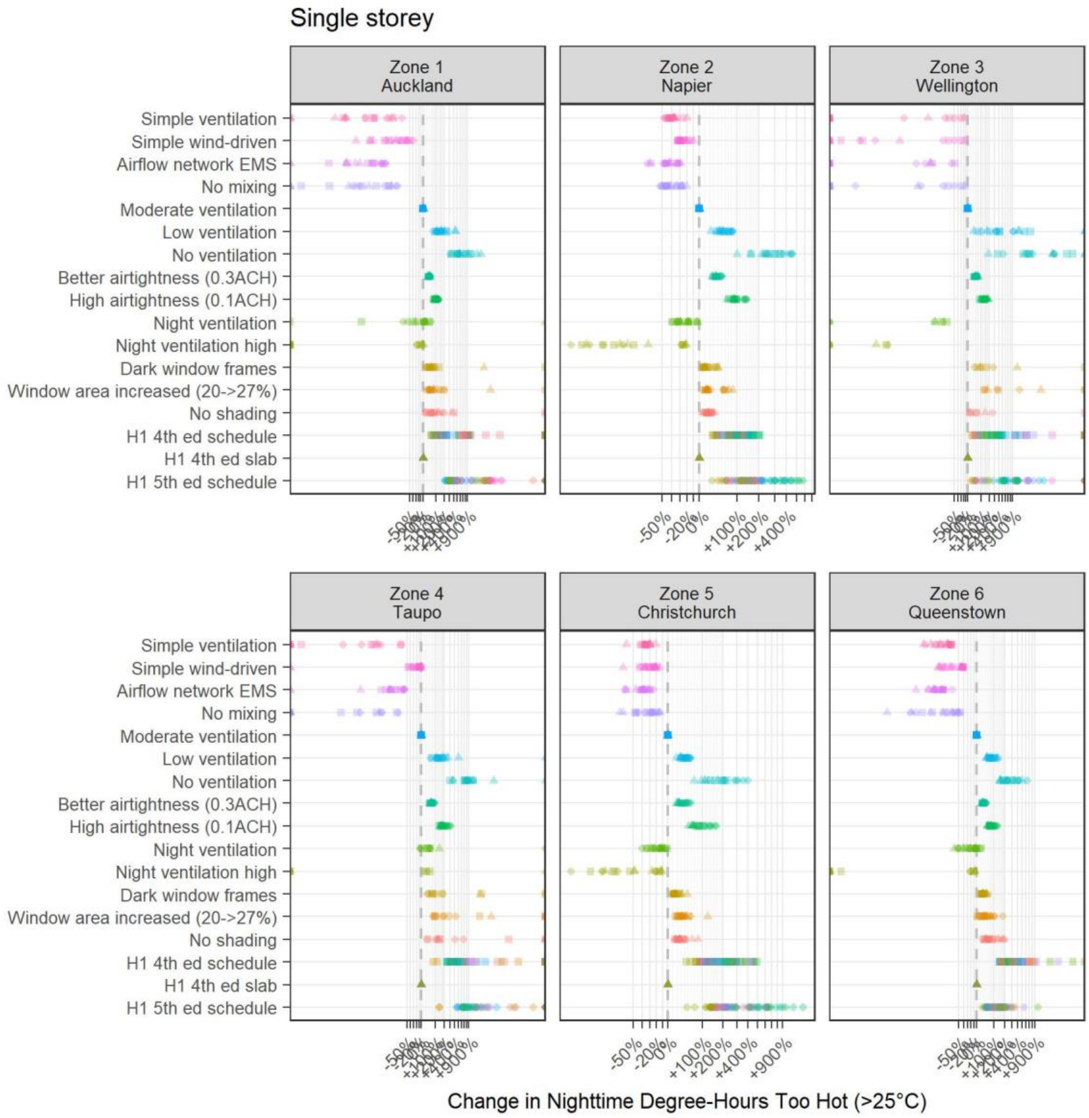


Figure 90: Relative change in night-time overheating in the single-storey house as a result of different factors

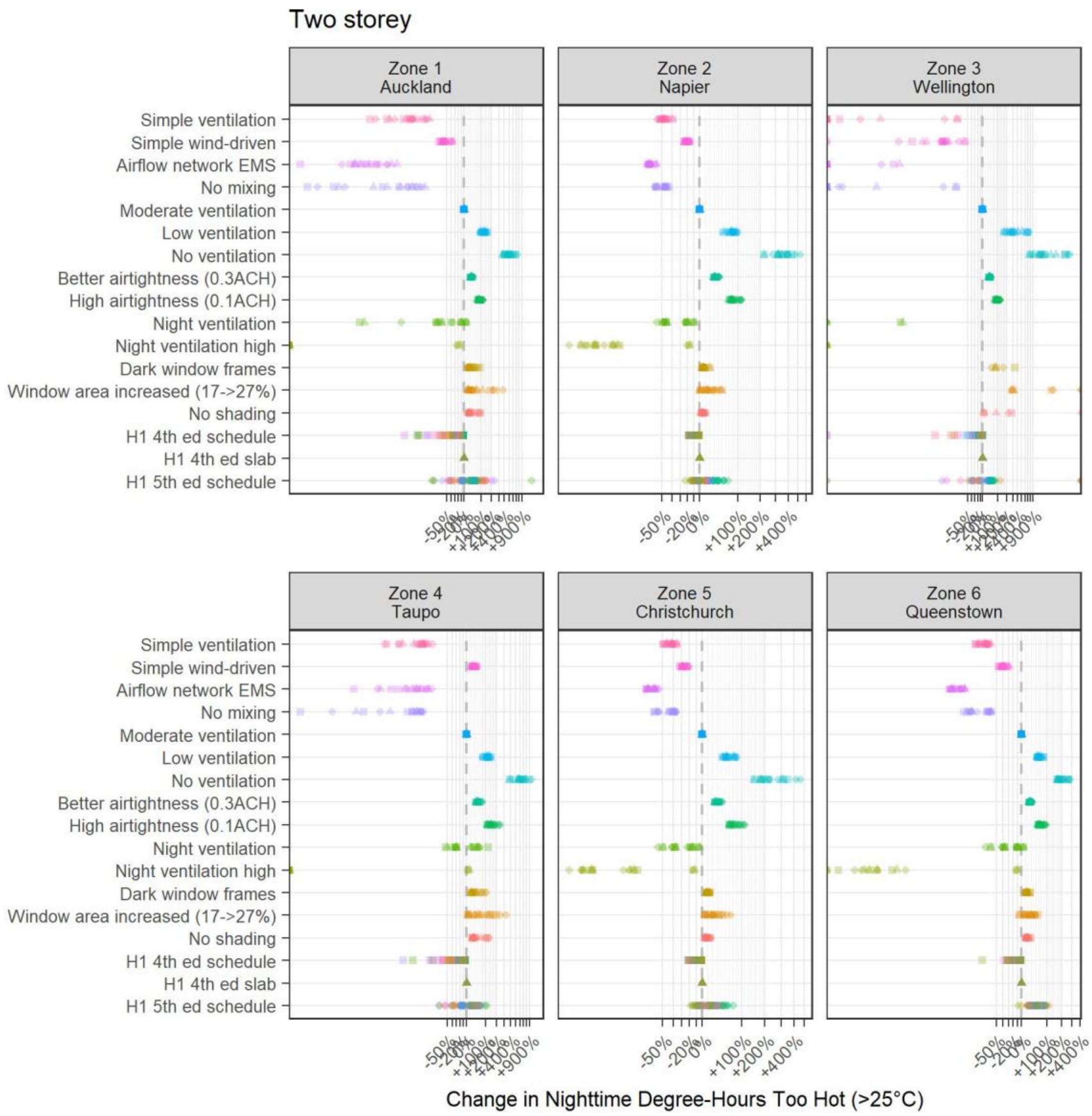


Figure 91: Relative change in night-time overheating in the two-storey house as a result of different factors

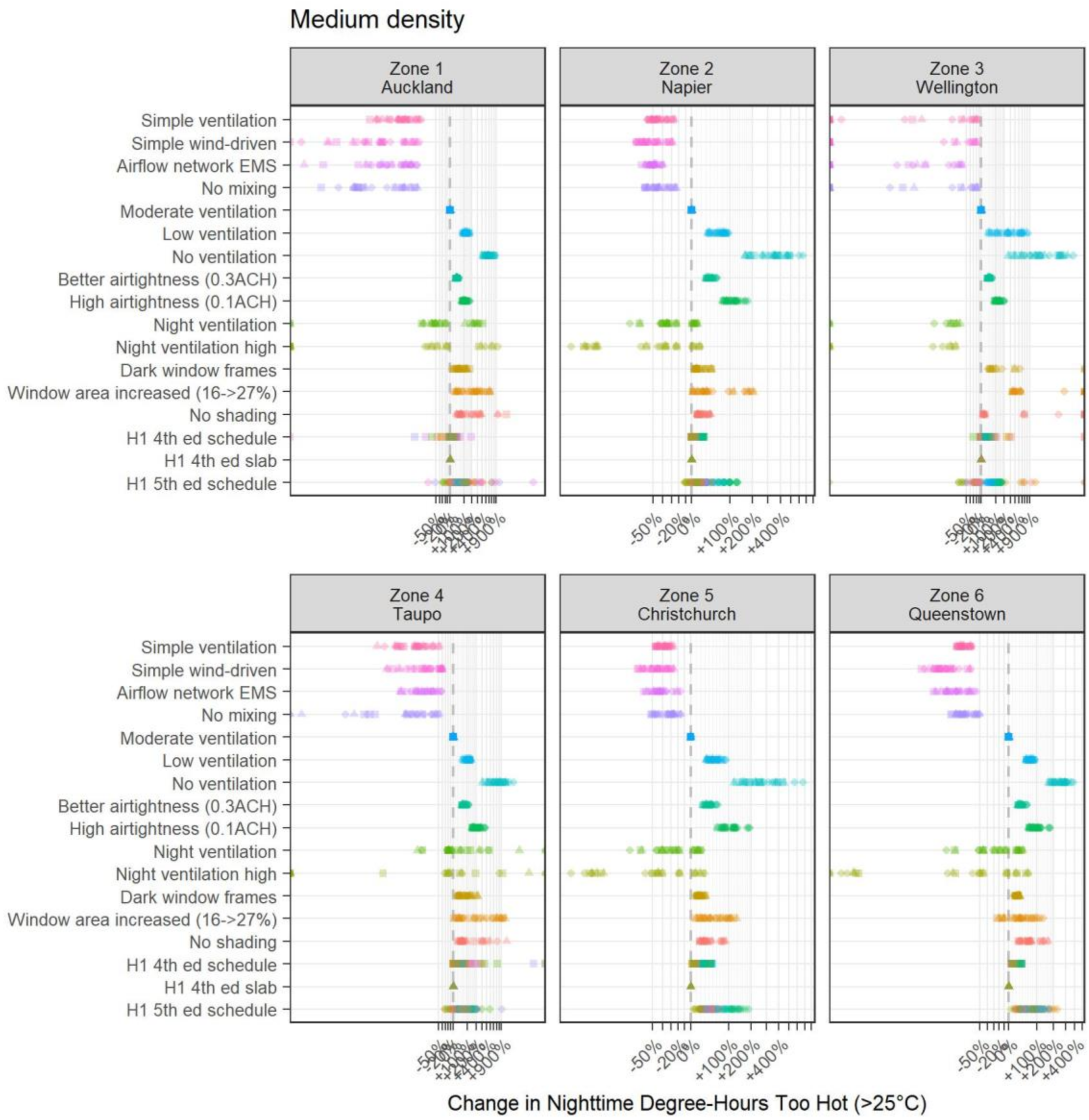


Figure 92: Relative change in night-time overheating in the medium-density house as a result of different factors

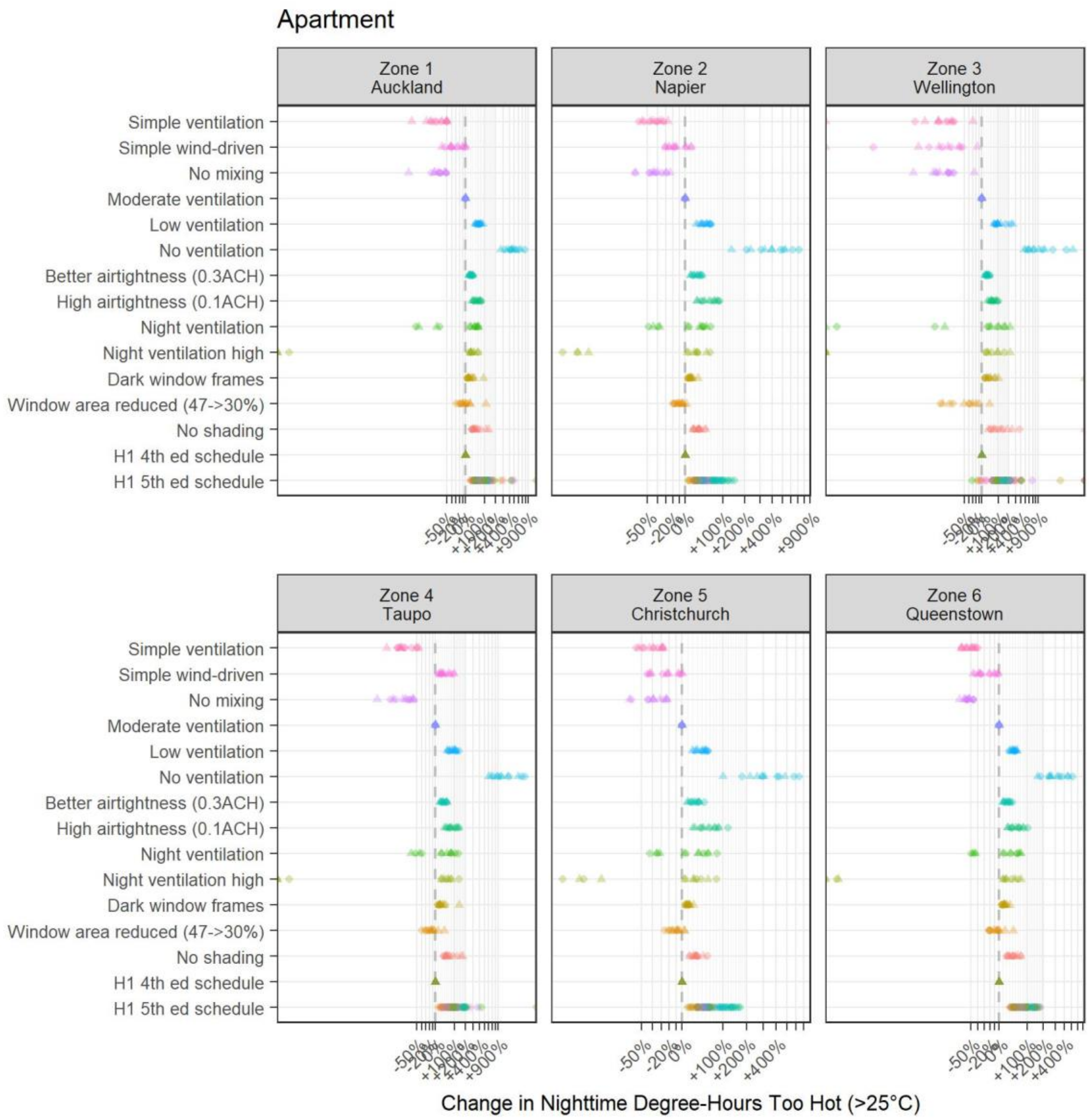


Figure 93: Relative change in night-time overheating in the apartments as a result of different factors

Additional overheating plots

Single-storey house

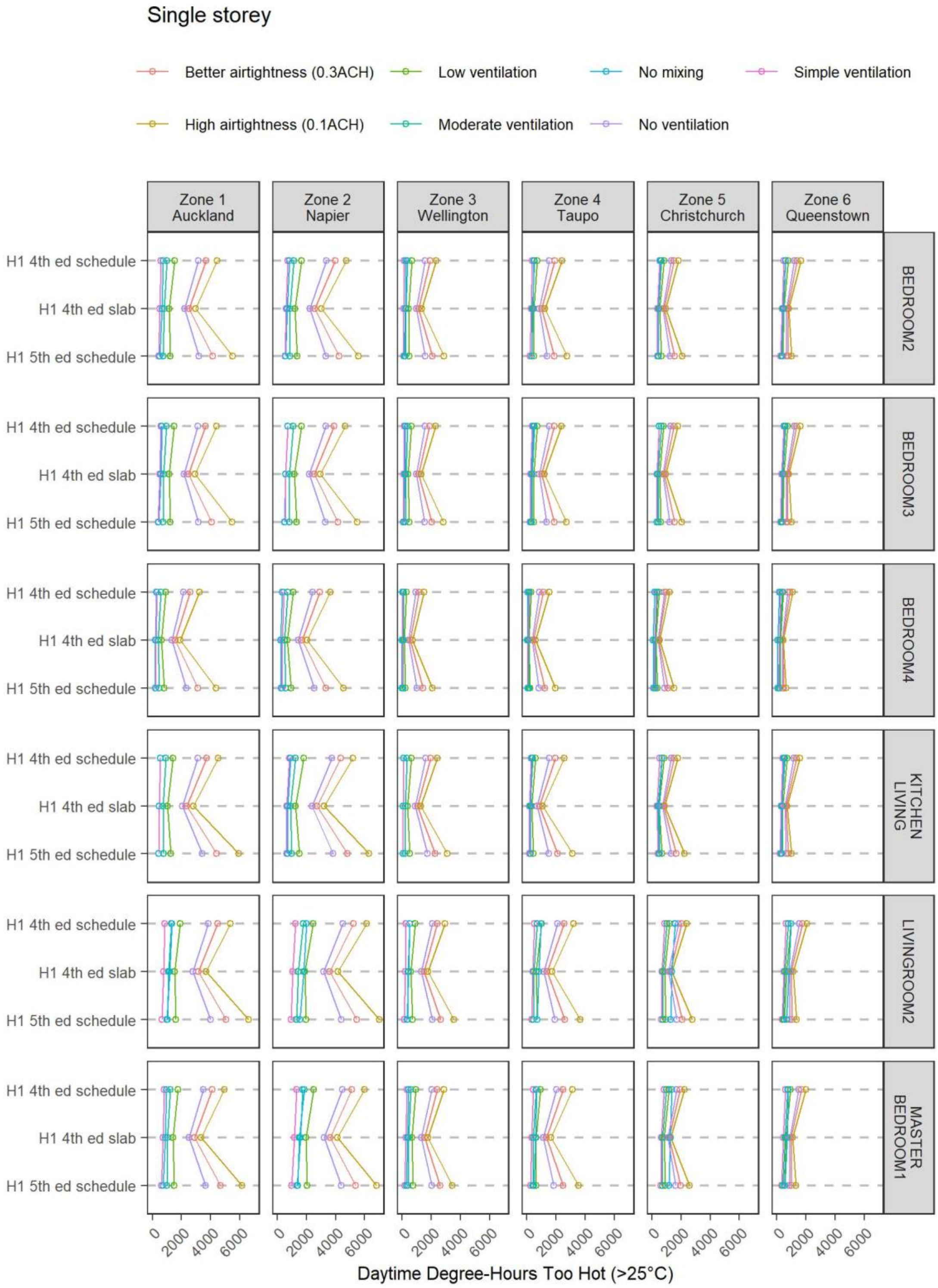


Figure 94: Daytime overheating under different ventilation assumptions

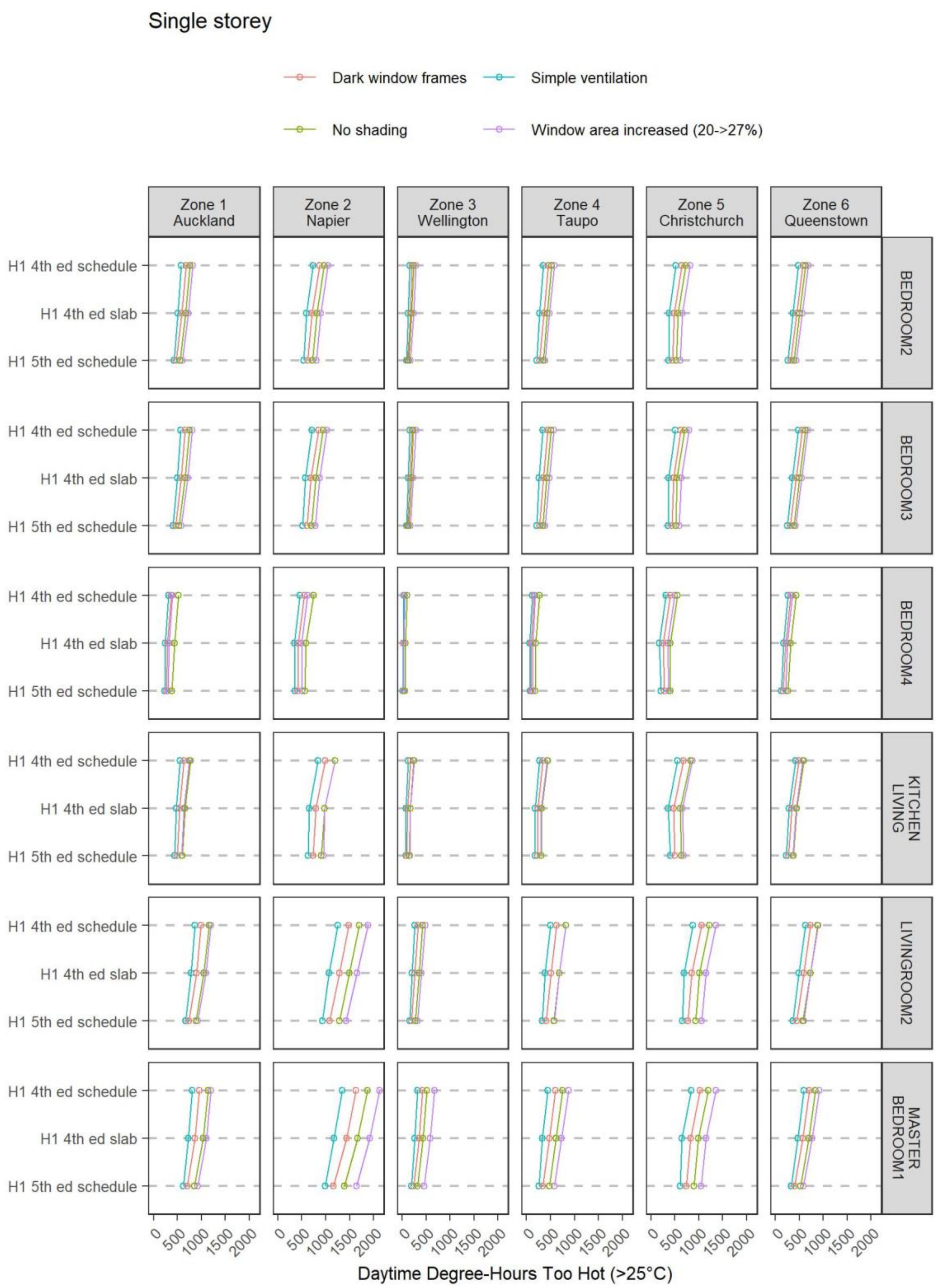


Figure 95: Daytime overheating under different design assumptions – simple ventilation is the base model

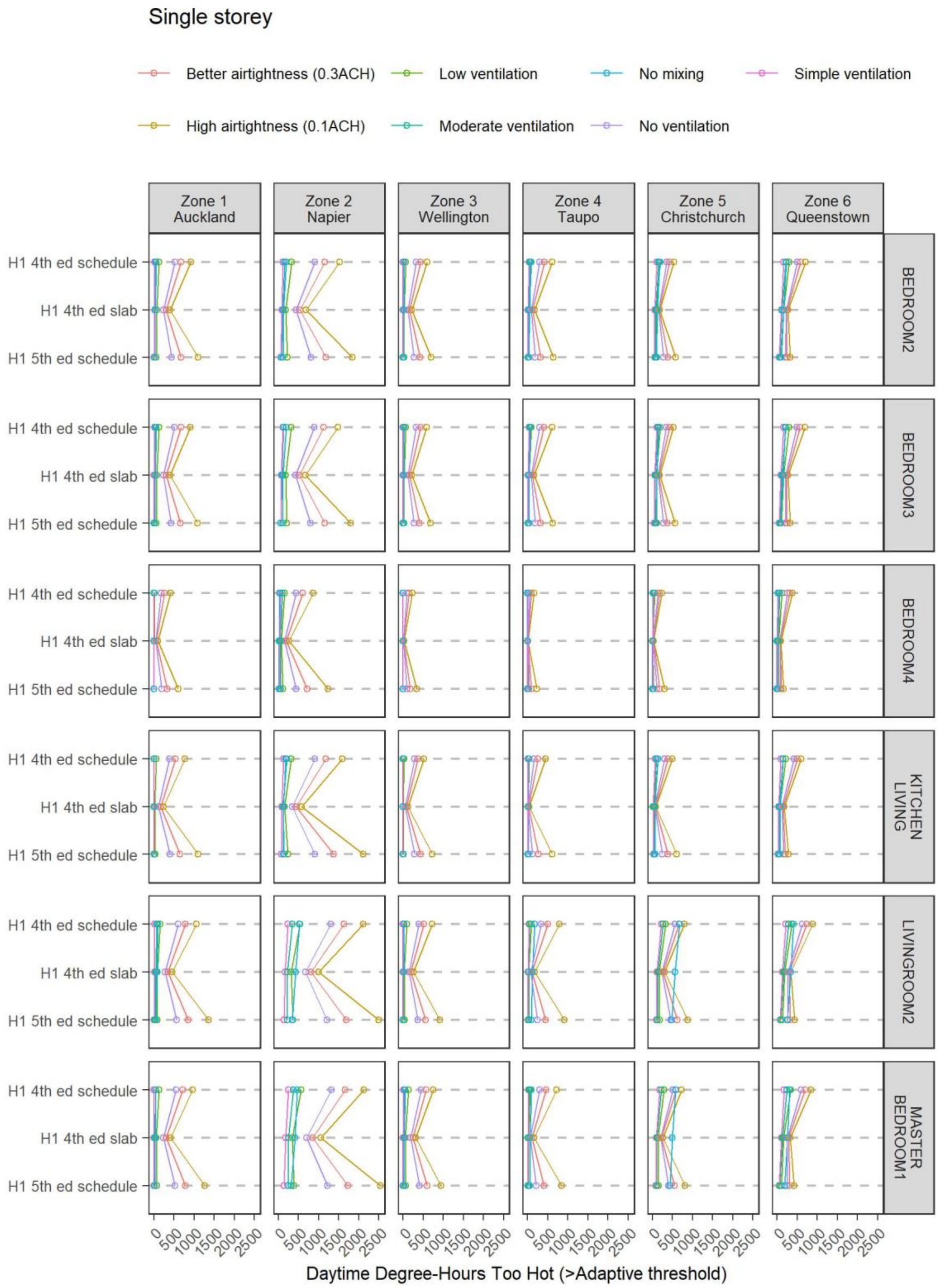


Figure 96: Daytime overheating under different ventilation assumptions using the TM52 adaptive comfort model

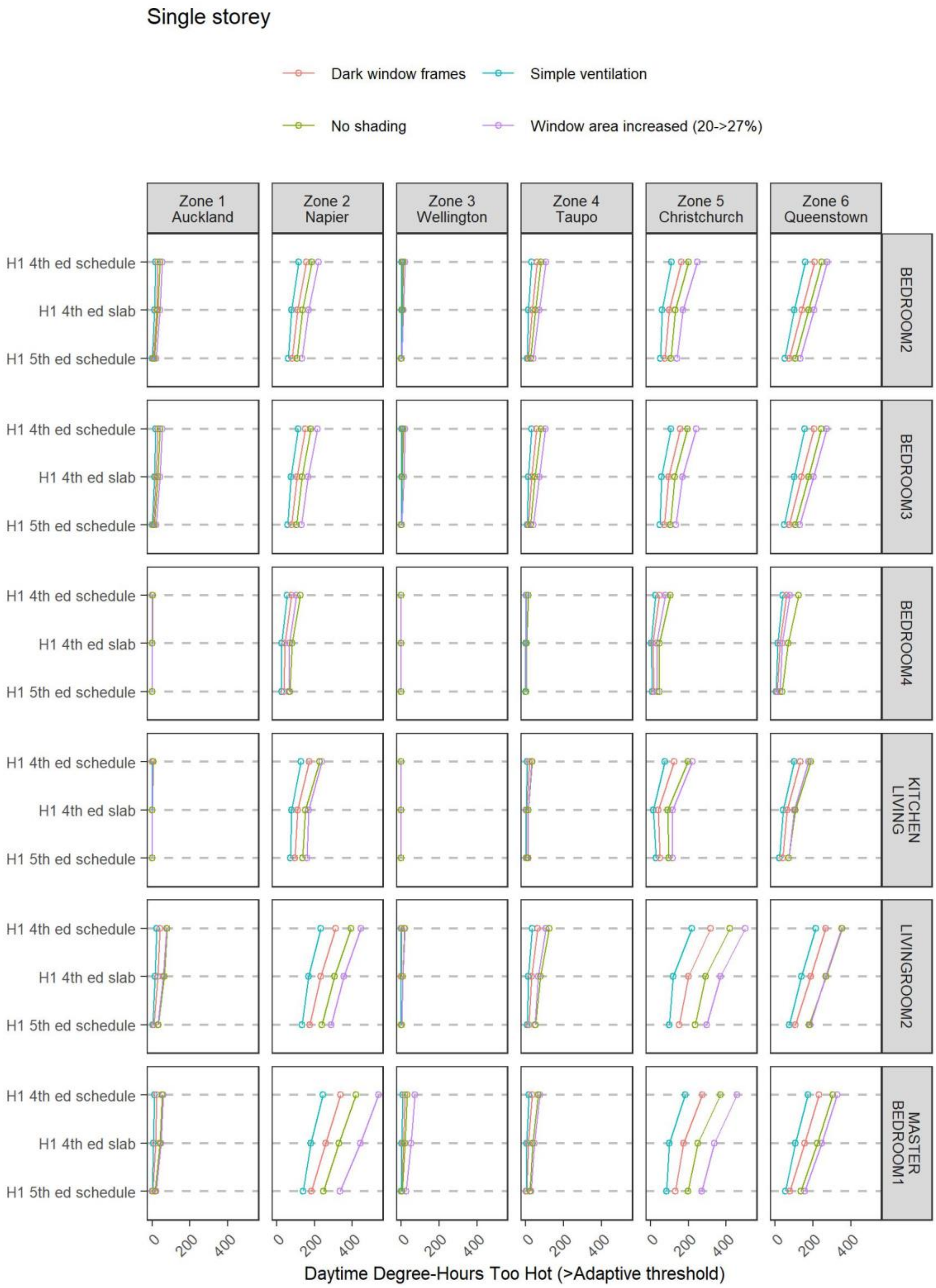


Figure 97: Daytime overheating under different design assumptions using the TM52 adaptive comfort model – simple ventilation is the base model

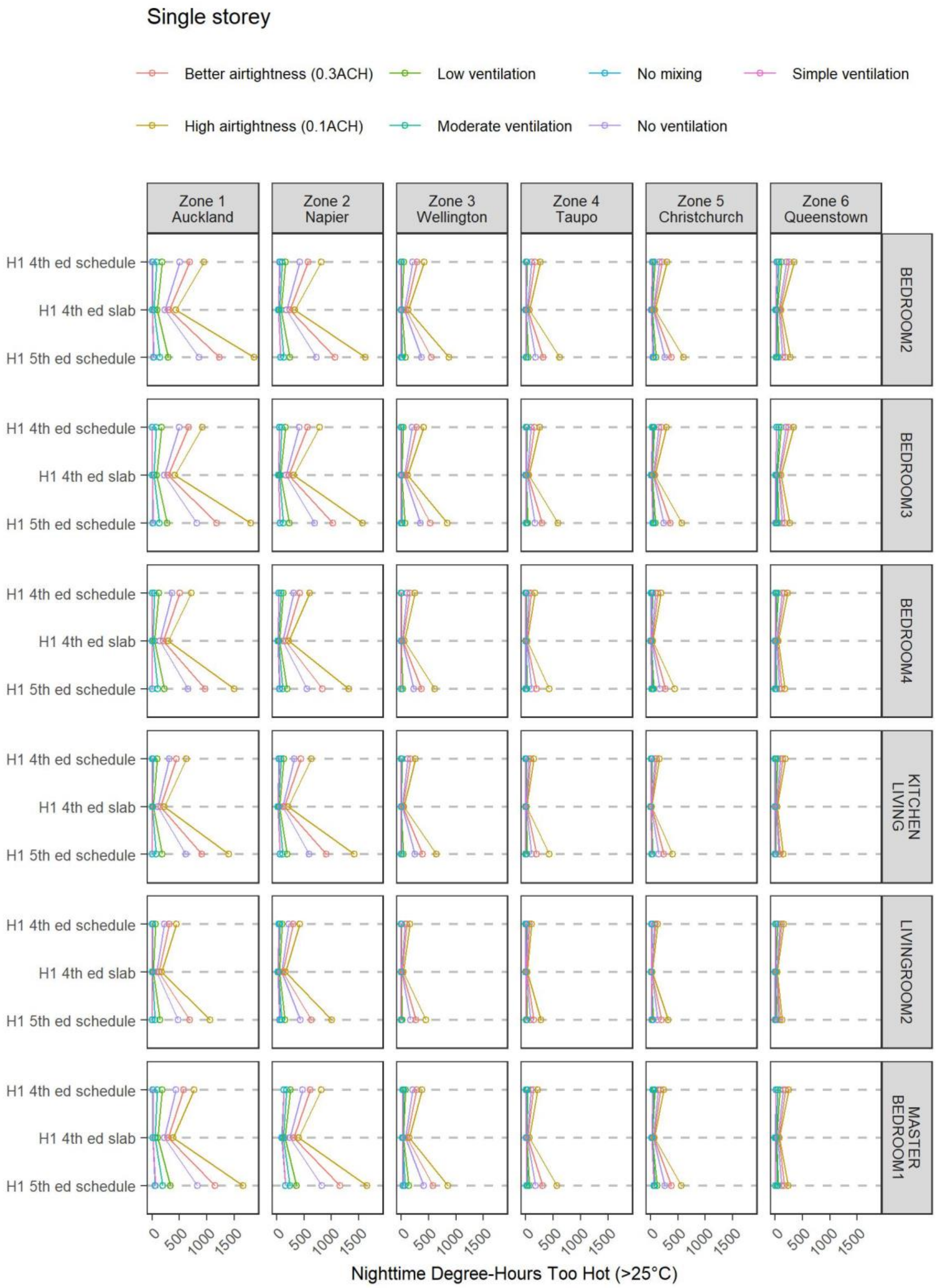


Figure 98: Night-time overheating under different ventilation assumptions

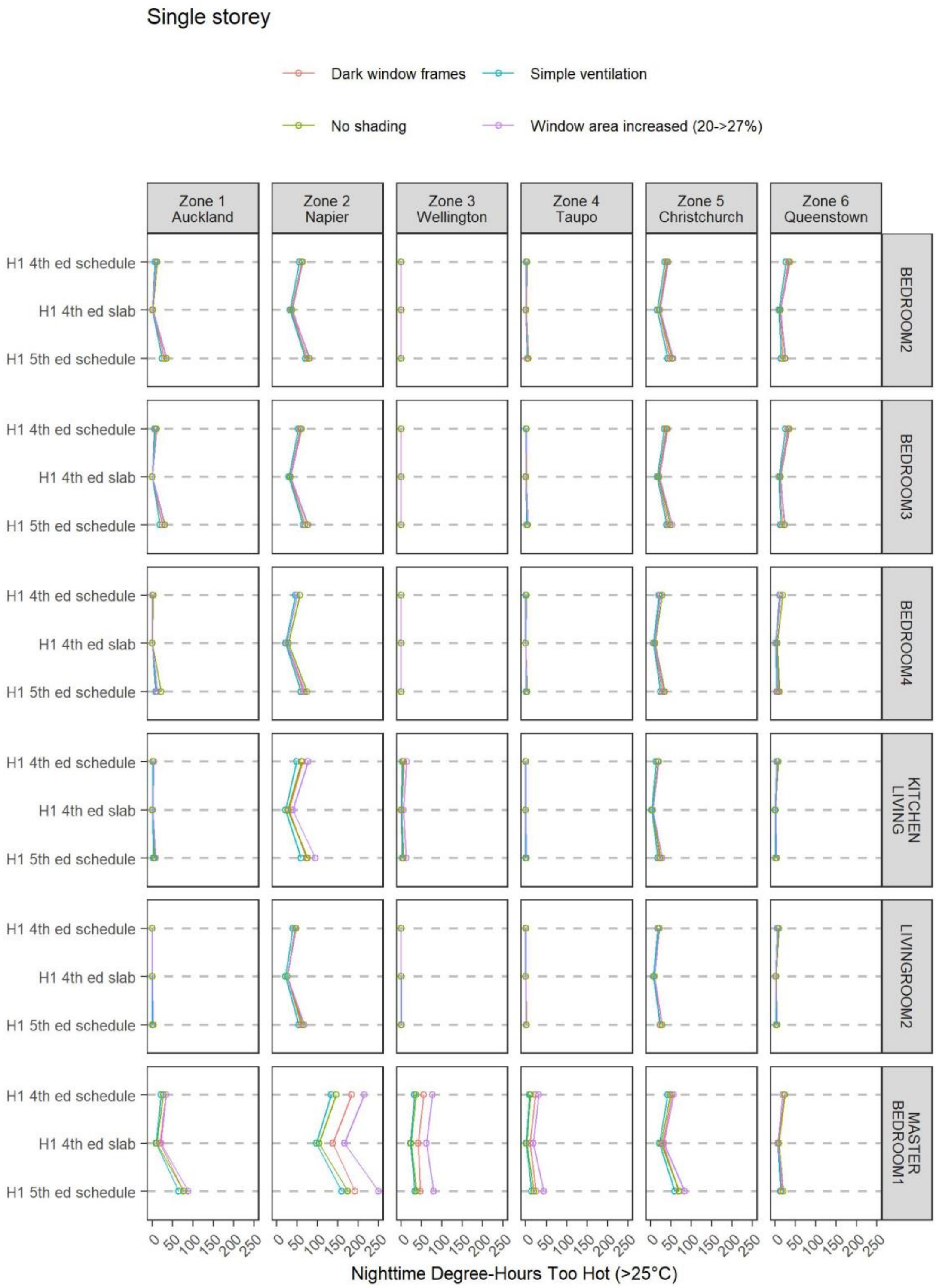


Figure 99: Night-time overheating under different design assumptions – simple ventilation is the base model

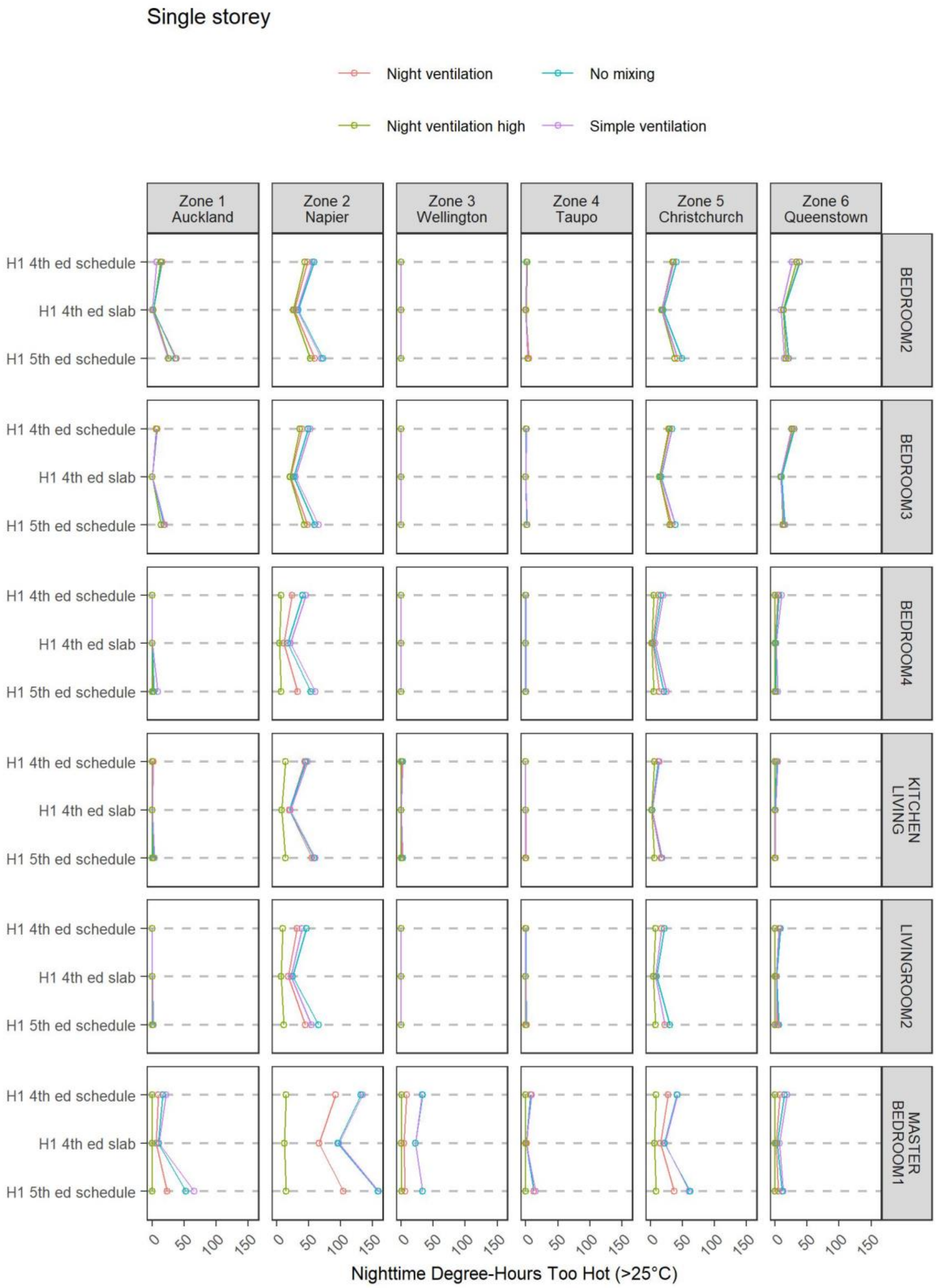


Figure 100: Night-time overheating under different night ventilation assumptions – simple ventilation is the base model

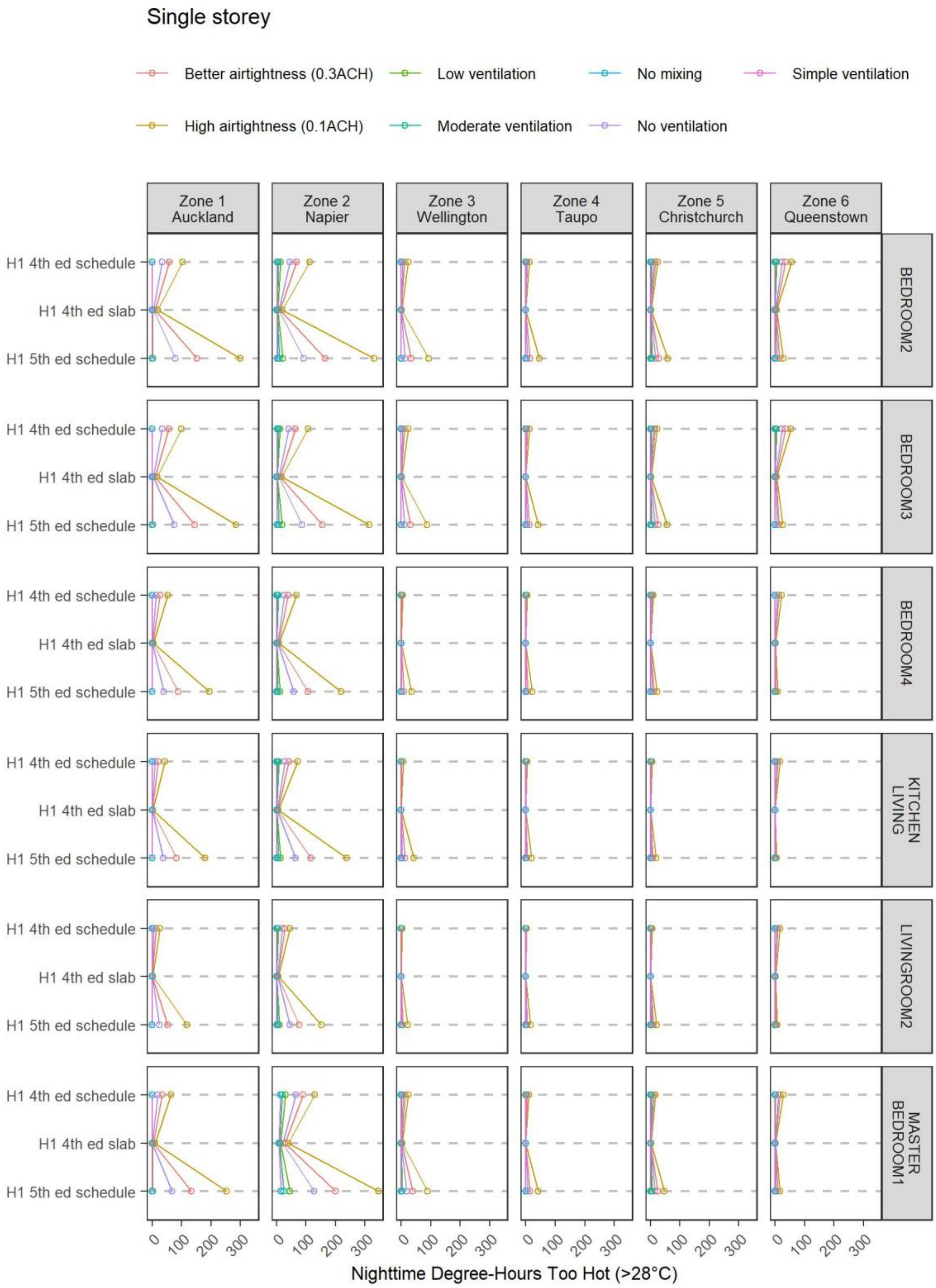


Figure 101: Night-time overheating under different ventilation assumptions using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023)

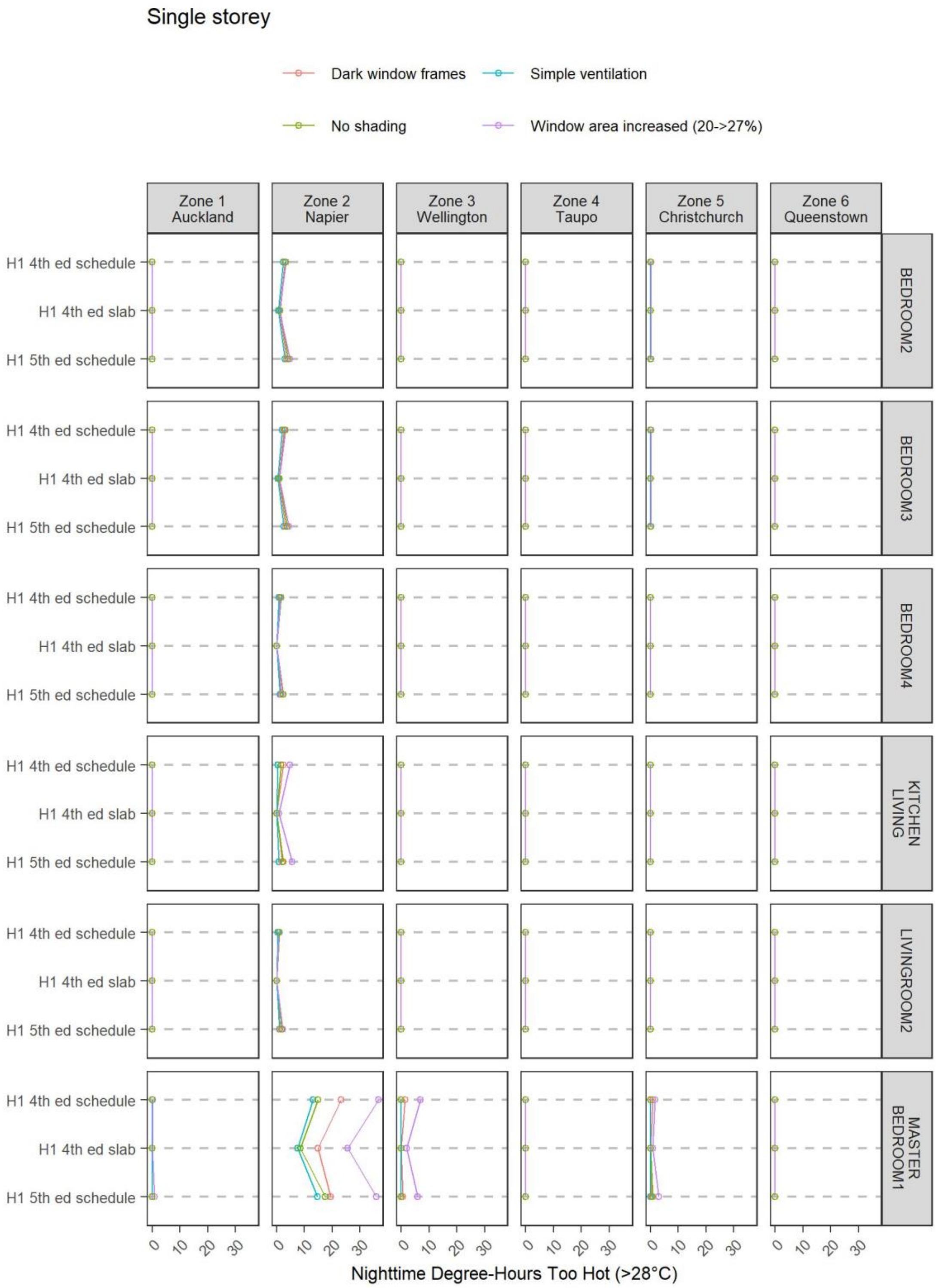


Figure 102: Night-time overheating under different design assumptions using the TM52 adaptive comfort model using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023) – simple ventilation is the base model

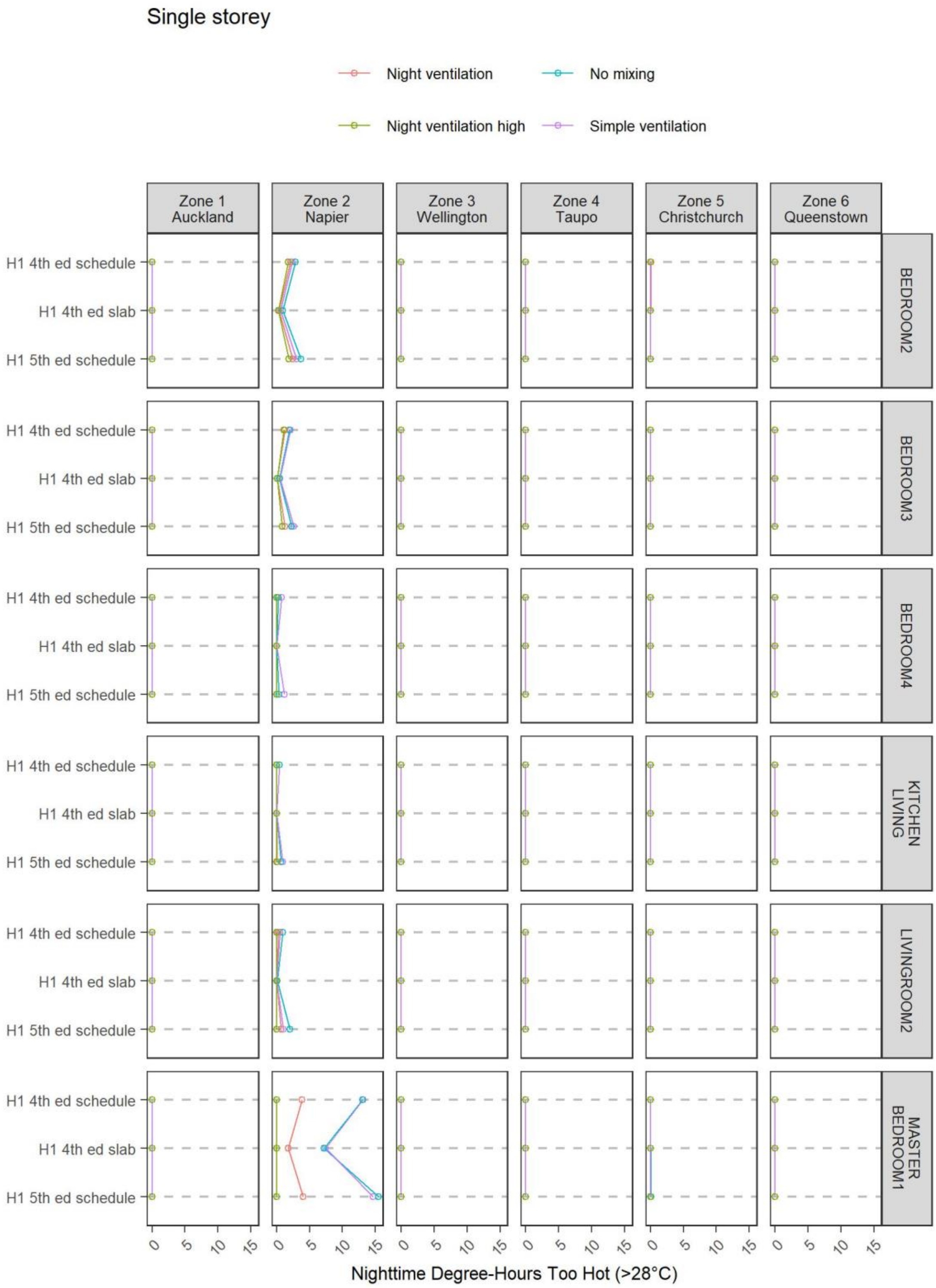


Figure 103: Night-time overheating under different night ventilation assumptions using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023) – simple ventilation is the base model

Two-storey house

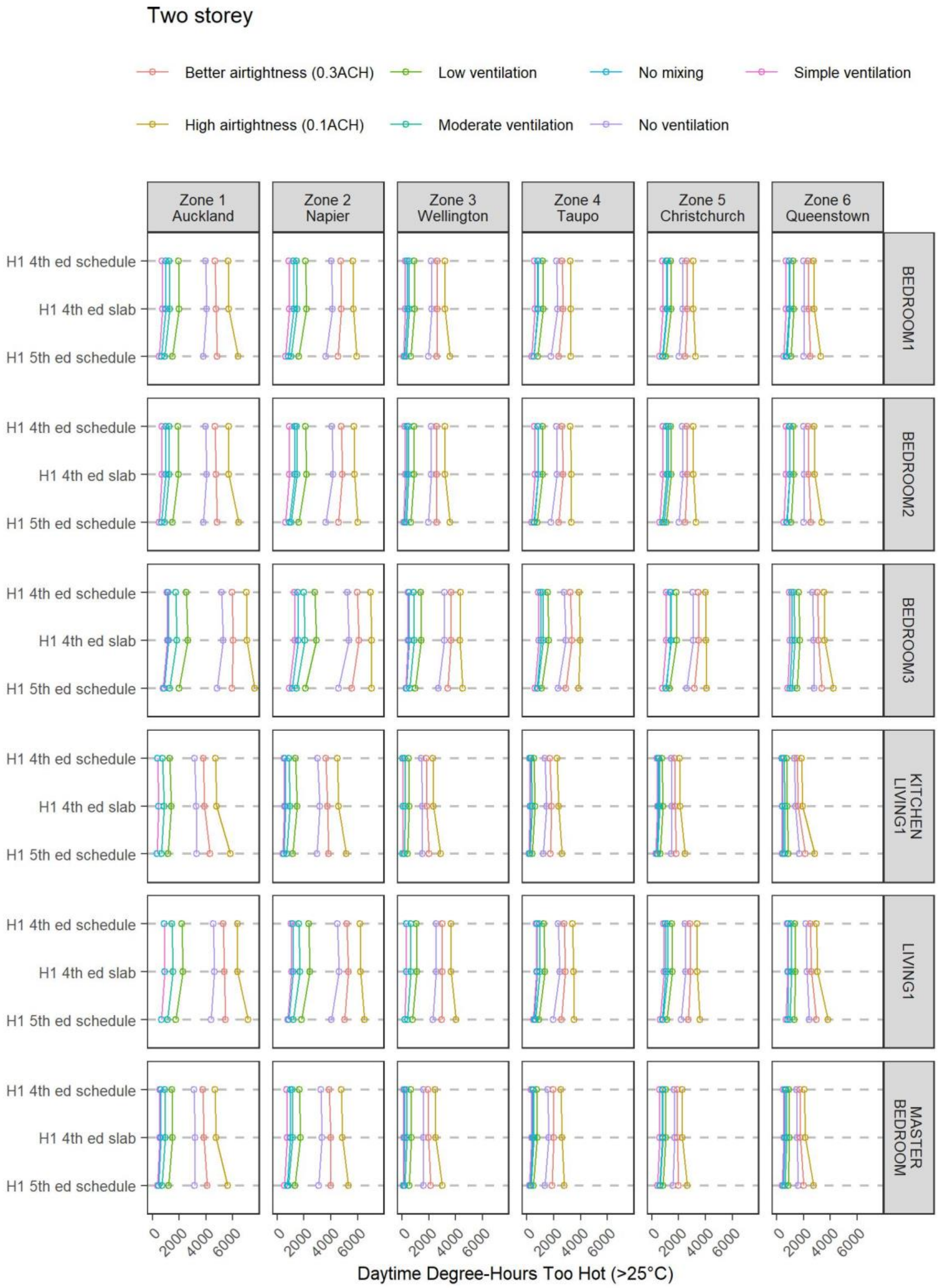


Figure 104: Daytime overheating under different ventilation assumptions

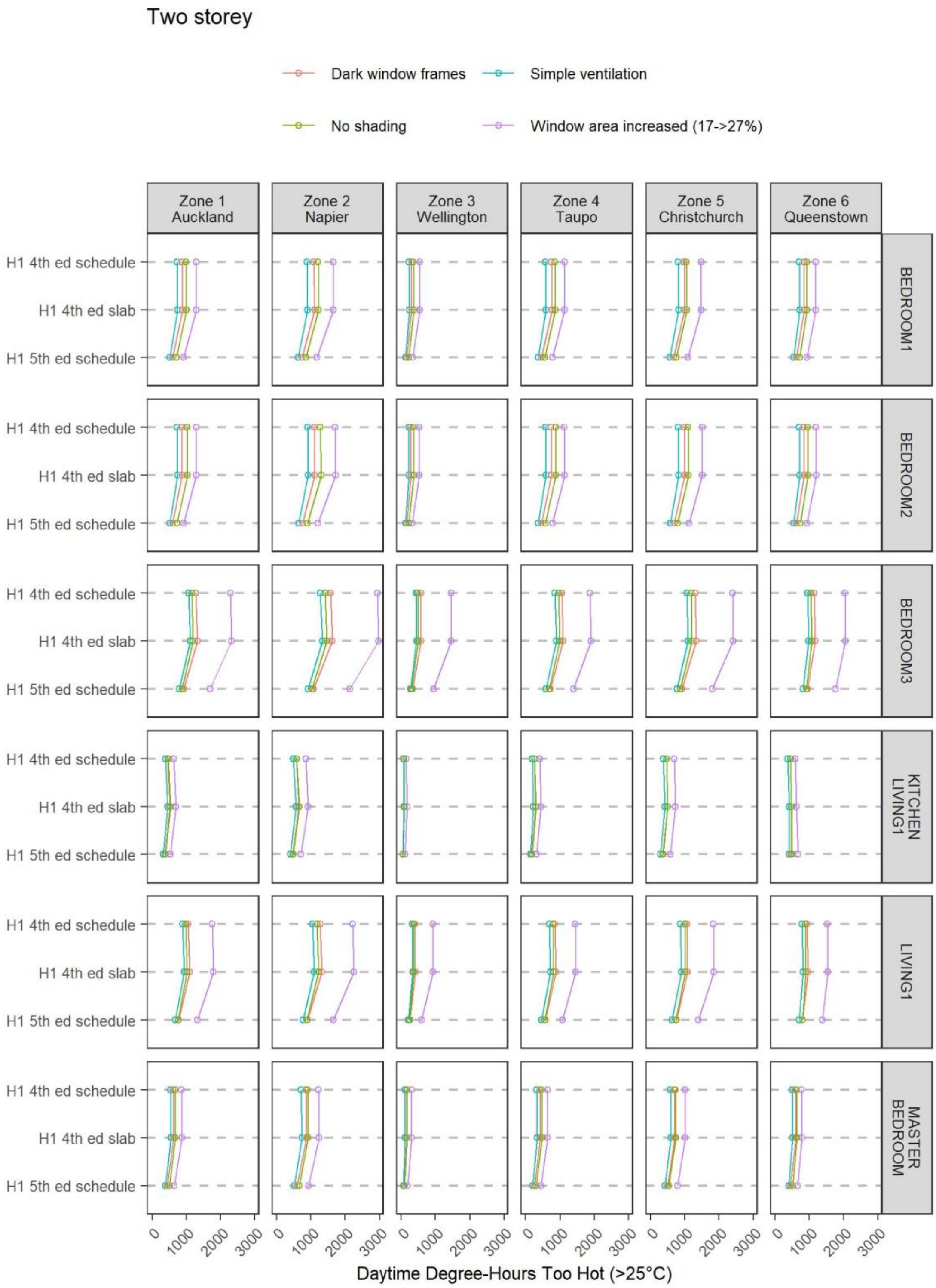


Figure 105: Daytime overheating under different design assumptions – simple ventilation is the base model

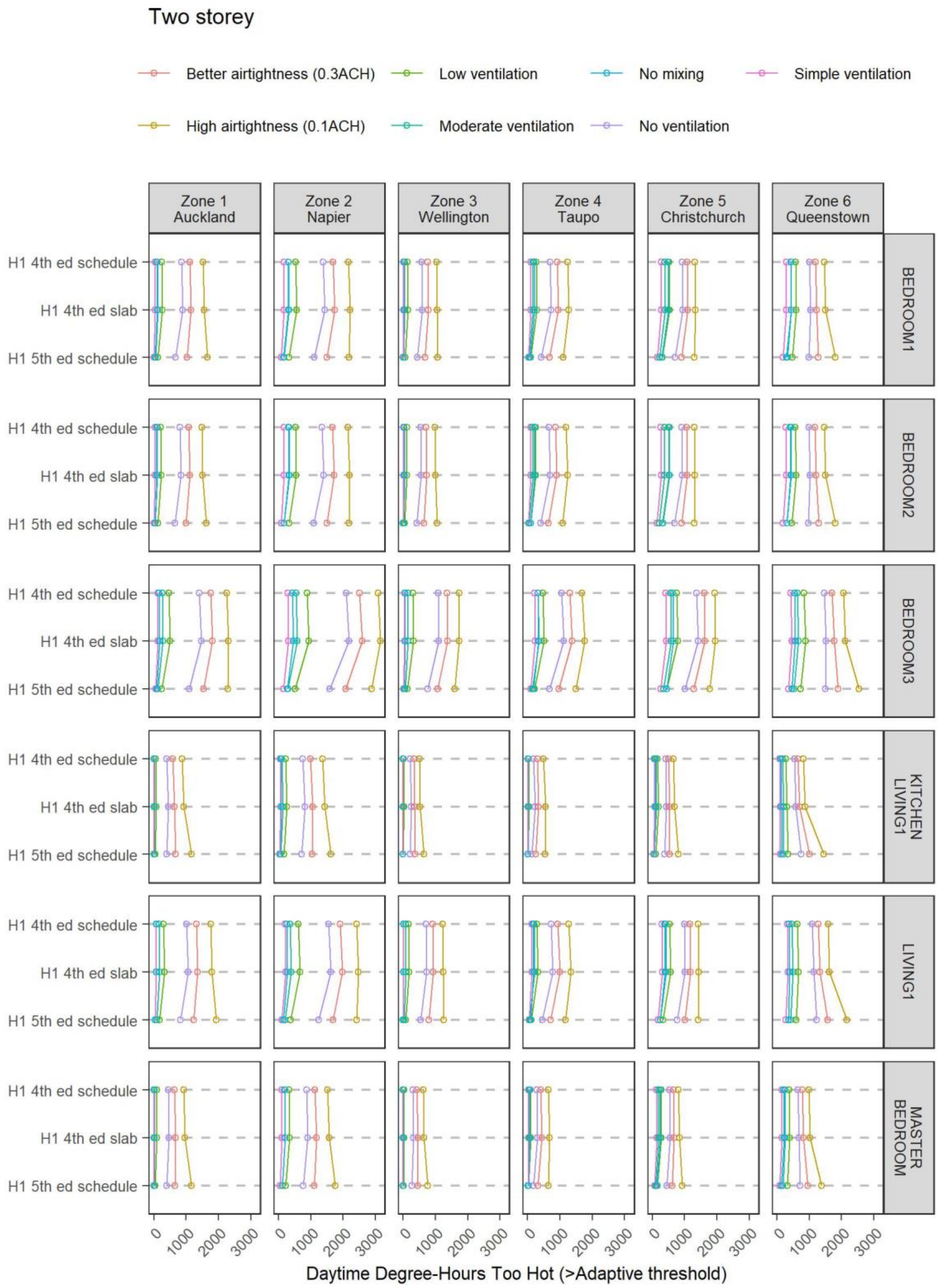


Figure 106: Daytime overheating under different ventilation assumptions using the TM52 adaptive comfort model

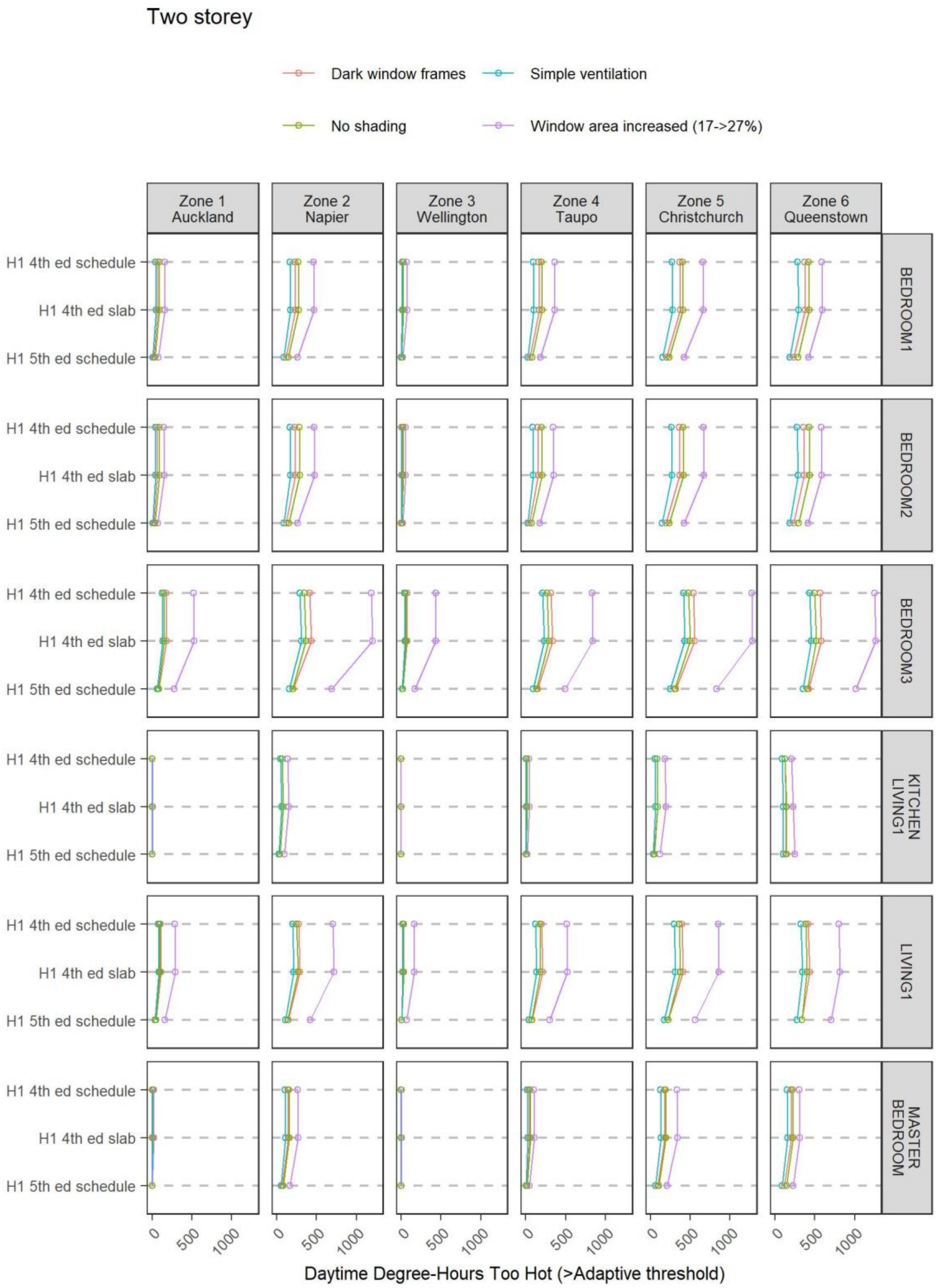


Figure 107: Daytime overheating under different design assumptions using the TM52 adaptive comfort model – simple ventilation is the base model

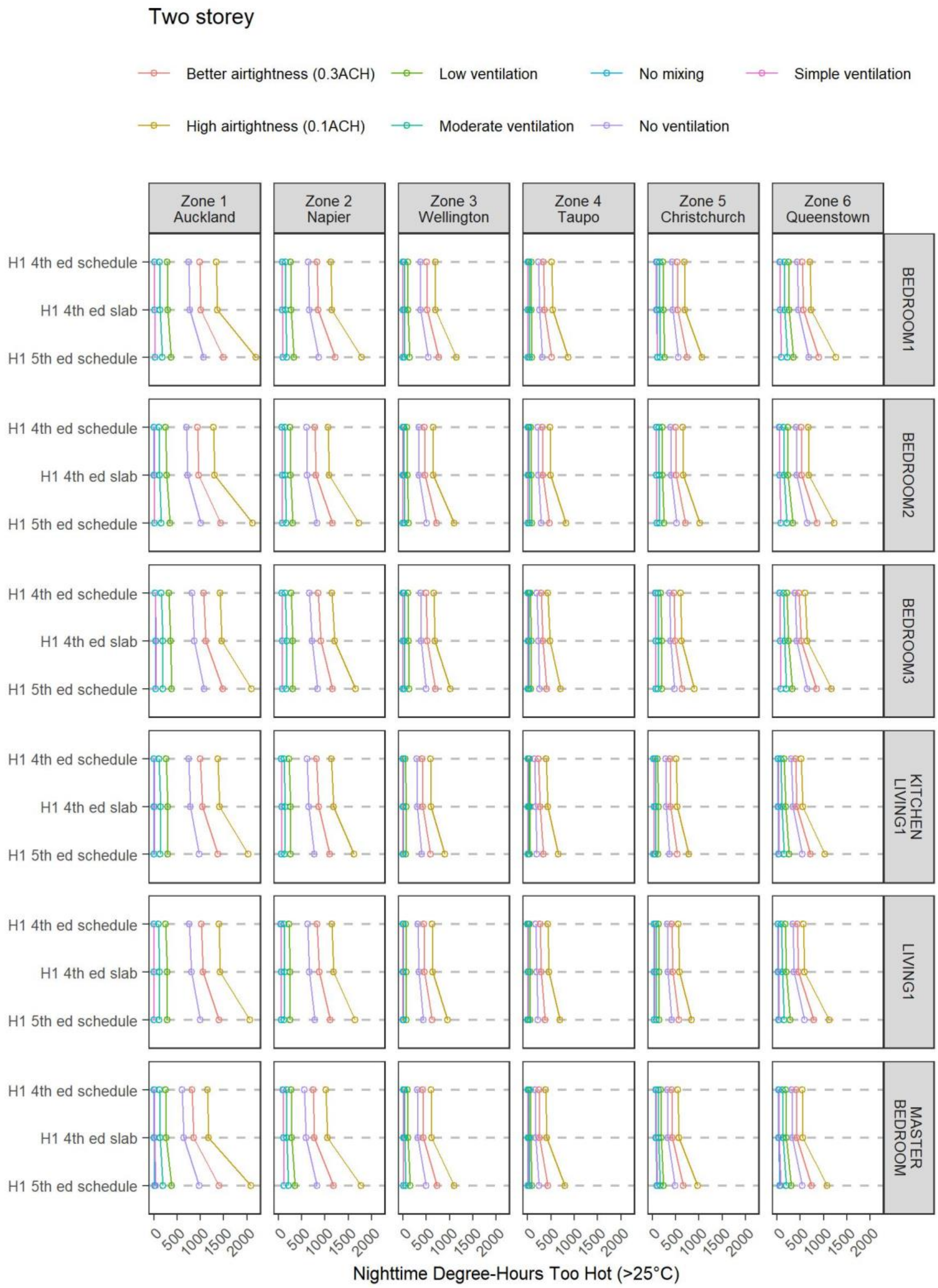


Figure 108: Night-time overheating under different ventilation assumptions

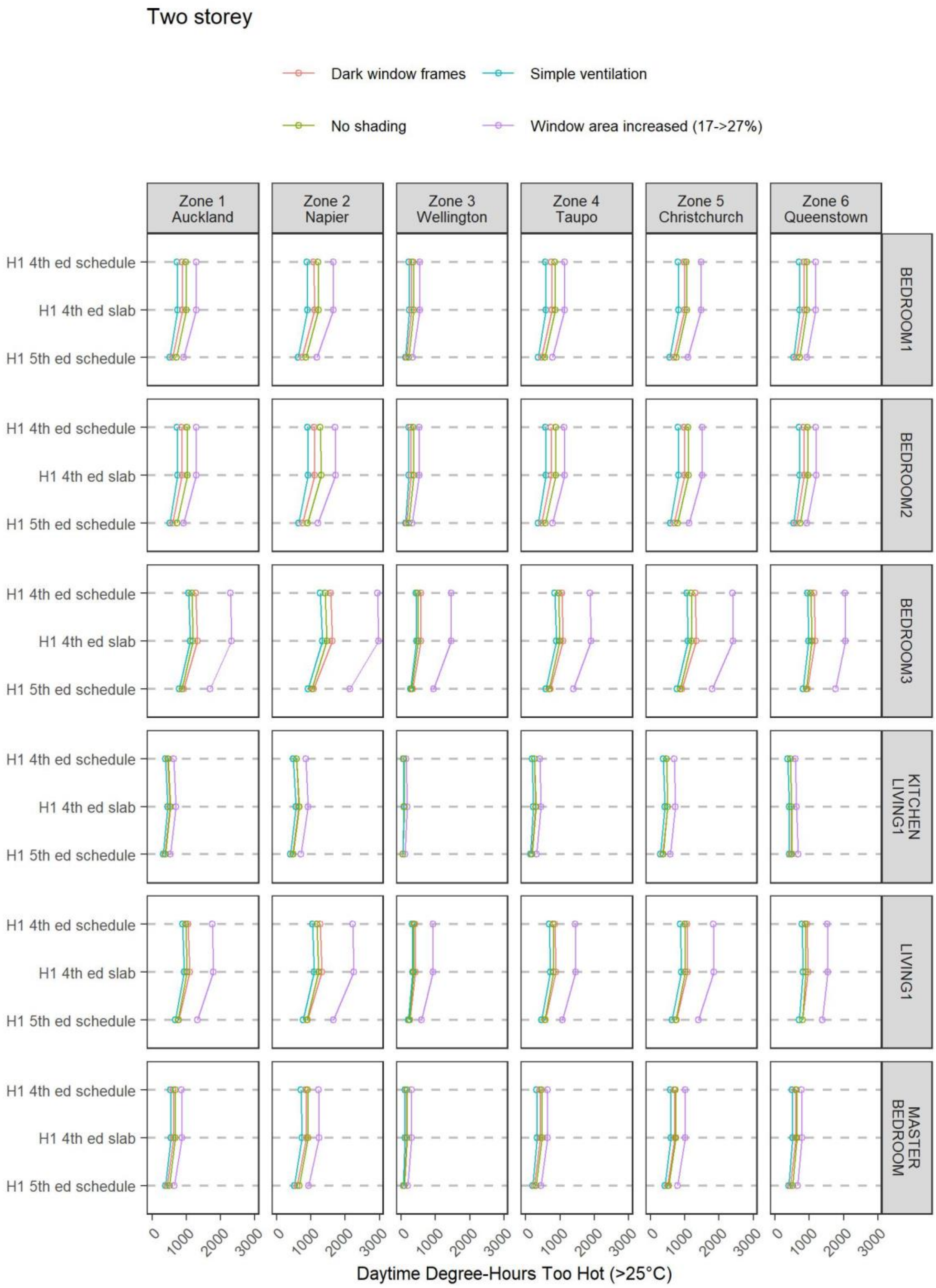


Figure 109: Night-time overheating under different design assumptions – simple ventilation is the base model

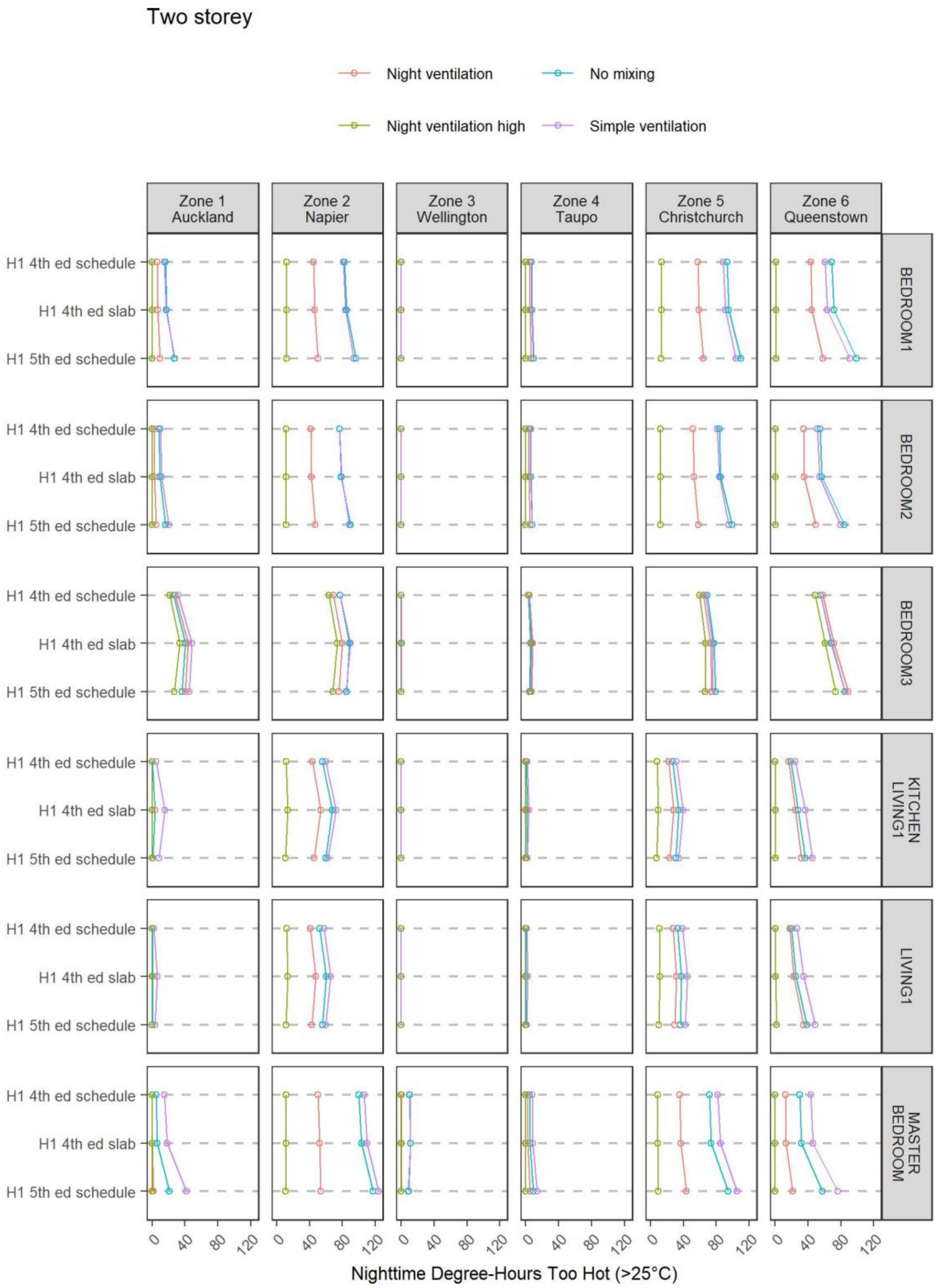


Figure 110: Night-time overheating under different night ventilation assumptions – simple ventilation is the base model

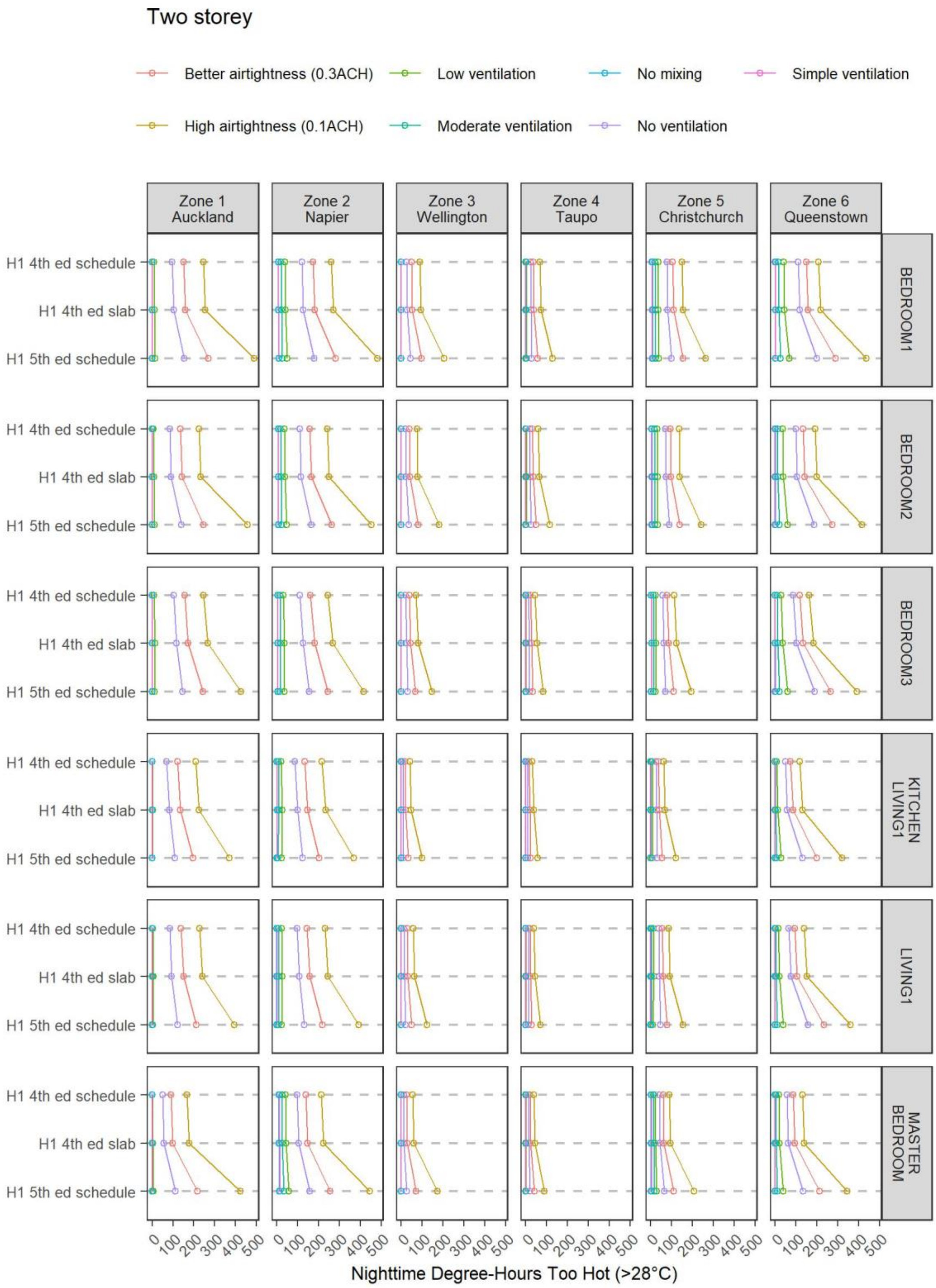


Figure 111: Night-time overheating under different ventilation assumptions using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023)

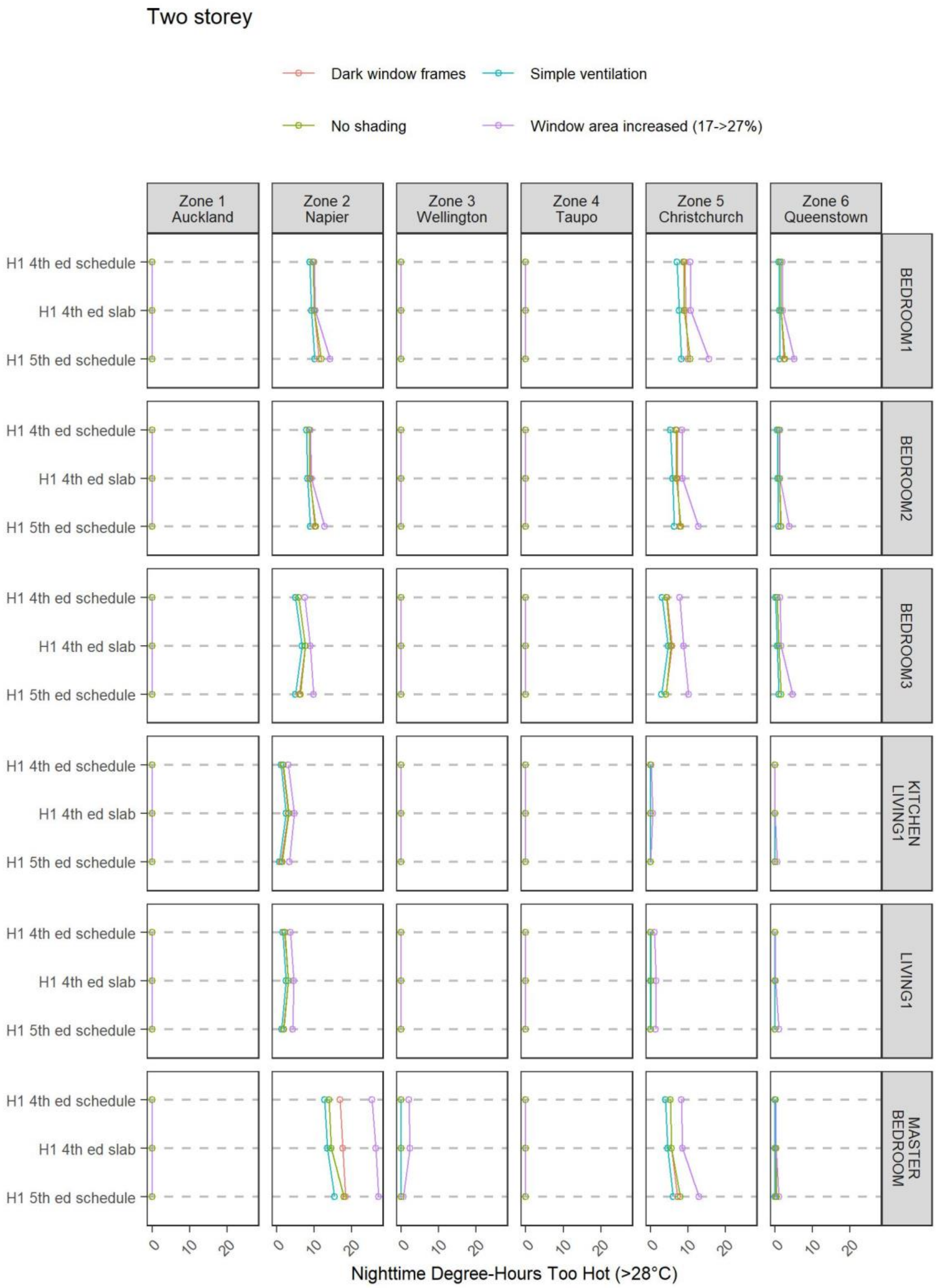


Figure 112: Night-time overheating under different design assumptions using the TM52 adaptive comfort model using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023) – simple ventilation is the base model

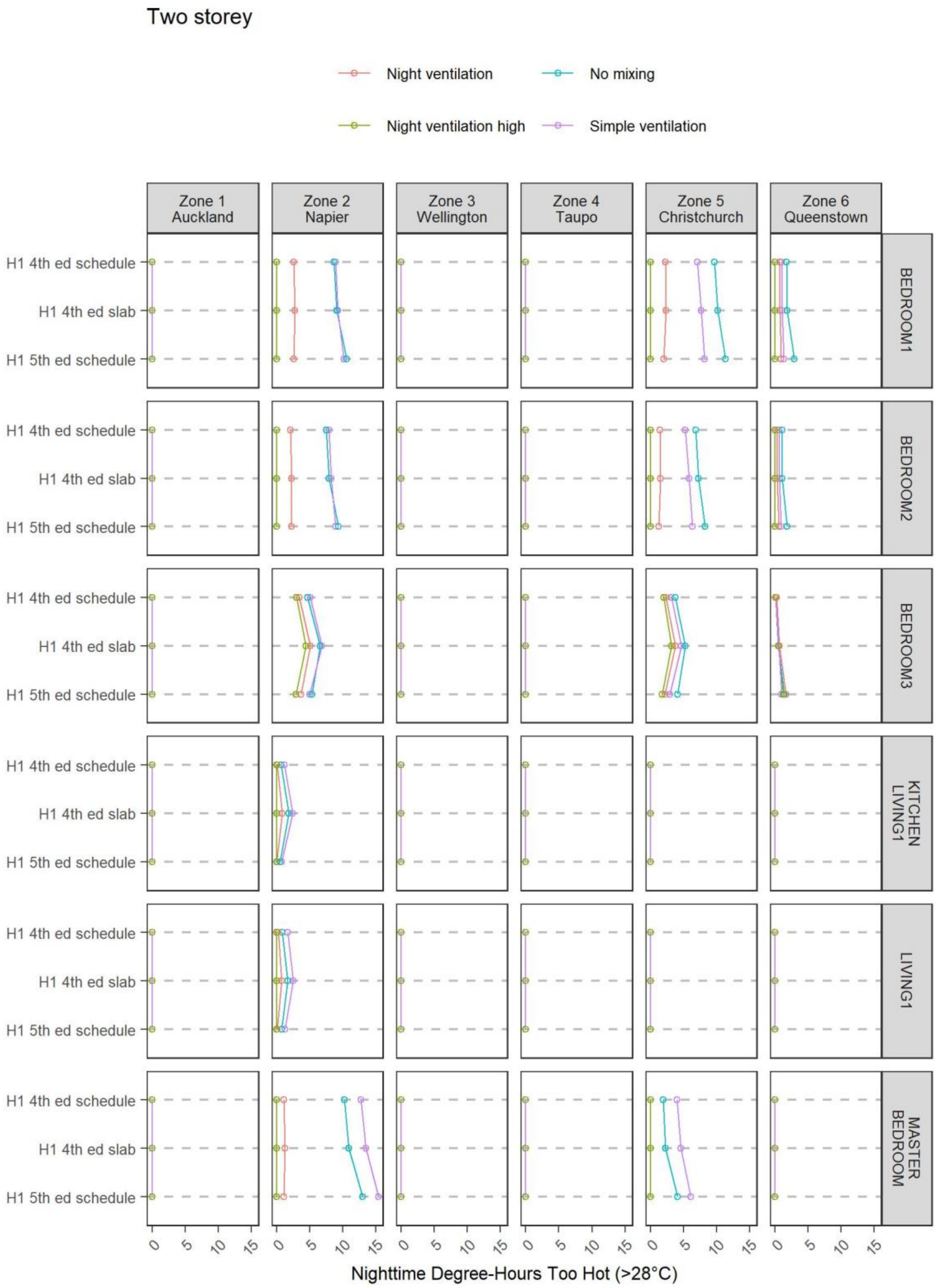


Figure 113: Night-time overheating under different night ventilation assumptions using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023) – simple ventilation is the base model

Medium density house

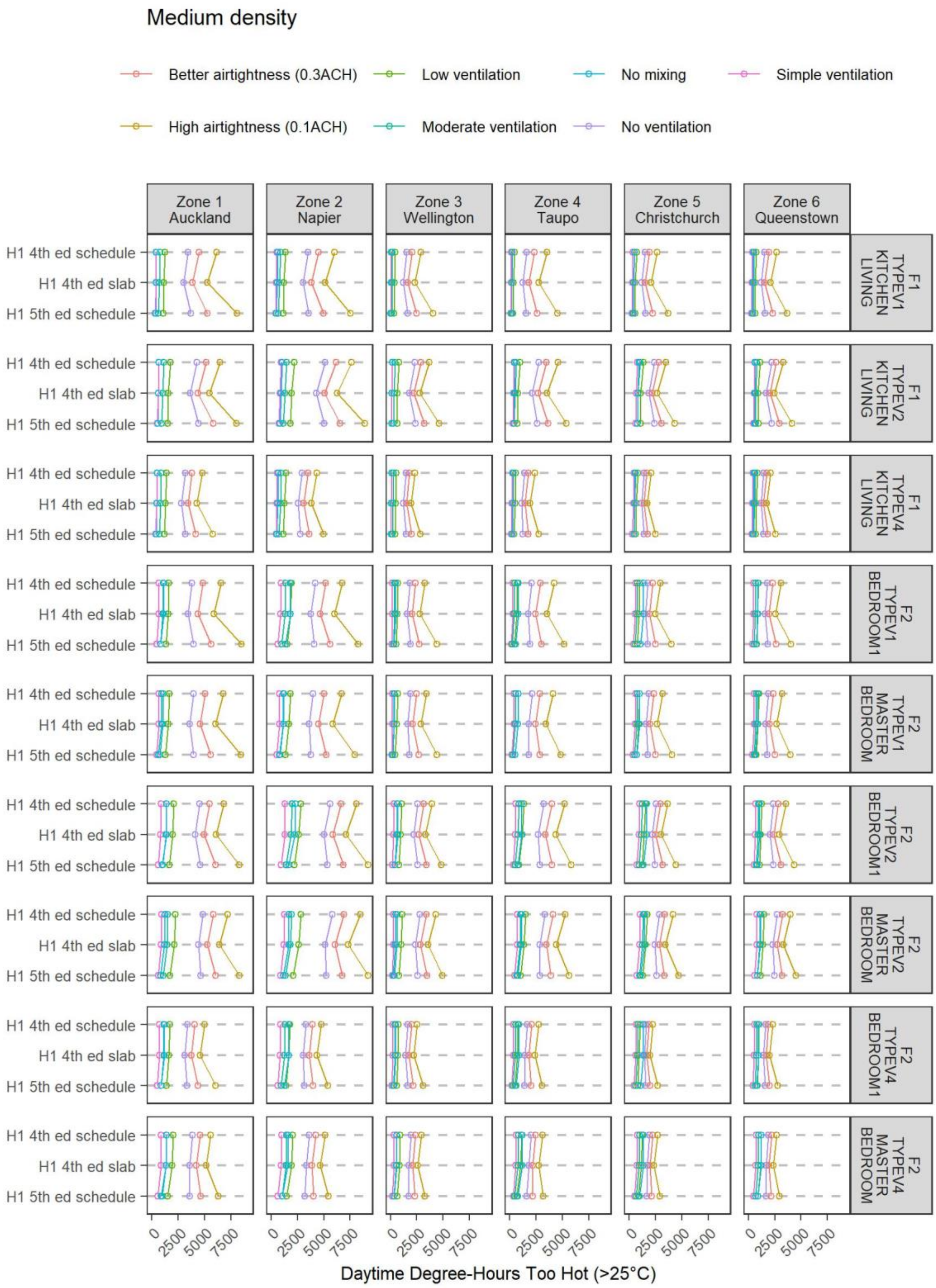


Figure 114: Daytime overheating under different ventilation assumptions

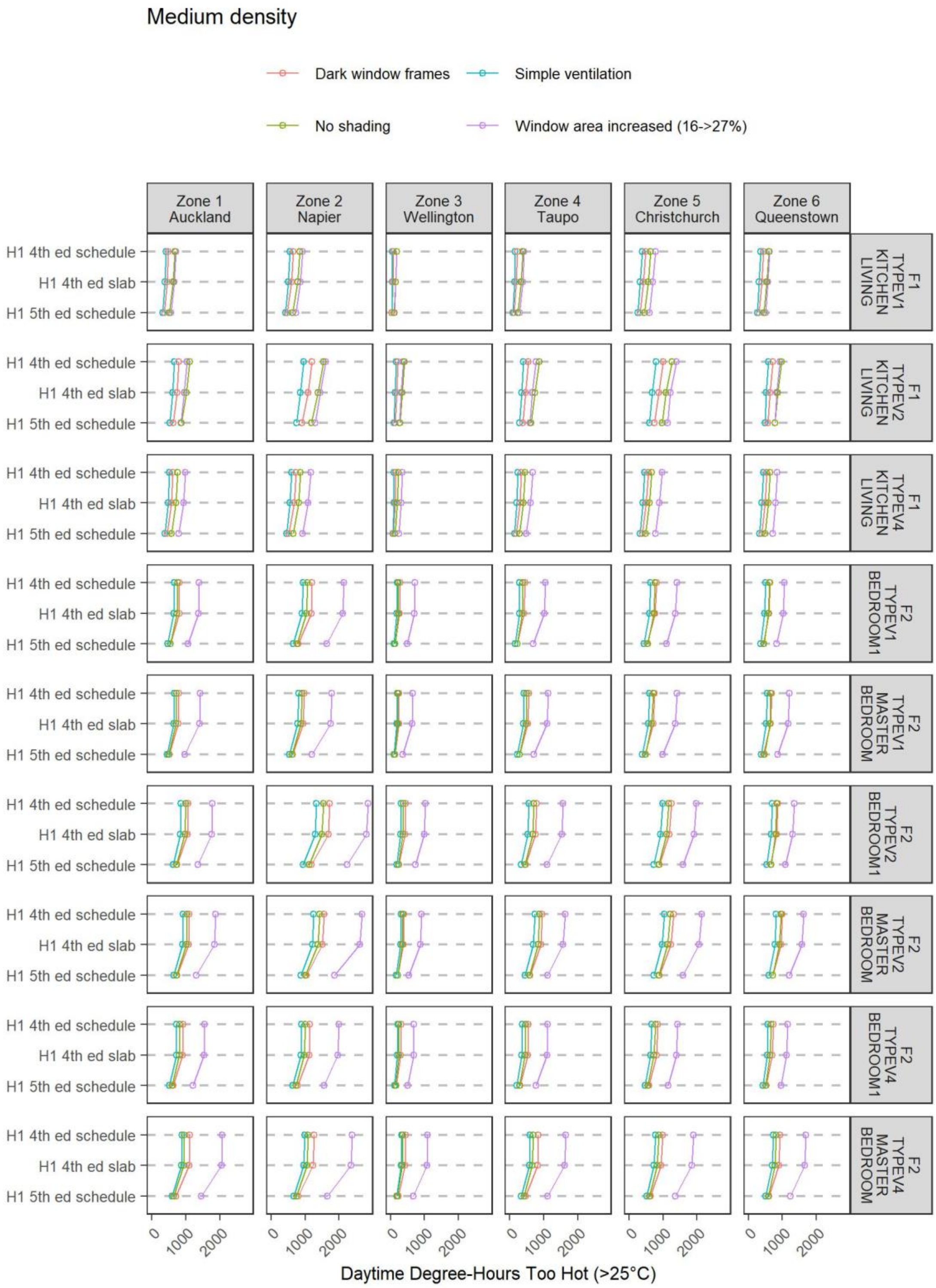


Figure 115: Daytime overheating under different design assumptions – simple ventilation is the base model

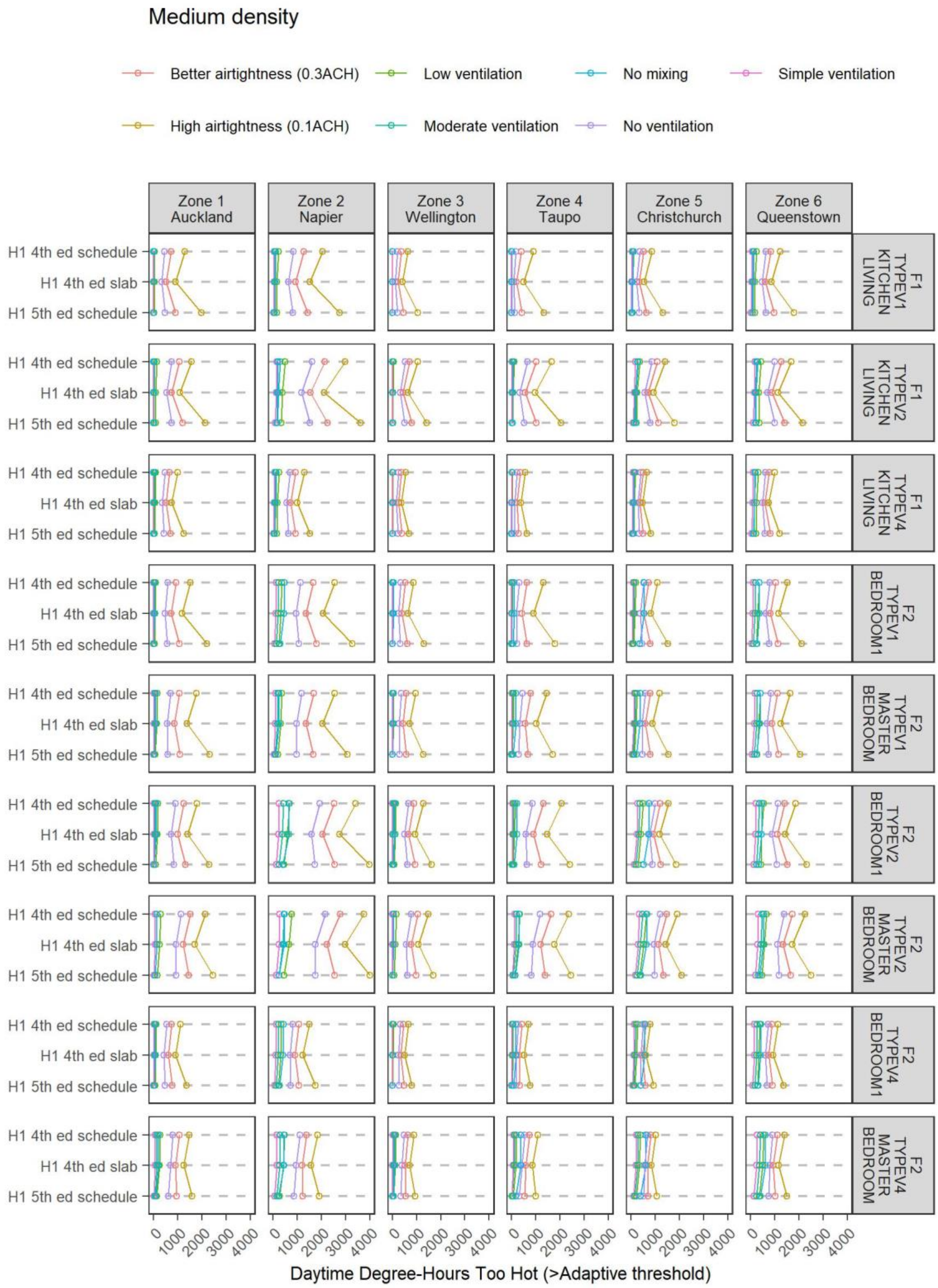


Figure 116: Daytime overheating under different ventilation assumptions using the TM52 adaptive comfort model

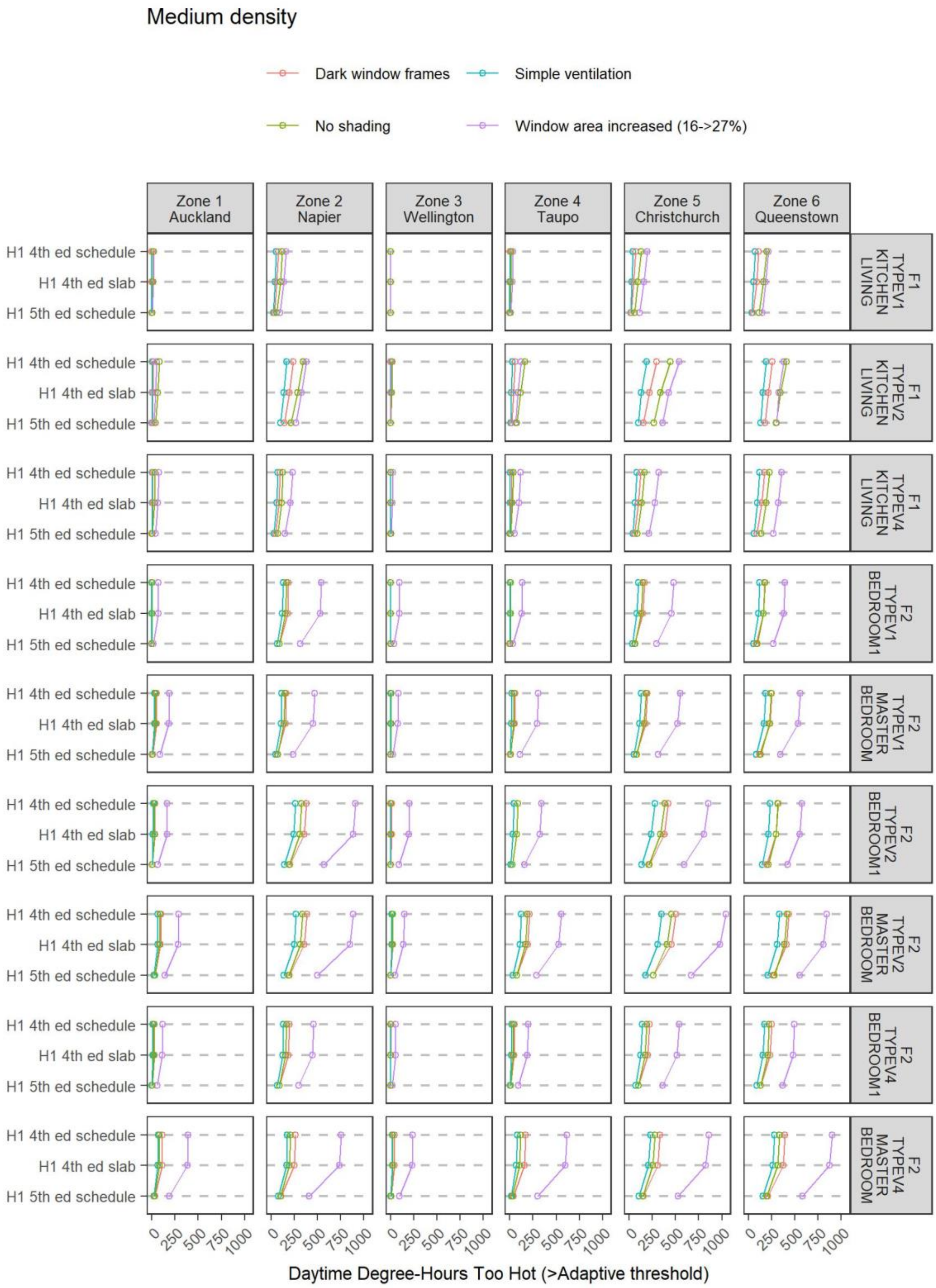


Figure 117: Daytime overheating under different design assumptions using the TM52 adaptive comfort model – simple ventilation is the base model

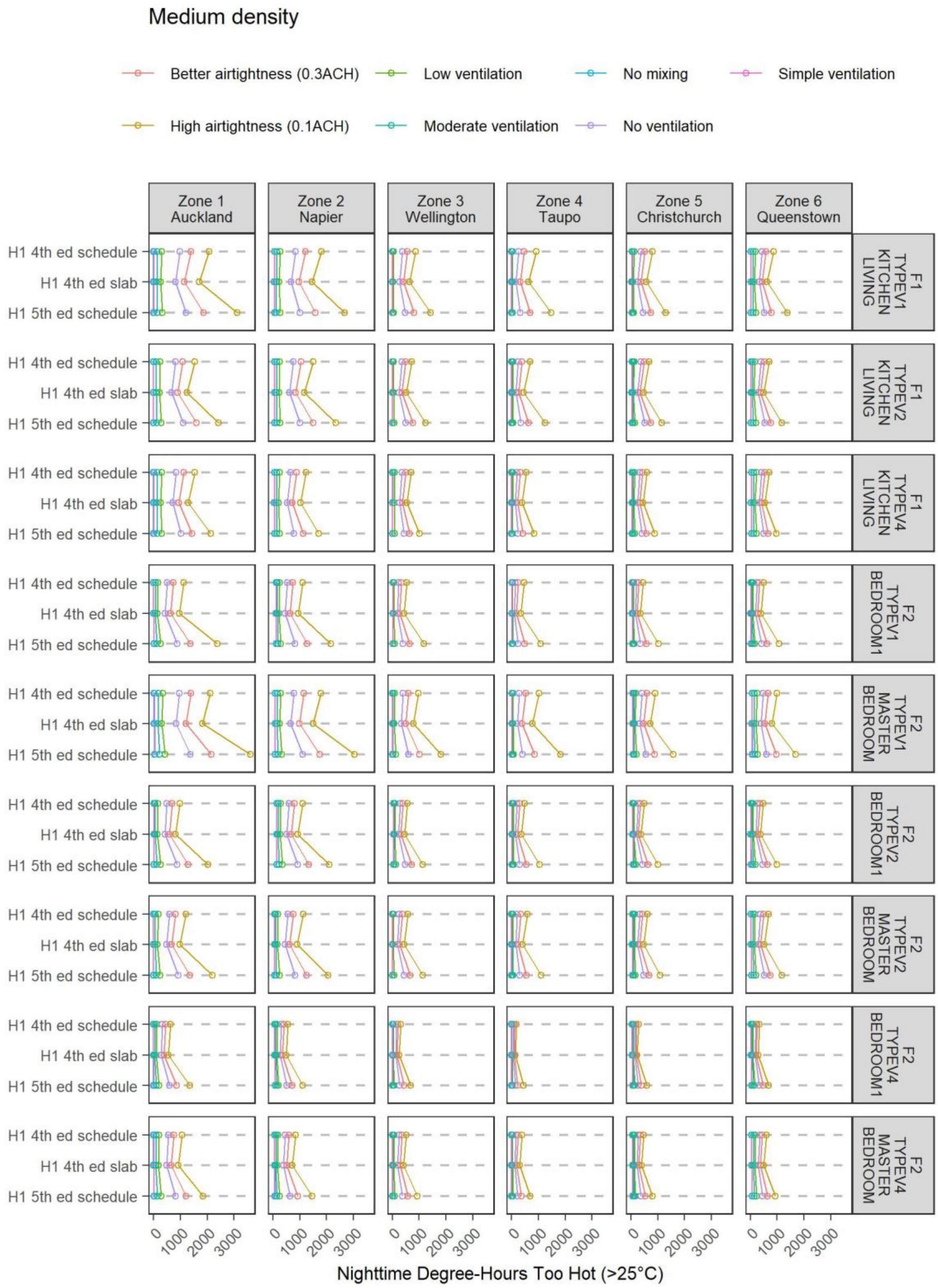


Figure 118: Night-time overheating under different ventilation assumptions

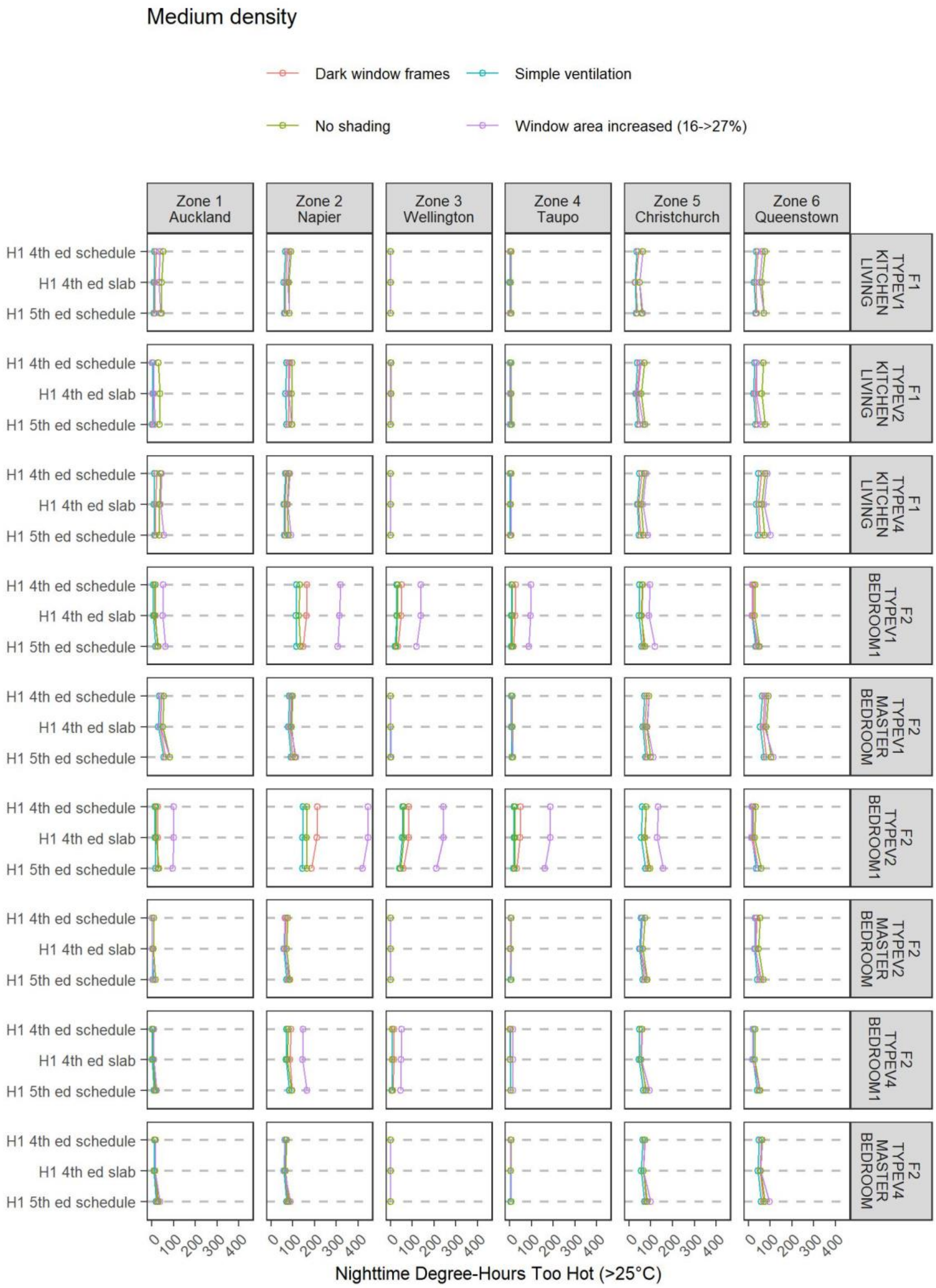


Figure 119: Night-time overheating under different design assumptions – simple ventilation is the base model

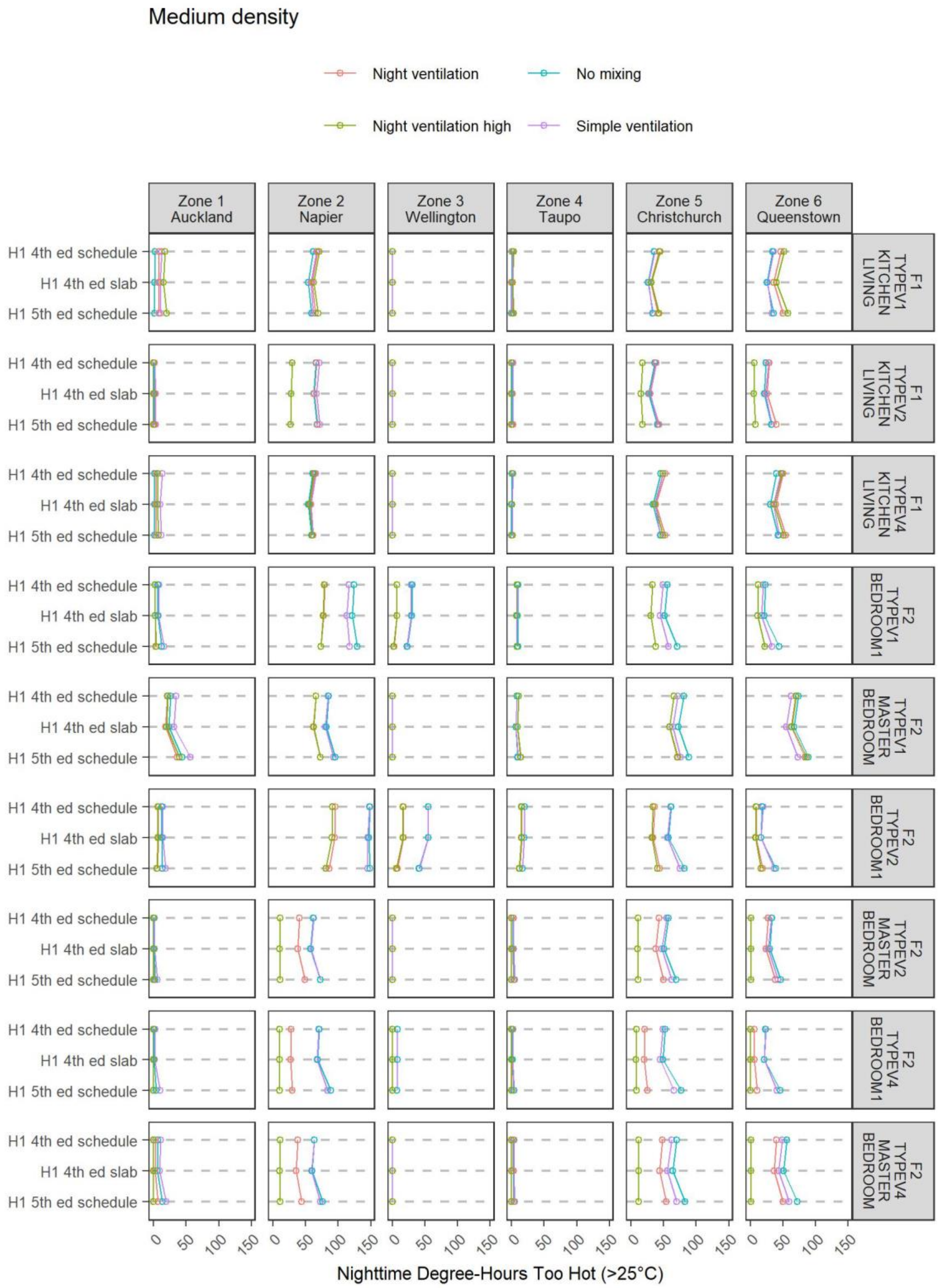


Figure 120: Night-time overheating under different night ventilation assumptions – simple ventilation is the base model

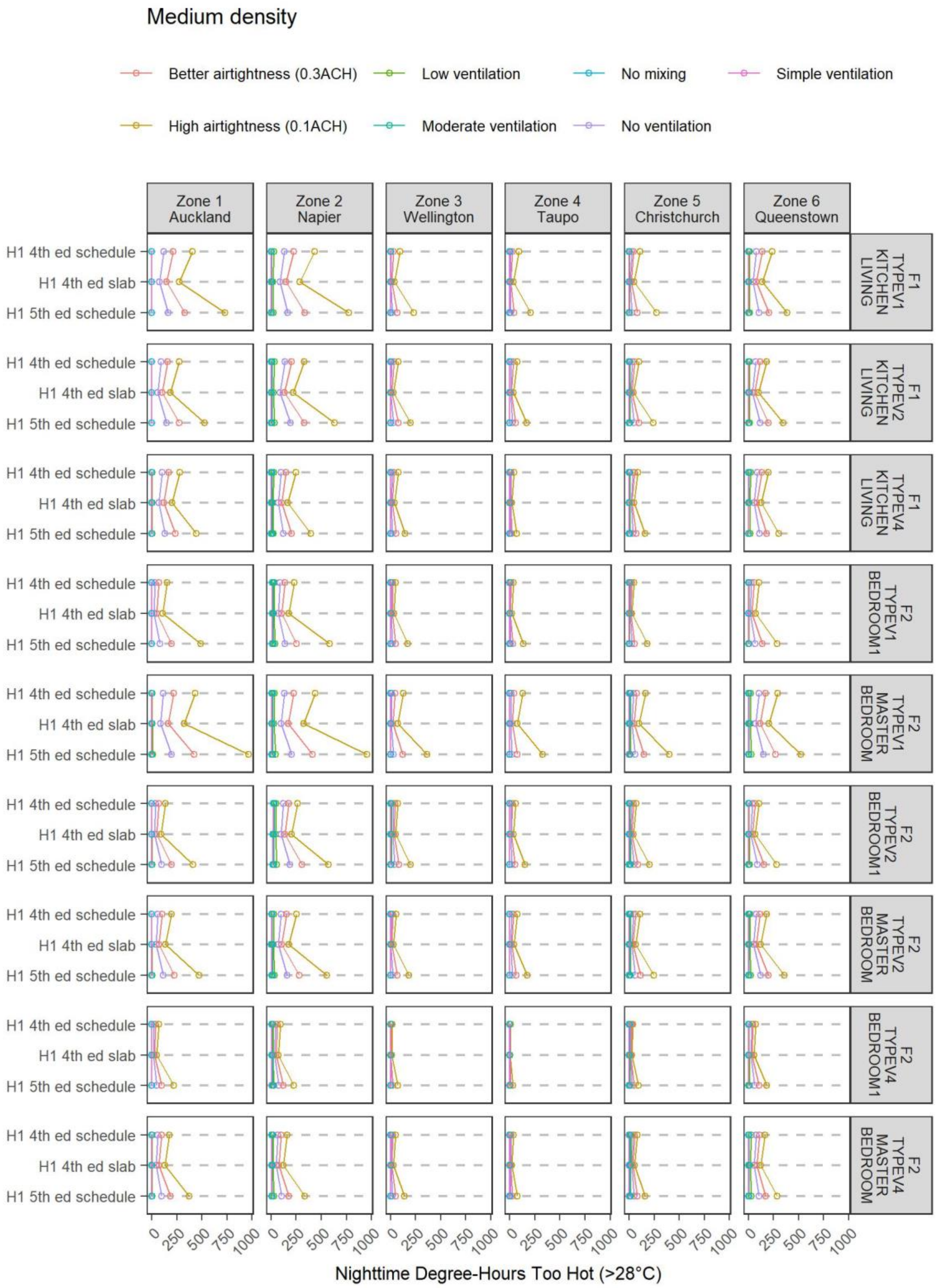


Figure 121: Night-time overheating under different ventilation assumptions using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023)

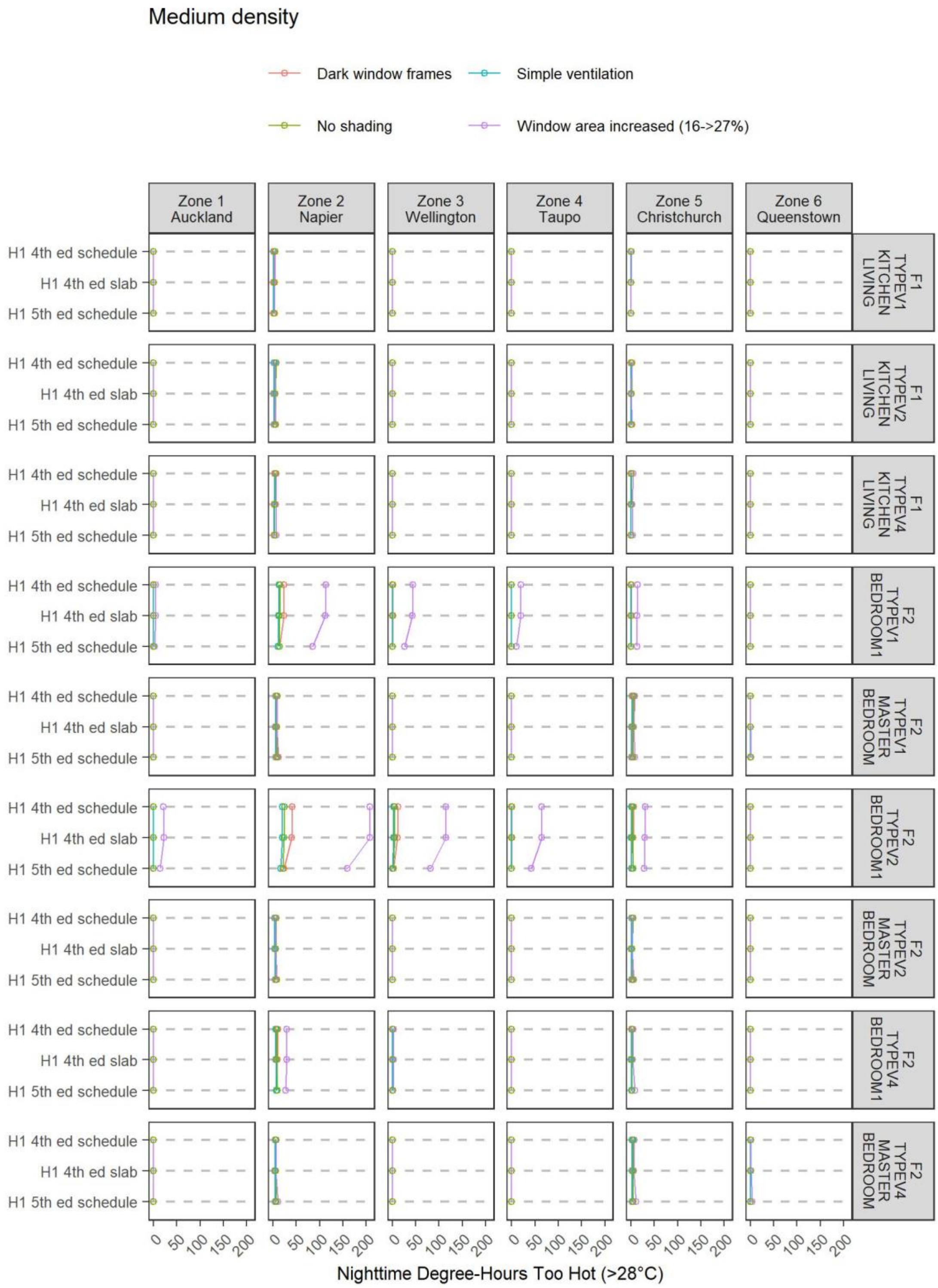


Figure 122: Night-time overheating under different design assumptions using the TM52 adaptive comfort model using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023) – simple ventilation is the base model

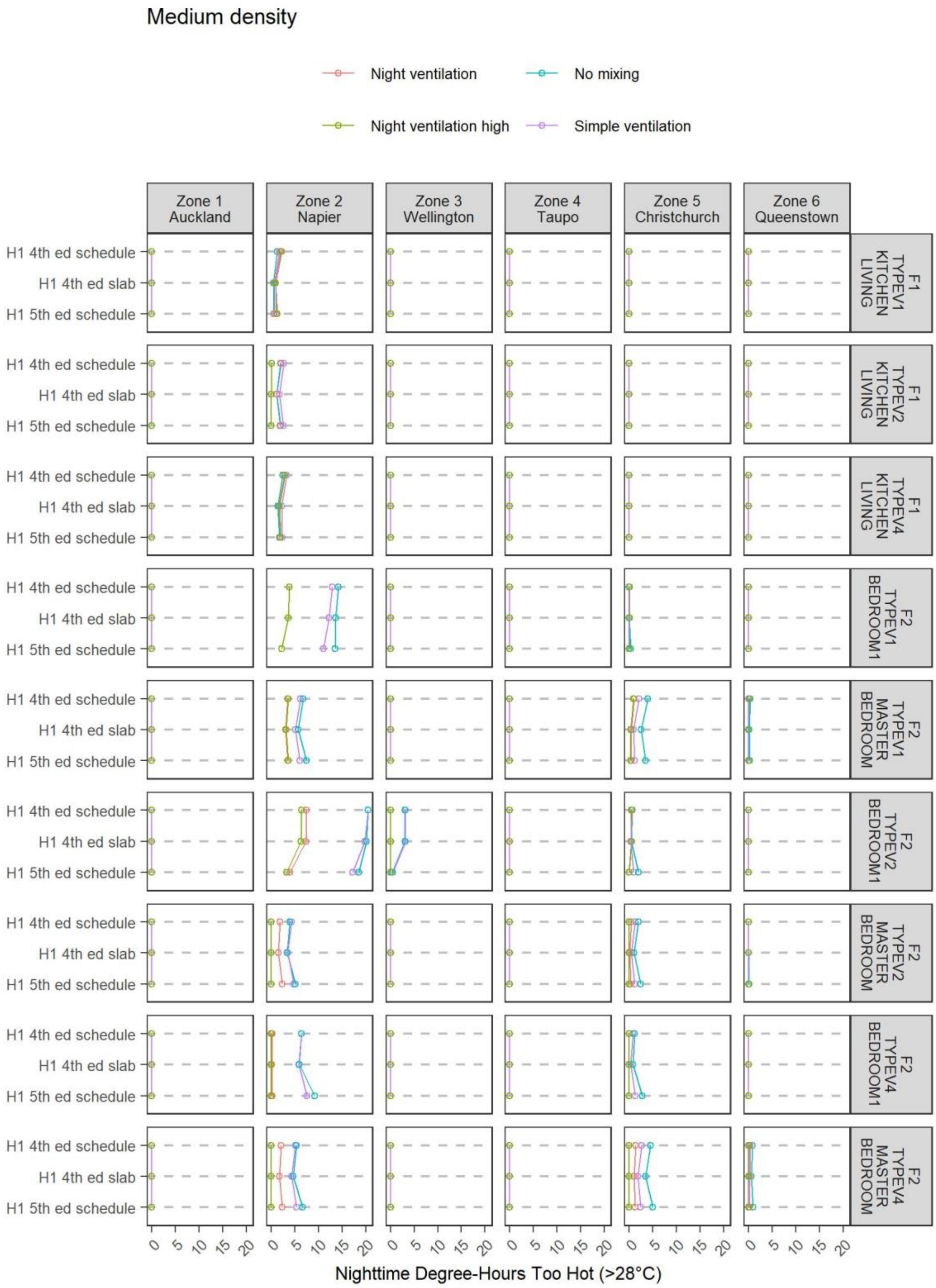


Figure 123: Night-time overheating under different night ventilation assumptions using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023) – simple ventilation is the base model

Apartments

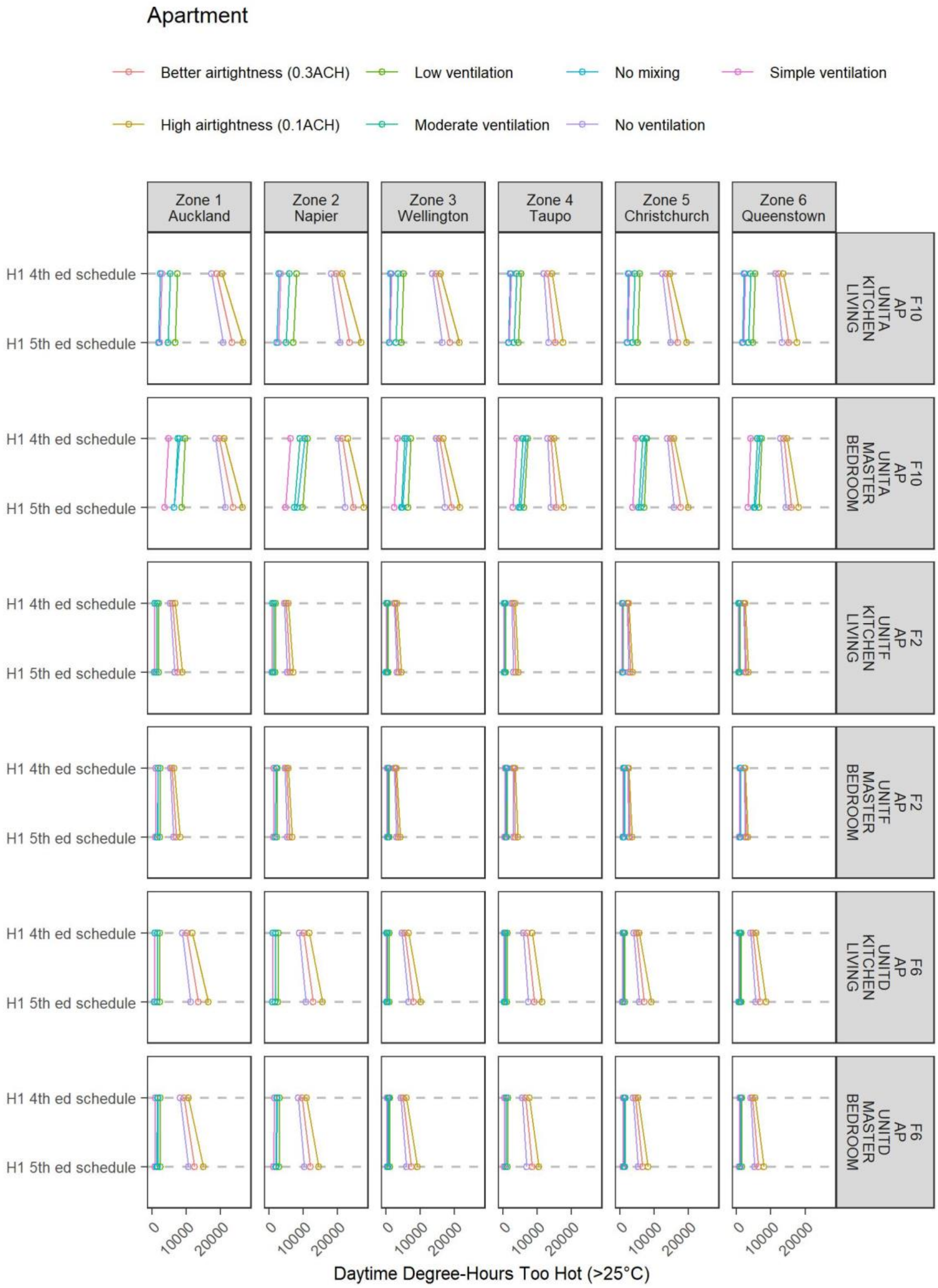


Figure 124: Daytime overheating under different ventilation assumptions

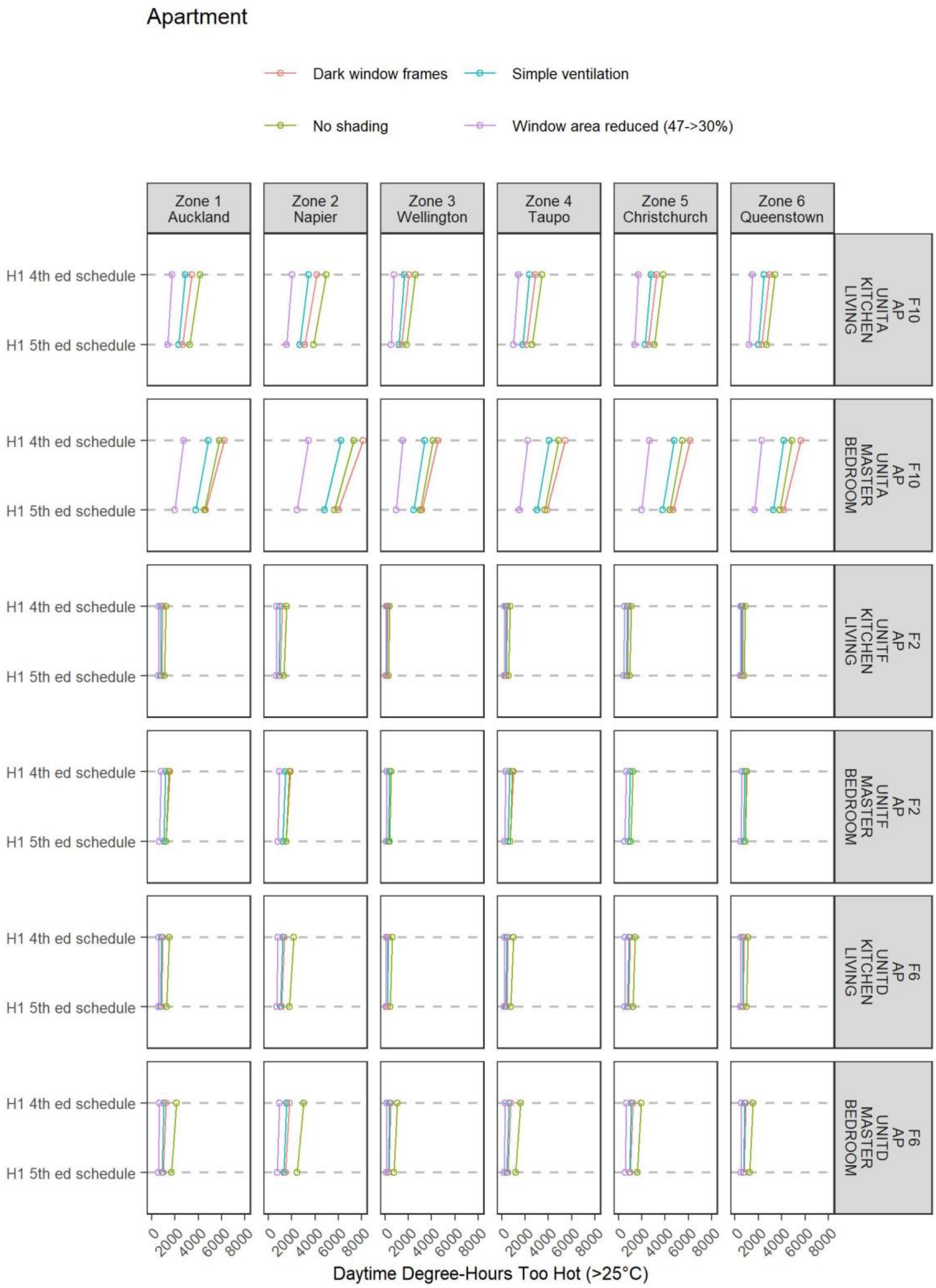


Figure 125: Daytime overheating under different design assumptions – simple ventilation is the base model

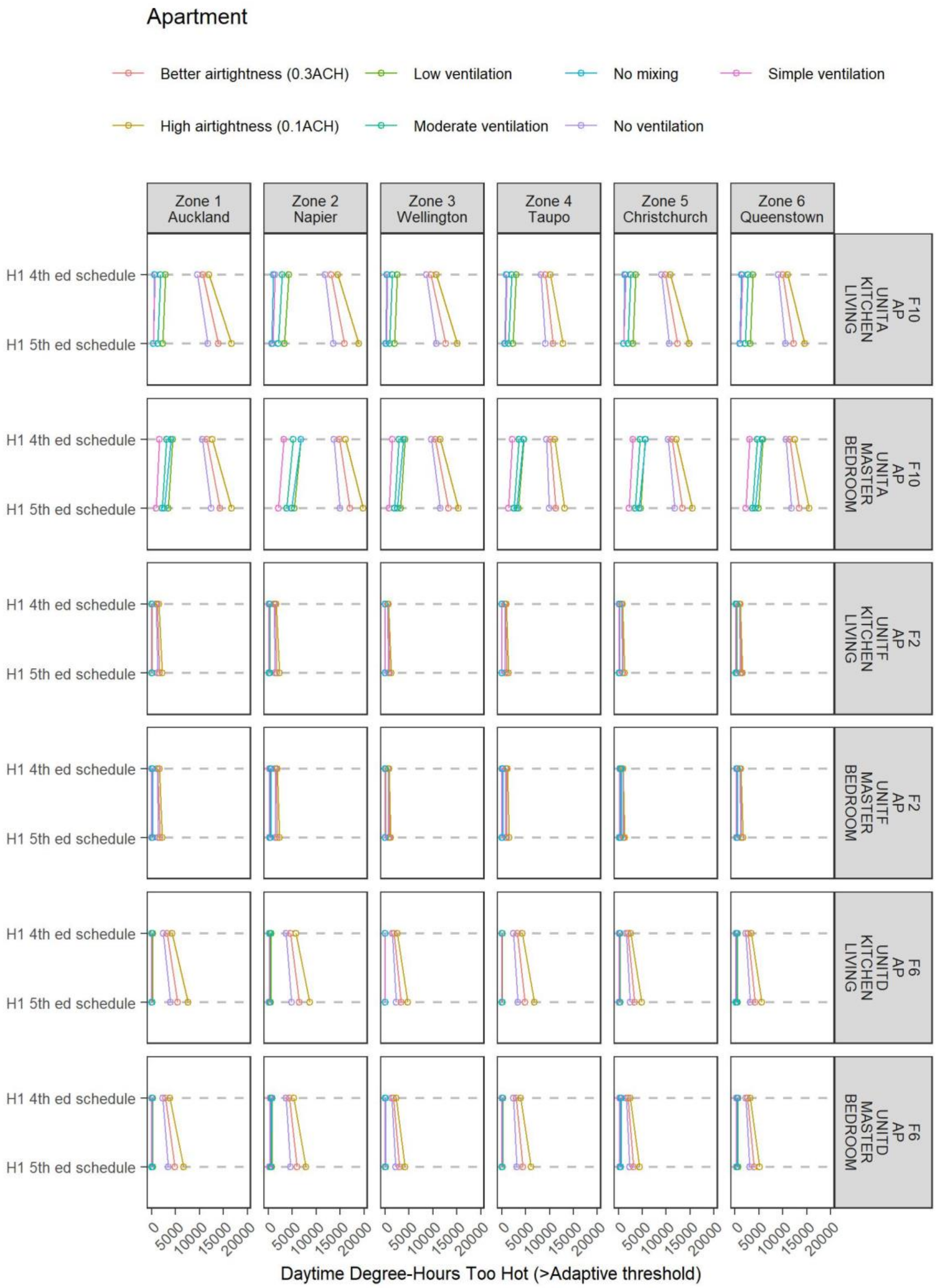


Figure 126: Daytime overheating under different ventilation assumptions using the TM52 adaptive comfort model

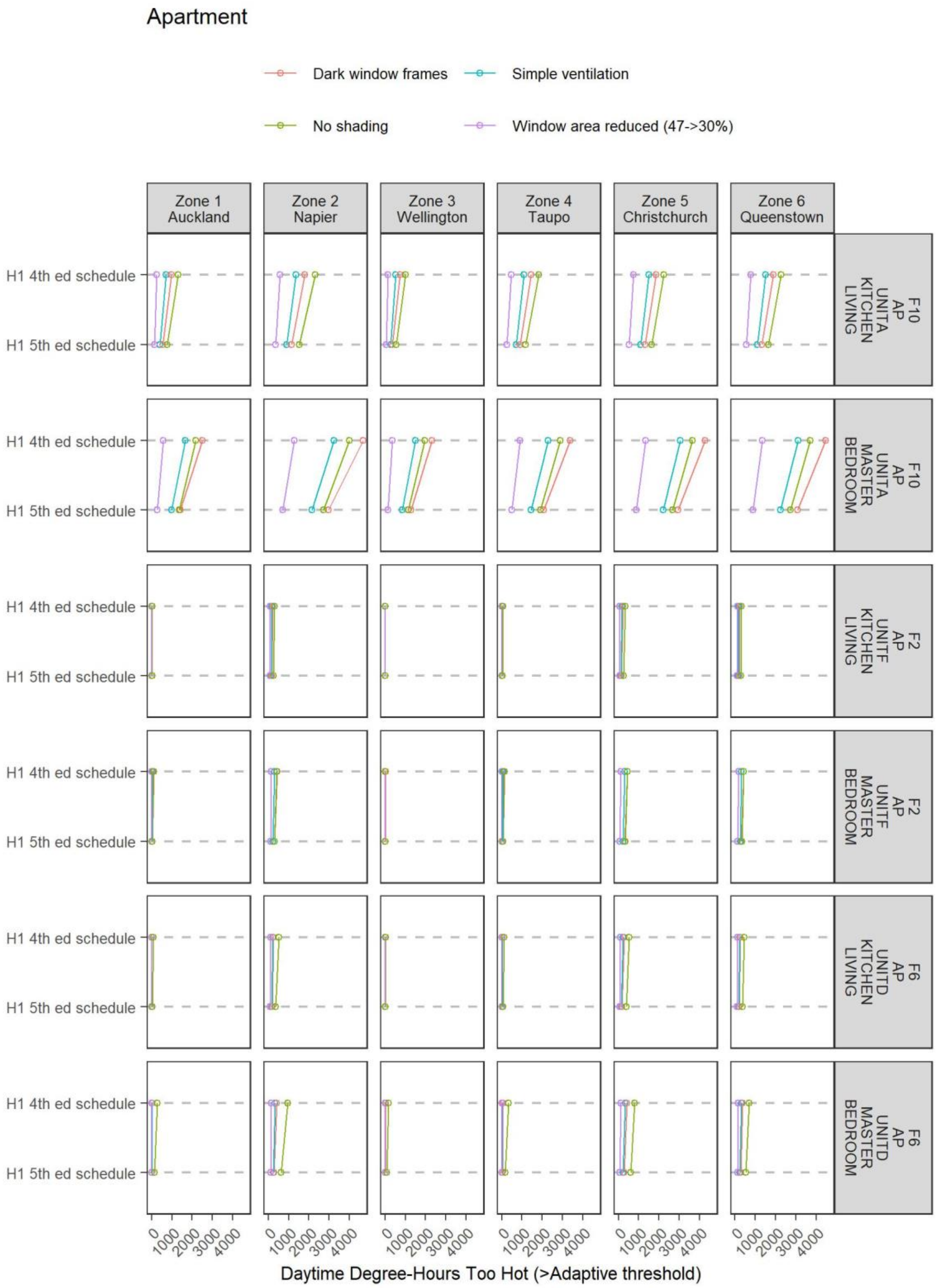


Figure 127: Daytime overheating under different design assumptions using the TM52 adaptive comfort model – simple ventilation is the base model

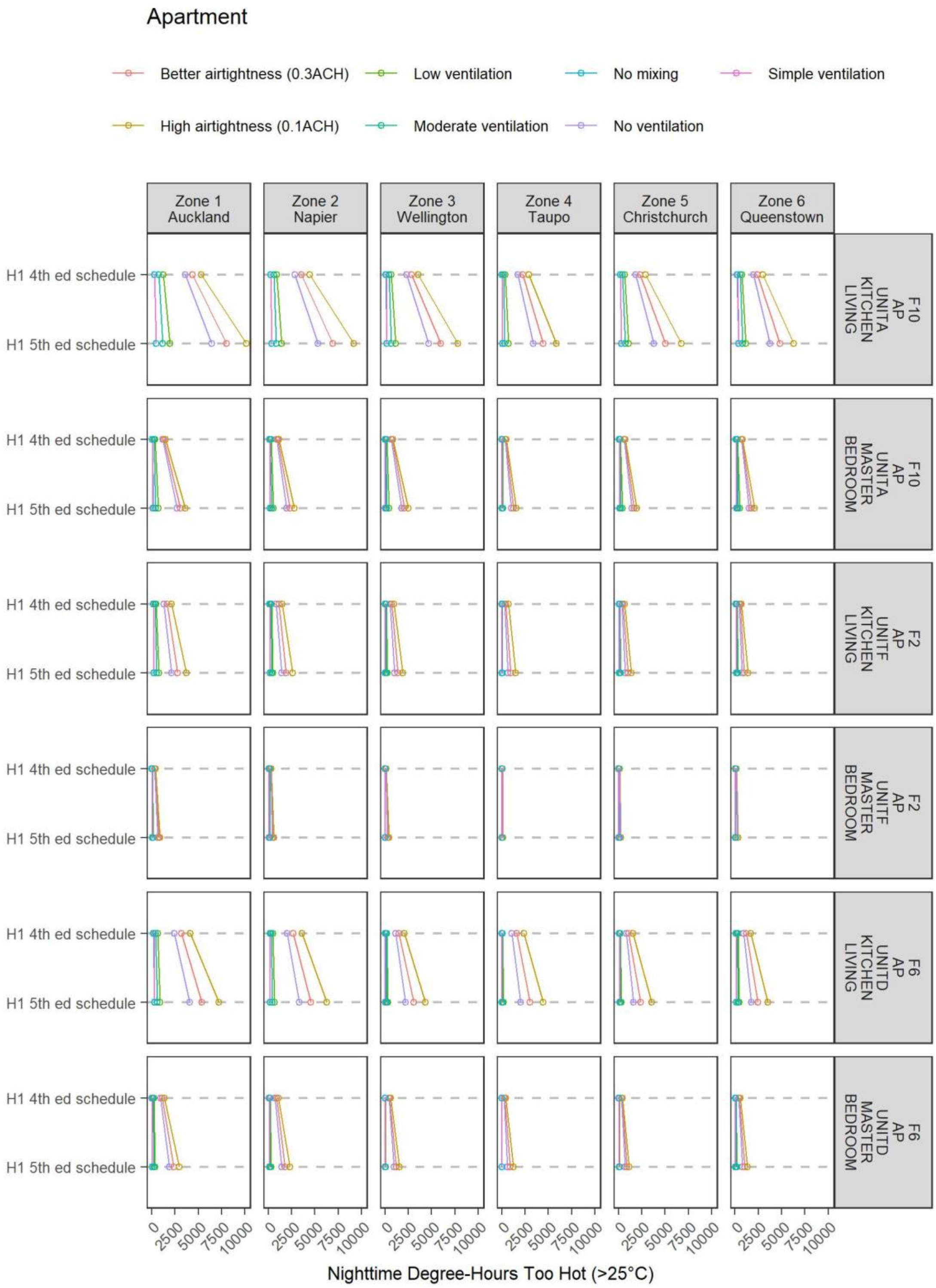


Figure 128: Night-time overheating under different ventilation assumptions

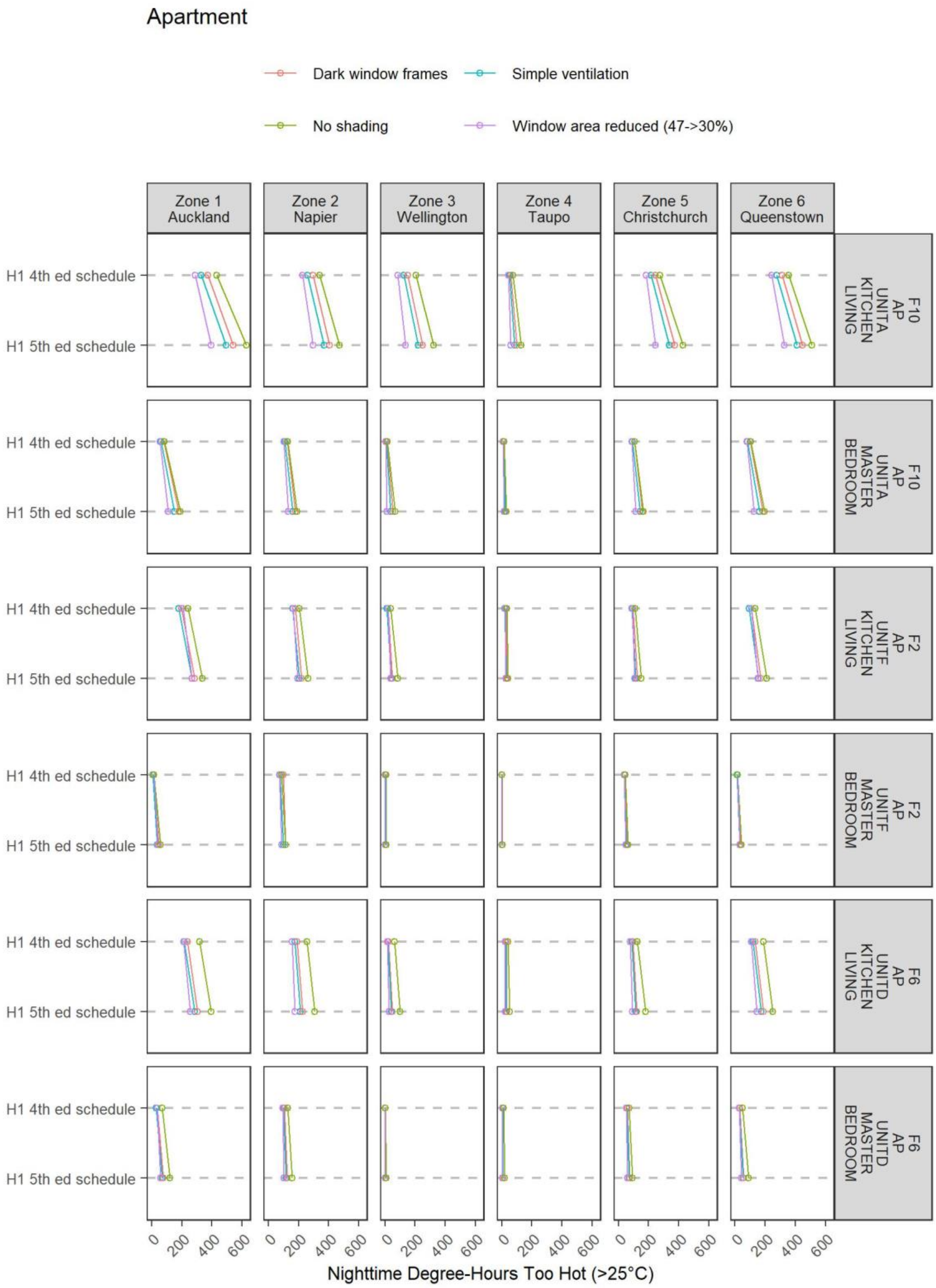


Figure 129: Night-time overheating under different design assumptions – simple ventilation is the base model

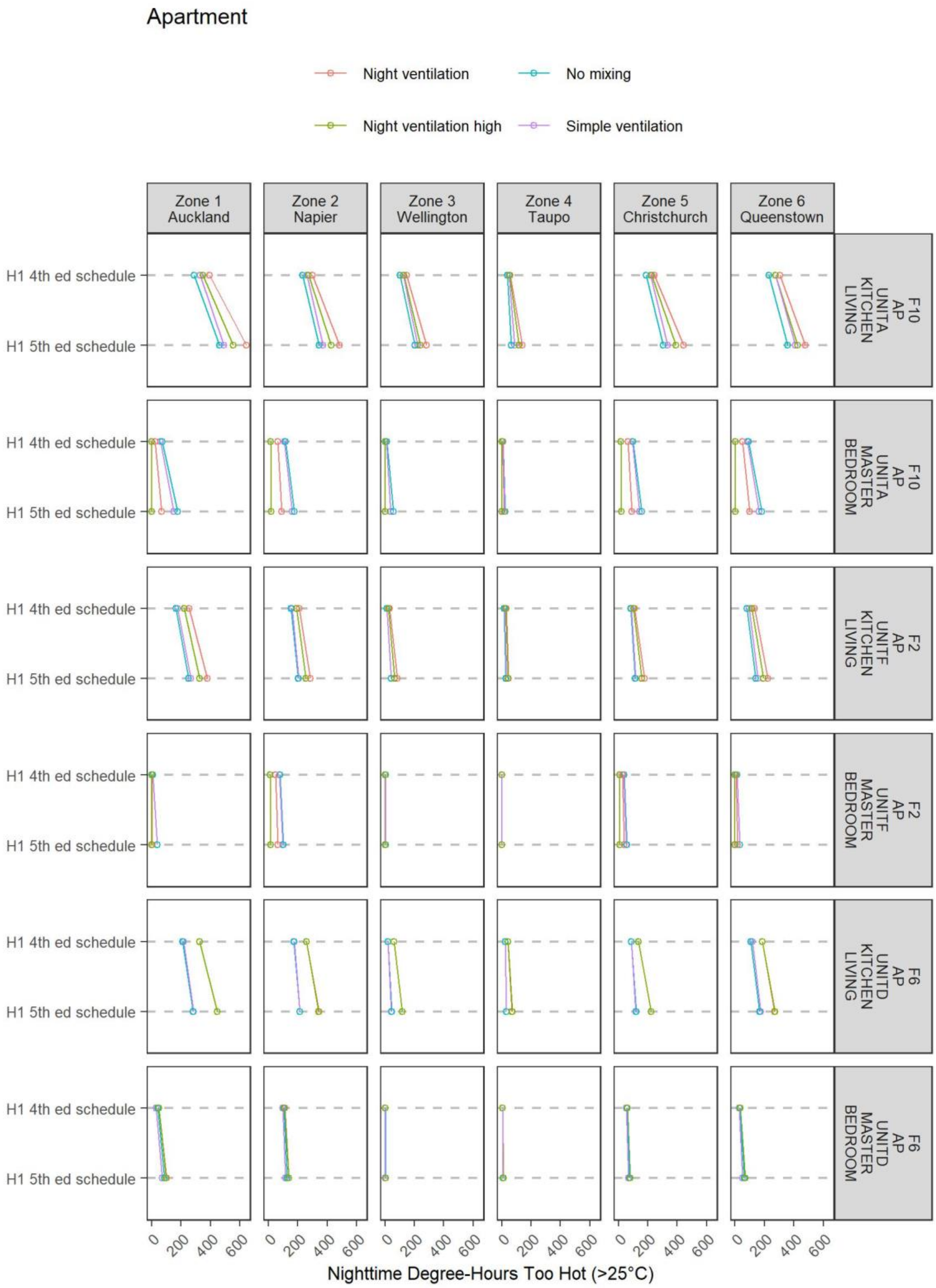


Figure 130: Night-time overheating under different night ventilation assumptions – simple ventilation is the base model

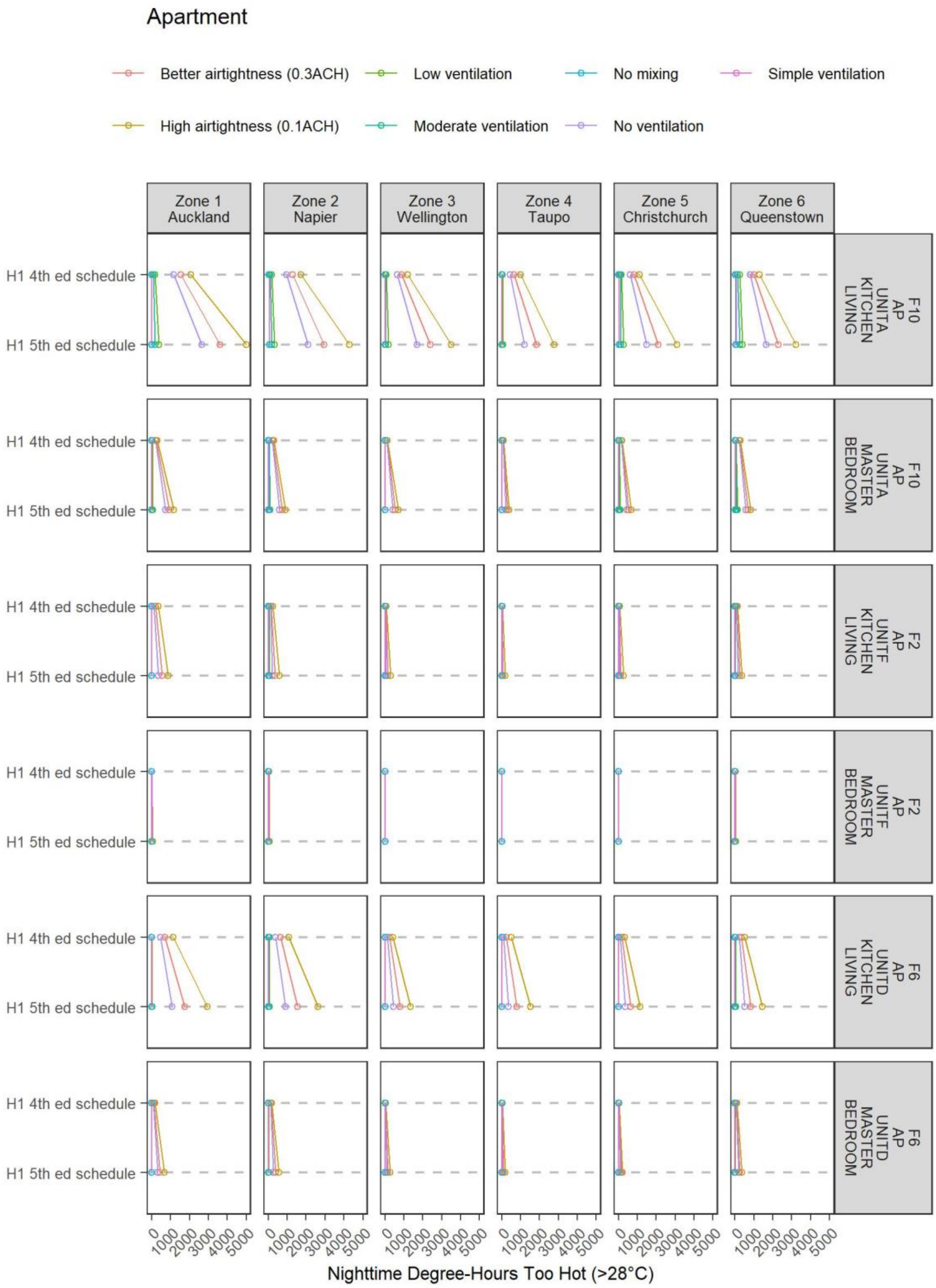


Figure 131: Night-time overheating under different ventilation assumptions using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023)

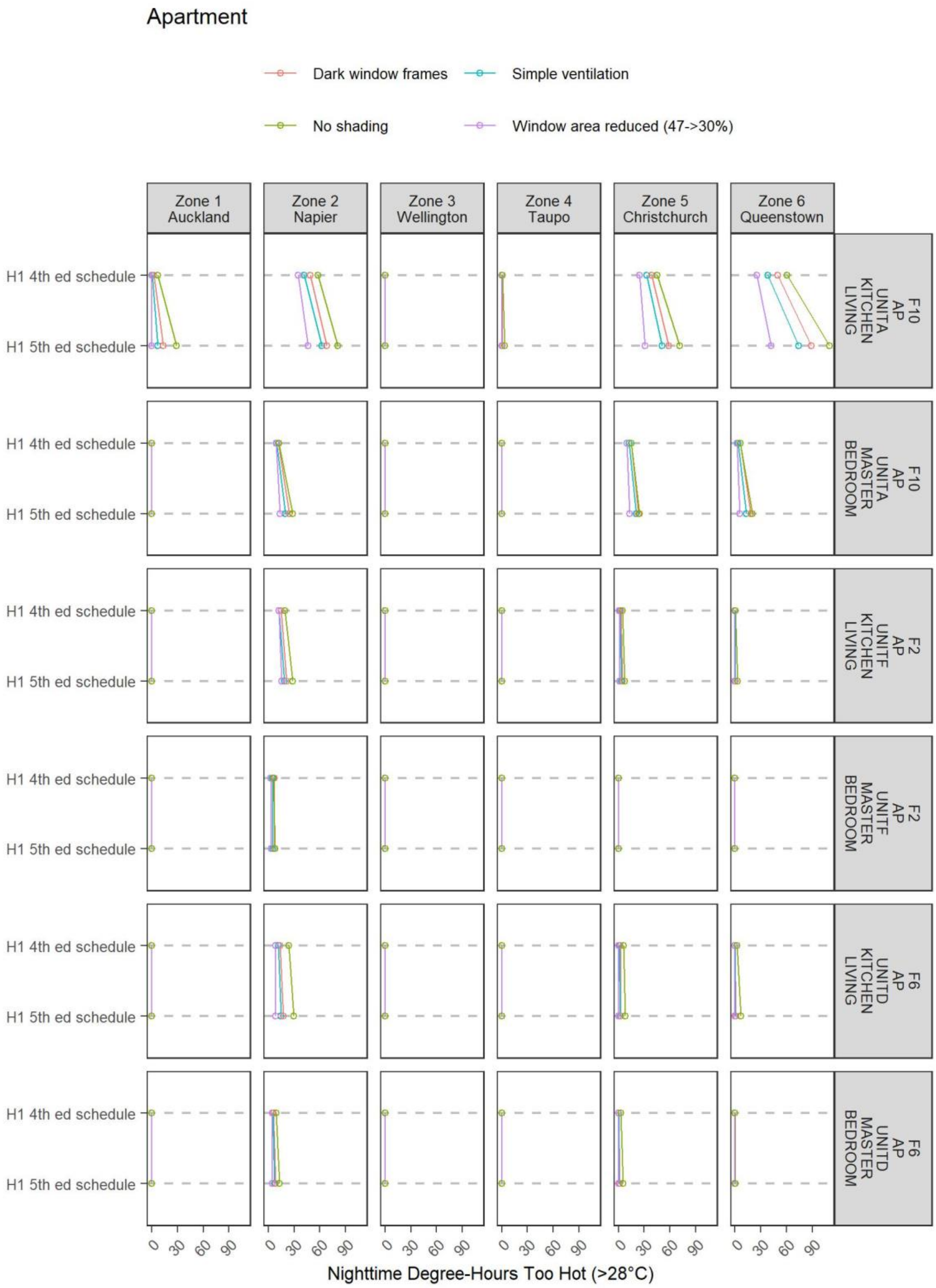


Figure 132: Night-time overheating under different design assumptions using the TM52 adaptive comfort model using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023) – simple ventilation is the base model

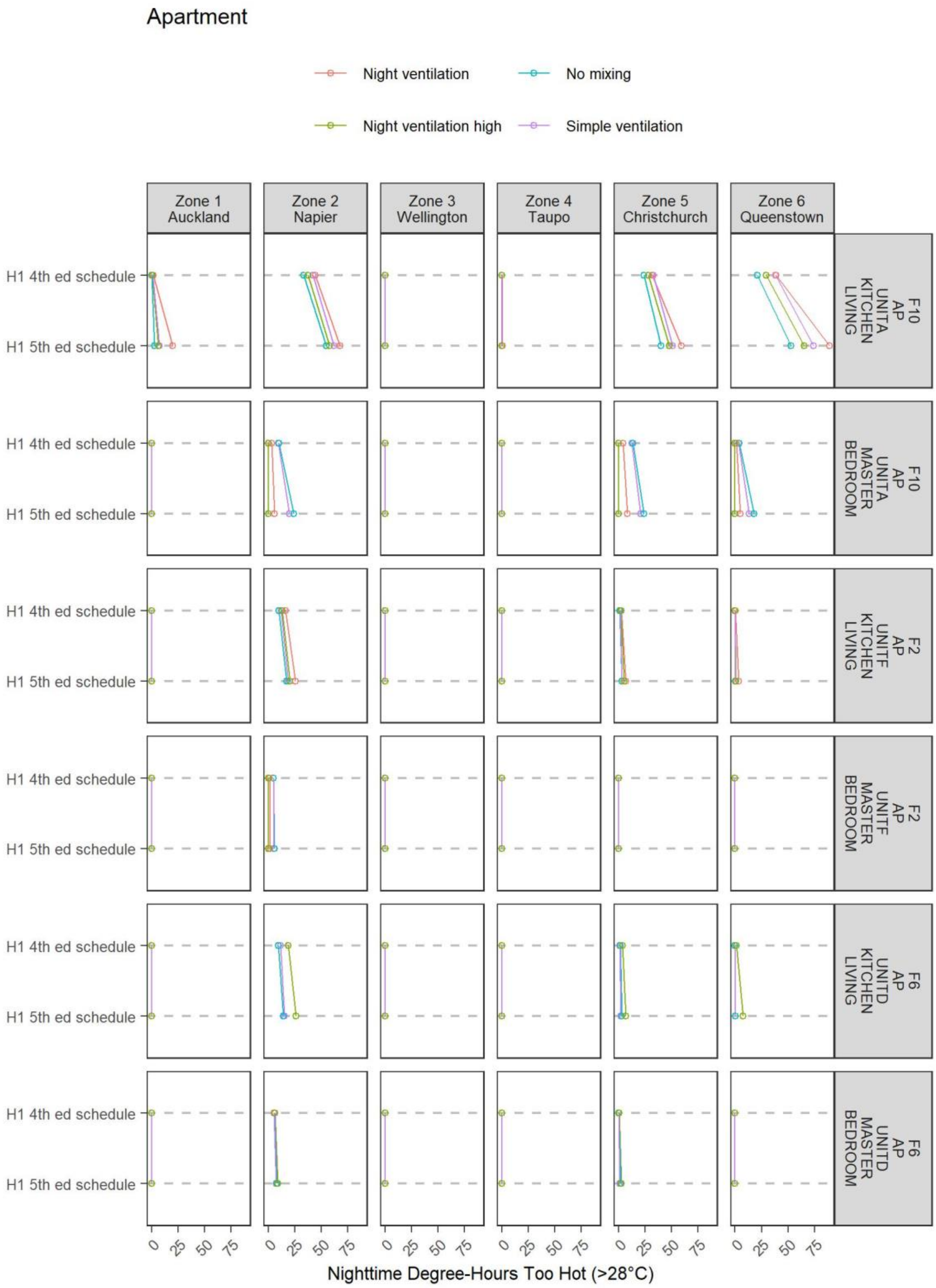


Figure 133: Night-time overheating under different night ventilation assumptions using a 28°C threshold following Lomas and Li (2023) and Kim et al. (2023) – simple ventilation is the base model