Carbon Challenge Seminar parametric energy simulation: methodology, background and assumptions

Jamie Sullivan, Roman Jaques and David Dowdell

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1222 Moonshine Rd, RD1, Porirua 5381
Private Bag 50 908, Porirua 5240
New Zealand
branz.nz

Preface

As part of the preparation for the Carbon Challenge seminar series, BRANZ carried out a parametric energy simulation exercise to investigate and establish “rules of thumb” that, if applied in design, should lead to stand alone house designs with lower carbon footprints than business-as-usual.

Whilst there is no substitute for investigating a specific design in a specific location iteratively through the design process, the aim of this exercise was to provide designers with a better understanding of some key aspects of a house design which, depending on decisions taken, can increase or decrease the carbon footprint.

Energy simulation is not necessarily good at predicting future energy use, unless properly calibrated. However, it is a useful tool for understanding the relative difference (in terms of energy use and comfort, for example) between alternative design scenarios. When used parametrically, we can investigate multiple variables to obtain a picture of how these may vary.

Inevitably, such an exercise relies on some simplifications and assumptions. This document sets out the approach that was taken, the underlying data and assumptions used.

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Authors

Jamie Sullivan, Roman Jaques and David Dowdell

Reference

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Abstract

This report documents the methodological details and assumptions with regards to the energy simulation done for the Carbon Challenge Seminar. It is intended to provide supporting information for those who are interested in the details of the models, and it is assumed that readers have seen the seminar and results for context.

Additionally, various cross-checks were carried out using a second energy simulation tool to corroborate some surprising results, and they are documented here.

Keywords

Carbon Challenge Seminar, Low Carbon, Energy Simulation, Methodology, Housing

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1. Introduction

This modelling sought to explore some rules of thumb with a single zone model to see what impact decisions such as window-to-wall ratio (WWR), house shape, floor type and so on could have on the operational and material carbon of stand-alone new housing.

It should be stressed that real houses and households are highly variable, and that an 'average' house or household does not exist. Thus, these results provide an indication of what factors are likely to be important to consider in low-carbon design, but specific magnitudes may vary considerably depending on individual situations. Understanding why an element is having a specific effect and what factors may be contributing to it is important to keep in mind. For example, when dealing with glazing, an increase in the window area will result in increased material greenhouse gas emissions because windows are more carbon intensive (per m^2) than timber framed external walls. However, the effects on energy use may be more variable due to the complex interactions between orientation, location, construction and other characteristics.

The basic model used was a box generally 150 m², 12.25 x 12.25 x 2.4 m with 600 mm eaves and 4 occupants, representing an abstraction of a common modern house (not counting the garage). Insulation levels were based on the MBIE medium H1 proposal (Jaques, Sullivan, Dowdell, Curtis & Butler, 2020) as shown in Table 1.

Table 1. Summary of construction R values used in modelling.

Climate	Roof	Walls	Floor	Windows
Zone 1 – Auckland	R5.0	R2.4	R1.9	R0.39
Zone 2 – Napier	R5.4	R2.6	R2.2	R0.42
Zone 3 – Wellington	R6.0	R2.8	R2.5	R0.45
Zone 4 – Turangi	R6.6	R3.2	R2.8	R0.49
Zone 5 – Christchurch	R7.0	R3.5	R3.2	R0.55
Zone 6 – Queenstown	R7.4	R3.8	R3.6	R0.62

Additionally, to approximate the mass and materials of the internal walls that would be present in a house, these were added as internal mass to the models (and accounted for in the embodied carbon calculations). Their area was estimated based off examinations of the ratios of internal wall length to floor area from a sample of real house models. For the basic 150 m² model, this was estimated at ~41.7 m of internal wall. These were modelled in the six different climate zones used in the recent MBIE H1 proposals (see Table 1). Energy simulations were then run using EnergyPlus 9.4 based on the current TMY weather files for New Zealand produced by NIWA.[1]

The basic modelling assumptions were as follows:

- The model is heated to 18°C and cooled to 25°C (operative temperature) 24 hours a day using an ideal loads system.[2] Models were operated in this way for comfort and to ensure a warm, dry, healthy internal environment.

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[1] https://energyplus.net/weather-region/southwest_pacific_wmo_region_5/NZL

[2] An ideal loads system is a simplified theoretical space conditioning system that meets all the heating and cooling setpoint targets specified with 100% efficiency rather than attempting to model all the mechanical details of a real heating system.

- Constant baseline infiltration/ventilation rate of 0.5 air changes per hour (ACH) following NZS 4218:2009 *Thermal insulation – Housing and small buildings.*
- Natural ventilation of up to 15 ACH with a setpoint of 23°C. This assumes some degree of anticipatory window opening behaviour to try to keep the temperatures below the upper limit where the cooling would be activated.
- Internal gains schedules derived from modifying schedules developed from HEEP[3] data and adjusting them to attempt to account for potential efficiency improvements in modern houses. The internal gains (accounting for 4 occupants, equipment, lighting, hot water and cooking) are on average around 4.19 W/m² compared to 5.39 W/m² for the original HEEP schedules and 6.39 W/m² using the assumptions in NZS 4218:2009.
- Ground modelling using EnergyPlus's GroundDomain model with an assumed ground water depth of 2 m.
- No curtains.

The basic geometry was modelled in OpenStudio[4], and then an R script (Model_processing.R) was used to process it and add elements such as the windows, internal gains, heating systems, infiltration and so on. This produced the base parameterised models[5] of which there are four versions, one for each of the different floor types (exposed concrete floor slab ('slab'), carpeted slab, exposed timber subfloor (Figure 1) and carpeted timber subfloor). These models were then run through the Parametric_gen.R script to parametrically generate all the different models needed for each set[6].

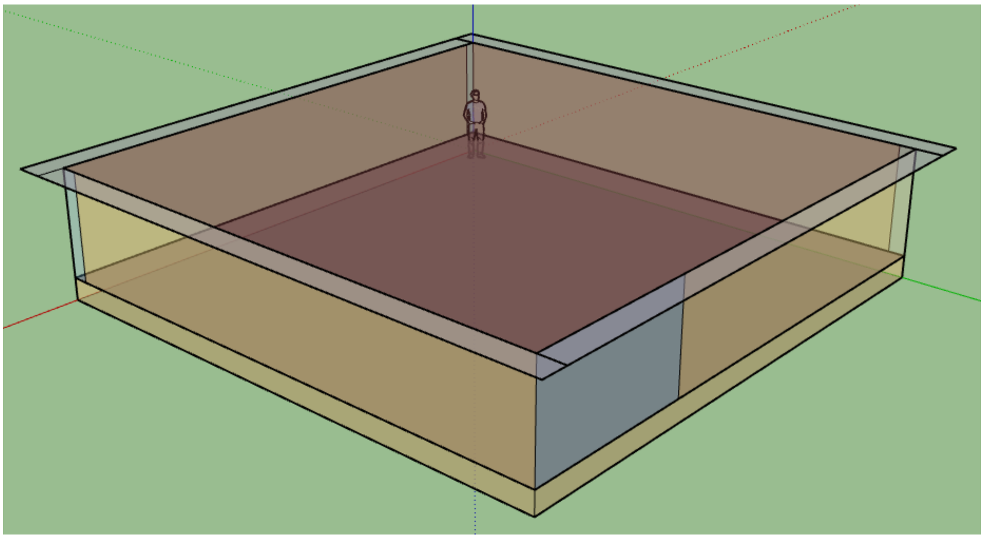

Figure 1. Example of one of the simple models with a subfloor.

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[3] https://www.branz.co.nz/environment-zero-carbon-research/heep2/heep/

[4] For BRANZ reference, files located in R:\Research and Commercial Services\4 Research\ER\1 Current\ER0970 Low Impact Buildings\3. Data & Analysis\Parametric Energy Simulation\Simulation\Models\1_Windows\1-Base.

[5] For BRANZ reference, located in the same folder as shown in footnote 4, except ending in the sub-folder .\3-FullModel\.

[6] For BRANZ reference, located in the same folder as shown in footnote 4, except ending in the sub-folder .\4-Parametric\.

To examine different questions, a range of different sets of models were produced as follows:

Windows

- Window to wall ratio (WWR): the WWR set looked at the effect of different window-to-wall ratios for several different glazing distributions. A version of this with current (4th Edition, pre-November 2021) New Zealand Building Code (NZBC) H1 construction R-values was also run.
- Orient: this set looked at the effect of rotating the model given different glazing distributions.
- Deopt: this "deoptimization" set explored the effects of glazing distribution and orientation and how much flexibility is available to designers by starting with an optimally oriented model with all the glazing facing north and then slowly shifting fractions of it away to other faces to see how much such decisions reduced performance.

Storeys

This small set looked at the effect of having a two-storey house, breaking the basic 150 m² cell into two 75 m² floors. Its results are compared with the analogous single-storey models from the WWR runs above to see the difference.

Area

The area set looked at the effect of house size. As this is intrinsically related to occupancy, multiple sizes and occupant densities were examined.

Shape

This set looked at the effect of one of the basic elements of the question of simple versus complex house shapes – the area/perimeter ratio and resulting increase in exposed wall area that more complex houses have compared to more compact forms.

Shading

This set looked at a selection of simple shading design decisions in terms of eaves and movable shades on the east and west sides of the house.

Optimal

This set of runs looked at the effects of combining what looked like the optimal set of design decisions from the above analyses to improve a simplified version of a fairly typical real house (in terms of size, WWR and construction).

The model details and assumptions are elaborated on in Section 2.

2. Parametric simulation sets

2.1 Windows

The WWR and orient sets used five different distributions designed to approximate the range of different distribution shapes that may be found in real houses. This ranged from the one-side distribution (where the glazing is mostly on one face) to distributions where there are two main faces (either two adjacent faces producing a trapezoid distribution or two opposite faces) to a three-way distribution (glazing mostly on the north, east and west faces) to an even distribution over all faces.

The distribution of glazing over each face for each of the distributions is summarized in Table 2.

Table 2 Modelled window distributions

Distribution	North	East	West	South
One-side	80.0%	7.5%	7.5%	5.0%
Trapezoid	40.0%	10.0%	40.0%	10.0%
Two-way	45.0%	5.0%	5.0%	45.0%
Three-way	30.0%	30.0%	30.0%	10.0%
Even	25.0%	25.0%	25.0%	25.0%

For the WWR set, the window-to-wall ratio was incremented from 10% up in steps of either 5% or 10%. The exact steps used varied depending on the distribution, as the more even the distribution, the higher the potential WWR could go – for example, if all the glazing is on one face of a square box, covering that wall will at most allow a maximum WWR of 25%.

Thirty one models were generated for each of the 6 climate zones and 4 floor types (Table 3).

Table 3. WWR set models.

W	Distribution	WWR
1	One-side	10%
2	One-side	15%
3	One-side	20%
4	One-side	25%
5	One-side	30%
6	Trapezoid	10%
7	Trapezoid	15%
8	Trapezoid	20%
9	Trapezoid	30%
10	Trapezoid	40%
11	Trapezoid	50%
12	Two-way	10%
13	Two-way	15%
14	Two-way	20%
15	Two-way	30%
16	Two-way	40%

W	Distribution	WWR
17	Two-way	50%
18	Three-way	10%
19	Three-way	15%
20	Three-way	20%
21	Three-way	30%
22	Three-way	40%
23	Three-way	50%
24	Even	10%
25	Even	20%
26	Even	30%
27	Even	40%
28	Even	50%
29	Even	60%
30	Even	70%
31	Even	80%

For the orientation analysis, the WWR was set to 20% (a fairly typical level in modern houses), and each of the five distributions was then rotated by 45° around the eight compass directions. This produced 40 models for each climate zone and floor type (Table 4).

Table 4. Orient set models.

W	O	Orientation	Distribution	WWR
1	1	0°	One-side	20%
2	1	0°	Trapezoid	20%
3	1	0°	Two-way	20%
4	1	0°	Three-way	20%
5	1	0°	Even	20%
1	2	45°	One-side	20%
2	2	45°	Trapezoid	20%
3	2	45°	Two-way	20%
4	2	45°	Three-way	20%
5	2	45°	Even	20%
1	3	90°	One-side	20%
2	3	90°	Trapezoid	20%
3	3	90°	Two-way	20%
4	3	90°	Three-way	20%
5	3	90°	Even	20%
1	4	135°	One-side	20%
2	4	135°	Trapezoid	20%
3	4	135°	Two-way	20%
4	4	135°	Three-way	20%
5	4	135°	Even	20%
1	5	180°	One-side	20%
2	5	180°	Trapezoid	20%
3	5	180°	Two-way	20%
4	5	180°	Three-way	20%

W	O	Orientation	Distribution	WWR
5	5	180°	Even	20%
1	6	225°	One-side	20%
2	6	225°	Trapezoid	20%
3	6	225°	Two-way	20%
4	6	225°	Three-way	20%
5	6	225°	Even	20%
1	7	270°	One-side	20%
2	7	270°	Trapezoid	20%
3	7	270°	Two-way	20%
4	7	270°	Three-way	20%
5	7	270°	Even	20%
1	8	315°	One-side	20%
2	8	315°	Trapezoid	20%
3	8	315°	Two-way	20%
4	8	315°	Three-way	20%
5	8	315°	Even	20%

For the deopt set, the WWR was again set to 20%, and the glazing was shifted away from 100% north in eight different steps (Table 5).

Table 5. Deopt set models.

W	Distribution	WWR	North	East	West	South
1	Optimal	20%	1	0	0	0
2	25% E/W	20%	0.75	0.125	0.125	0
3	50% E/W	20%	0.5	0.25	0.25	0
4	40% E/W, 10% S	20%	0.5	0.2	0.2	0.1
5	30% E/W, 20% S	20%	0.5	0.15	0.15	0.2
6	50% S	20%	0.5	0	0	0.5
7	50% E/W, 20% S	20%	0.3	0.25	0.25	0.2
8	25% E/W, 75% S	20%	0	0.125	0.125	0.75

2.2 Storeys

The two-storey model was simply a version of the basic one-sided 20% WWR single-storey model with two 75 m² floors (Figure 2). Assumptions such as total internal gains, infiltration and ventilation were held constant. For consistency, the window area was set to be the same as in the single-storey model. As the wall area is actually higher for the two-storey model, this means that the WWR technically falls to ~18%. The internal wall area was also reduced slightly (by 10%), as it was treated as two 75 m² zones, and the amount of internal wall/floor area seemed to increase somewhat as floor area increased in the sample of houses looked at. For consistency, whether the mid-floor was carpeted was dependent on whether the ground floor was. Internal loads were simply divided evenly between the two floors.

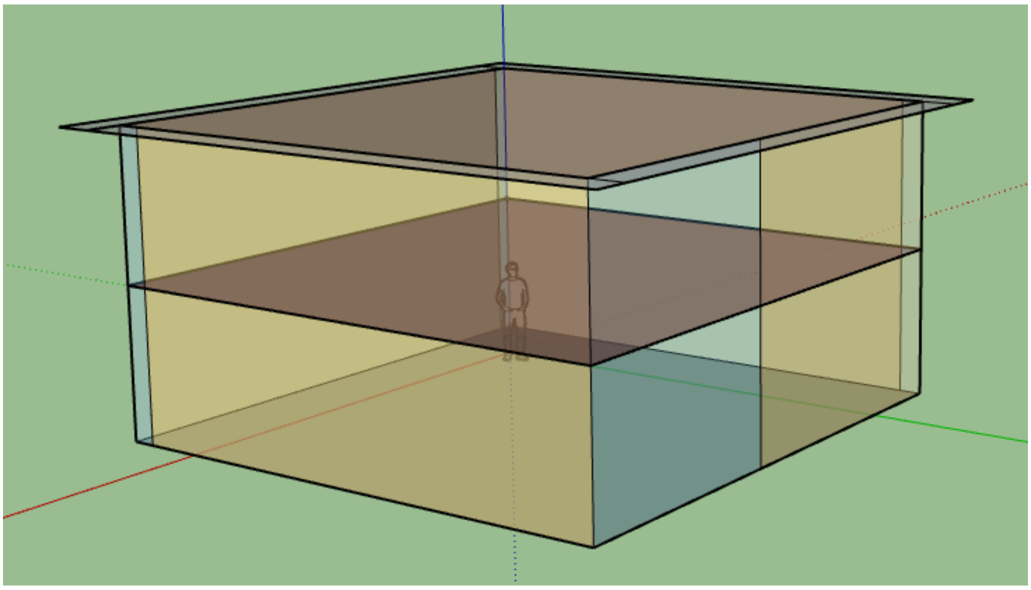

Figure 2. Two-storey model.

2.3 Area

Five different house sizes were considered: 50 m², 75 m², 100 m², 150 m² and 200 m² (Table 6). WWR was assumed to be 20%, while the distribution was 50% north, 20% east, 20% west and 10% south. Dimensions were a square with external wall lengths of 7.07 m, 8.66 m, 10 m, 12.25 m and 14.14 m respectively.

Table 6. Area set models.

A	Area (m²)	Occupants	Internal gains (W/m²)	ACH
1	50	2	8.9	0.43
2	75	2	6	0.29
3	75	3	6.93	0.43
4	100	2	4.79	0.22
5	100	3	5.48	0.32
6	100	4	6.17	0.43
7	150	2	3.26	0.14
8	150	3	3.72	0.22
9	150	4	4.19	0.29
10	150	5	4.65	0.36
11	150	6	5.11	0.43
12	200	3	2.96	0.16
13	200	4	3.31	0.22
14	200	5	3.66	0.27
15	200	6	4	0.32
16	200	8	4.7	0.43

Occupancy was also varied from a minimum of 2 occupants to a maximum of 1 occupant/25 m² (based off the occupancy assumptions in NZS 4218:2009). Several other assumptions also had to be varied because of the changes in area and occupancy: internal gains, baseline infiltration/ventilation and number of bathrooms.

Internal gains from equipment, lighting, and range loads were scaled using the relationships derived from the Household Energy Efficiency Resource Assessment (HEERA) model developed for HEEP. This is important because simply assuming a one-to-one relationship with area or occupancy would be highly inaccurate – a house that is twice as big will probably not have twice as many electric appliances. Number of bathrooms matters because we are assuming they have heated towel rails. In this case, we assumed that the small houses (50 m^2 and 75 m^2) have one bathroom, the 100 m^2 and 150 m^2 houses have two bathrooms and the large 200 m^2 house has three. Internal gains are discussed in more detail in Section 3.6.

Finally, it is important to consider that the fresh air requirements depend on the number of occupants in a house. A house with fewer occupants can afford to be more airtight without compromising indoor air quality. Hence, instead of just assuming that the baseline infiltration/ventilation rate would be the standard 0.5 ACH here, we estimated the requirements based off the minimum of 7.5 L/s/person required by NZS 4303:1990 *Ventilation for acceptable air quality*.

2.4 Shape

Examining the effects of house shape is challenging and overlaps with examination of orientation and shading, with two different factors that can affect performance:

- More-complex shapes are less compact and so have greater external envelope area and more heat loss and material use.
- More-complex shapes create alcoves where windows are likely to be shaded by other parts of the house. The effects will depend on the individual situation – which way the window is facing, how much it is shaded, how much of the total window area is affected, how many storeys the house has, roof shape and so on.

In this light, we focused on the effect of compactness. Compactness was varied without producing confounding shading effects by extending the square model into increasingly extreme rectangles. This produces less-compact lower area/perimeter (a/p) ratios analogous to more complex shapes while holding other factors such as area and glazing distribution constant. Five shapes were modelled (Figure 3).

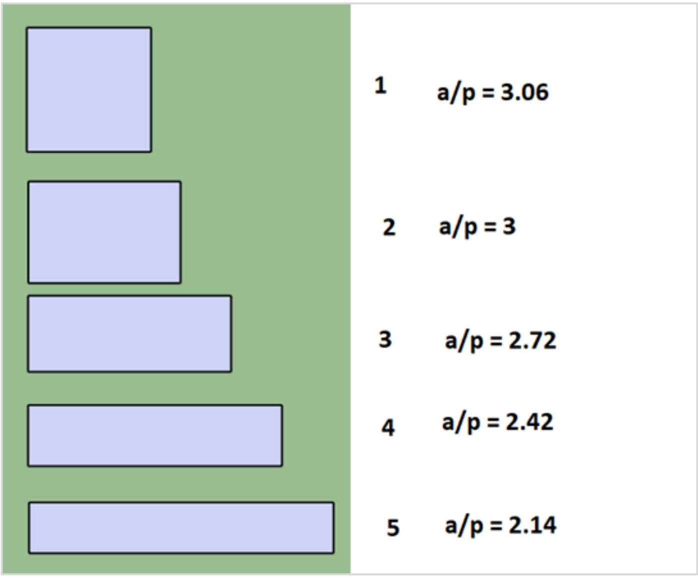

Figure 3. Area/perimeter ratios modelled.

For comparison, an L-shaped house might have an a/p ratio of ~2.5 while a U-shaped house might have a ratio of ~2.3 (Figure 4).

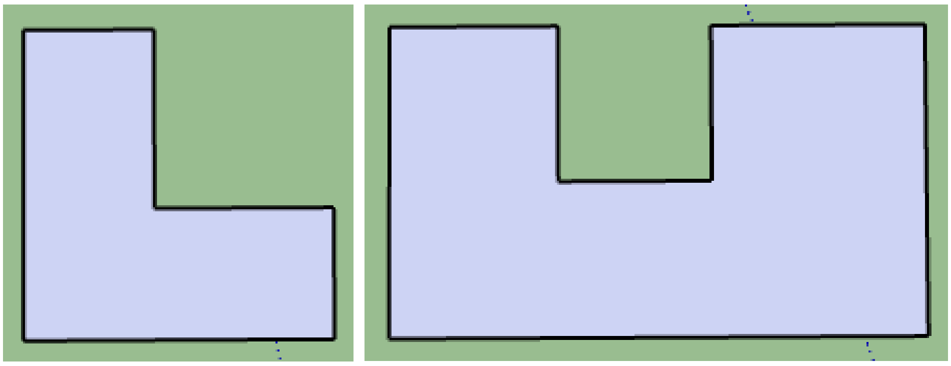

Figure 4. Comparative area/perimeter ratios for L-shaped and U-shaped houses.

For consistency, the total window area was held constant at the same level as the baseline 20% WWR model (23.5 m²), while the distribution was 50% north, 20% east, 20% west and 10% south. As the wall area increases across the models (up to ~43% more than a square box), the WWR declines (Table 7.

Table 7. Shape set models.

A	Length (m)	Width (m)	Perimeter (m)	a/p ratio	RelWall[7]	WWR
1	12.25	12.25	49	3.0625	1	20%
2	15	10	50	3	1.020621	20%
3	20	7.5	55	2.727273	1.122683	18%
4	25	6	62	2.419355	1.26557	16%
5	30	5	70	2.142857	1.428869	14%

2.5 Shading

A few simple options were explored for an initial look at shading. First, shading was removed entirely to look at the impact of standard 600 mm eaves. We then attempted to optimise north eave dimensions for the six different climate zones according to standard rules of thumb,[8] which suggested the following eave depths (given 2.4 m high windows):

- Zone 1 – 0.58 m
- Zone 2 – 0.70 m
- Zone 3 – 0.77 m
- Zone 4 – 0.65 m
- Zone 5 – 0.84 m
- Zone 6 – 0.91 m

Then we examined the possibility managing low-angle sun by using moveable shades to block east sun in the morning (8am–noon) and west sun in the afternoon (noon–6pm), considering several scheduling options – only summer versus spring–autumn

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[7] Increase in wall area relative to first scenario (a square).

[8] https://www.level.org.nz/passive-design/shading/external-shading/

versus just west shading (due to afternoon sun being the main source of overheating (Table 8)).

Table 8. Shading set models.

S	Shading	WWR	North	East	West	South
1	No shade	25%	0.3	0.3	0.3	0.1
2	600 mm eaves	25%	0.3	0.3	0.3	0.1
3	North (rules of thumb)	25%	0.3	0.3	0.3	0.1
4	+ moveable E/W screens (summer)	25%	0.3	0.3	0.3	0.1
5	+ moveable E/W screens (spring–autumn)	25%	0.3	0.3	0.3	0.1
6	+ moveable W screens (spring–autumn)	25%	0.3	0.3	0.3	0.1

The WWR was increased to 25% to make potential overheating effects more visible while staying within common glazing levels. Glazing was spread evenly over the north, east, and west so that the effects of solar gain could be examined from all directions. External screens were assumed to have ~8% openness/transmissivity/permeability and 60% reflectance, with around a 100 mm gap to the glass.

Note that the shading analysis was only undertaken to consider thermal performance – embodied carbon analysis that included consideration of materials used in the screens or eaves was not carried out.

2.6 Optimal

The optimal set looked at using the findings of the above simulations to reduce the carbon footprint of a four-bedroom 156 m² case study house[9] . The challenge, however, is that factors such as orientation and shape cannot be simply changed with existing house plans – they are elements that need to be designed in from the start and are inherently part of how the house is laid out. Maintaining comparability would be challenging if we worked directly with the existing house model, as many of the changes could effectively require turning it into a different house.

To deal with this problem, the house was abstracted into a similar single-zone model that had the same orientation, glazing distribution, area/perimeter ratio, occupancy and area (Figure 5).

The baseline infiltration/ventilation rate was set to 0.36 ACH to meet minimum fresh air requirements for the assumed 5 occupants (number of bedrooms + 1) as changing area was one of the intended optimisations. There were two bathrooms, and internal gains were scaled as in the area analysis as needed.

This simple house was then modified to explore the effects of the optimisations:

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[9] For BRANZ reference, house 4_M_SS.

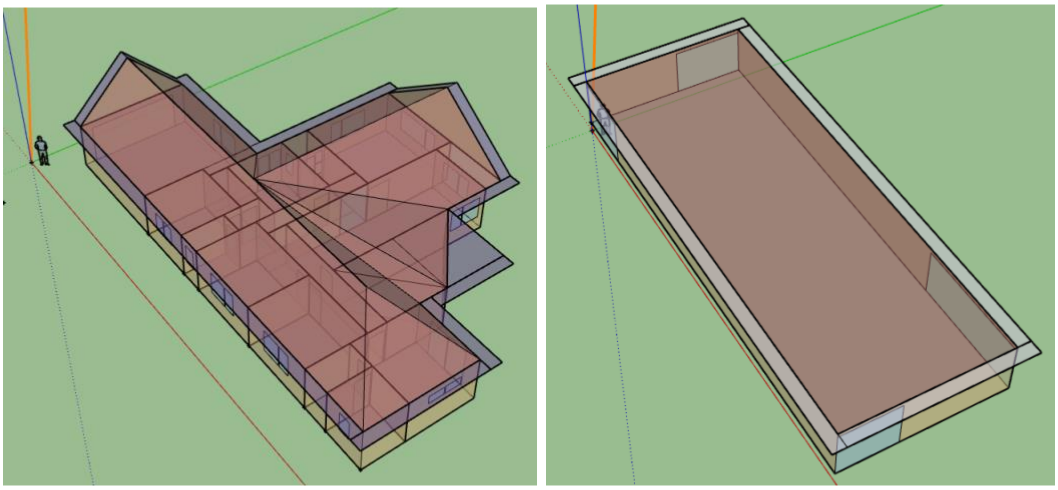

Figure 5. Original house model (left) and simple abstracted model (right)

- Increase the construction R values from the current NZBC H1 construction R values of the case study house to those suggested in the medium H1 upgrade suggested in Jaques et al. (2020)[10] and summarized in Table 1. (Building Performance, 2021).
- Select a floor type with a lower carbon footprint. The baseline house is a carpeted slab. Carpet can have a high carbon footprint (and also reduces the benefit afforded by the thermal mass of a slab floor), so either an exposed slab or exposed timber subfloor option look preferable. Both potential paths were tested.
- Optimise house shape to the most compact – 12.49 x 12.49 m square (156 m²).
- Reduce the WWR to 20%. This option was complicated. The results of the WWR analysis show a lot of different factors in play pulling in different directions, and they also vary substantially depending on whether there is exposed concrete. Windows tend to be more problematic when solar gains cannot be utilised. More windows are always worse for cooling and embodied carbon. EnergyPlus argues that increased window area can be beneficial for heating when there is exposed concrete. AccuRateNZ disputes this and it seems to be impacted by the level of natural ventilation operation. Additionally, if people use less heating energy than modelled, for example, by not heating the whole house 24/7 or using a system with a higher coefficient of performance (COP), this would also reduce the carbon benefits from reduced heating use. From this analysis, staying at typical WWR levels of ~15–25% appears to be a reasonable option. Note that, as the reference house was fairly typical, the change to a 20% WWR does not change the overall results much. This does not mean it does not matter, but rather, with this amount of glazing, it is not a major issue. People designing houses with very high amounts of glazing may need to look carefully at the implications.
- Improve glazing distribution and reorient it to face due north with 75% glazing on the north face and 25% on the east (which is better for heating without causing overheating as west glazing tends to). This was another complicated choice. The

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[10] Note, that since this parametric modelling was completed, MBIE published its Building Code update 2021 (MBIE, 2021) which contains minimum construction R values that differ to the medium H1 scenarios in Jaques et al (2020). MBIE (2021) sets the following minimum R values:

- Roof: R6.6 (all zones).
- Wall: R2.0 (all zones).
- Floor: Slab on ground R1.5 (zones 1 – 4), R1.6 (zone 5), R1.7 (zone 6), other floors (R2.5 (zones 1 – 3), R2.8 (zone 4), R3.0 (zones 5 – 6).
- Windows: R0.37 (zones 1 – 2), R0.46 (zones 3 – 4), R0.50 (zones 5 – 6).

effects of orientation and distribution are affected by a range of factors, particularly floor type. If the floor is exposed concrete, all glazing on the north is best. If the floor is timber, moving some windows to other orientations such as east may be better to reduce overheating in warmer climates. Overall, differences did not appear to be that large, so for simplicity, the same option was used for both variants especially since the exposed concrete option still has significantly lower energy use from heating/cooling anyway (Figure 6).

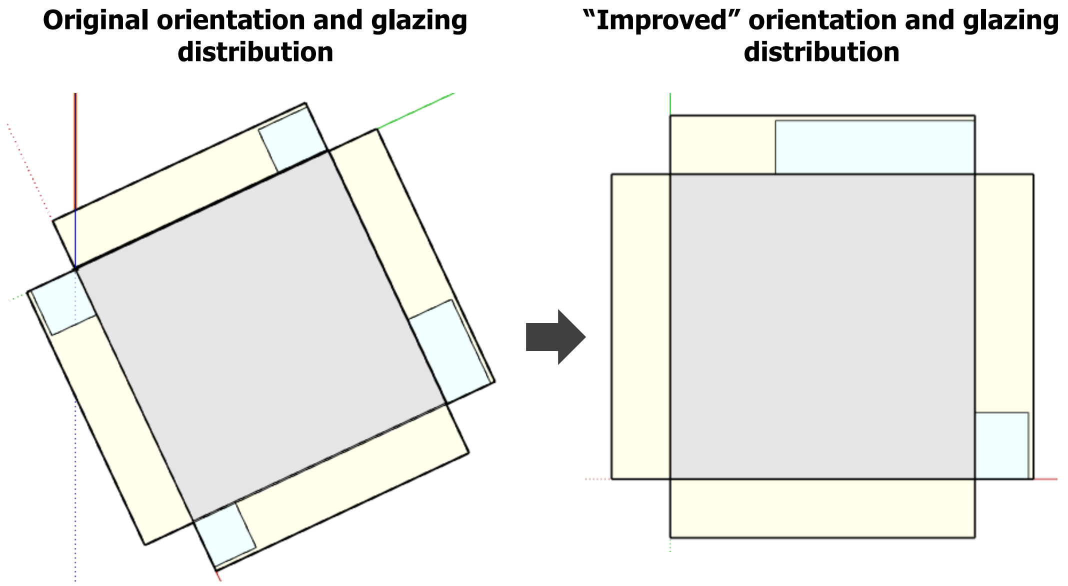

Figure 6. Reorientation and redistribution of the model and windows

- Reduce the area to improve occupancy density and per capita greenhouse gas emissions. Based on an assumed occupancy of 5 occupants (number of bedrooms + 1), it was reduced to 125 m² for 25 m²/occupant based on the occupancy assumptions in NZS 4218:2009.

Shading was not modified here, with standard 600 mm eaves assumed. Trade-offs were apparent in the results with eaves reducing cooling but increasing heating. The overall impact was dependent on how hot the climate is. Extending the eaves for more mid-summer shading in the south appears potentially detrimental overall. As glazing was predominantly north and west glazing was avoided, screens were not seen as useful here.

Similarly, the number of storeys was kept at one for simplicity and comparability on the grounds that this decision is generally based on other factors, although a case can be made that two-storey houses will tend to be more efficient.

3. Modelling assumptions

Thermal modelling was undertaken using EnergyPlus version 9.4. No site shading was modelled. Weather files were standard TMY files for New Zealand produced by NIWA. Insulation levels were the medium levels in MBIE's H1 upgrade proposal from Jaques et al, 2020 (Table 1).

3.1 Constructions

Walls

Walls were assumed to be timber framed with a plasterboard lining and timber weatherboard over cavity. The framing ratio was assumed to be 34% following the Beacon study into real timber framing ratios (Ryan, Penny, Cuming, Mayes & Baker, 2020).

- Zone 1 – R2.4 – 140 mm framing, R3.6 batts
- Zone 2 – R2.6 – 90 mm framing R2.4 batts + 45 mm service cavity
- Zone 3 – R2.8 – 90 mm framing R2.8 batts + 45 mm service cavity
- Zone 4 – R3.2 – 140 mm framing R3.2 batts + 45 mm service cavity
- Zone 5 – R3.5 – 140 mm framing R4.0 batts + 45 mm service cavity
- Zone 6 – R3.8 – 140 mm framing R3.2 batts + 90 mm service cavity

The service cavity was assumed to be 8% framing with R1.2 insulation (Quinn, 2021). A hypothetical 90 mm cavity needed for Zone 6 uses R1.8 batts.

Roof

The roof was assumed to be a standard timber truss 15° pitched roof with plasterboard lining, ceiling battens, corrugated steel roofing and 90 mm bottom chords (5% framing).

- Zone 1 – R5.0 – R3.2 batts between chords + R2.2 batts over top
- Zone 2 – R5.4 – R3.2 batts between chords + R2.6 batts over top
- Zone 3 – R6.0 – R3.6 batts between chords + R3.2 batts over top
- Zone 4 – R6.6 – R3.6 batts between chords + R3.2 batts over top
- Zone 5 – R7.0 – R3.6 batts between chords + R3.6 batts over top
- Zone 6 – R7.4 – R3.6 batts between chords + R4.0 batts over top

Floor

The floor varied between concrete slab and timber flooring over an enclosed subfloor. Carpet was not counted towards meeting the target construction R-values.

Slab floor

Concrete slab construction can have a significantly different R-value depending on house design, climate and the height of the water table. The equivalent R-values given for concrete slabs are thus somewhat nominal. Once a basic level of insulation has been provided (~R1.0), additional underslab or edge insulation appears to make a small additional contribution.[11] Therefore, the BRANZ *House Insulation Guide* (BRANZ, 2014) only provides a single option for each of perimeter and under slab insulation.

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[11] For example, increasing underslab insulation from R0.5 to R1.0 may only raise construction R-value by ~R0.1.

The level of granular R-value adjustment that can be achieved by practical tweaks to insulation thickness is also limited. Thin polystyrene sheets can have a tendency to break and be difficult to work with on site. The following were used as an example of what might be used in practice rather than trying to exactly meet target construction R-values:

- Zone 1 – R1.9 – R1.2 underslab insulation (50 mm EPS)
- Zone 2 – R2.2 – R1.0 edge insulation (30 mm XPS) + R1.2 underslab insulation
- Zone 3 – R2.5 – R1.0 edge insulation (30 mm XPS) + R1.2 underslab insulation
- Zone 4 – R2.8 – R1.0 edge insulation (30 mm XPS) + R1.2 underslab insulation
- Zone 5 – R3.2 – high-performance fully insulated slab system
- Zone 6 – R3.6 – high-performance fully insulated slab system

Following earlier work (Jaques et al., 2020), for the R3.2–3.6 values, a fully enclosed high-performance system such as MAXRaft is assumed. Actual construction R-value can vary widely depending on area/perimeter ratio. For houses used in that earlier study, this ranged from ~R3.4–R3.9. In this case, the same system has been used in both zones as roughly representative of what's likely to be needed to reach those R-values.

Timber floor

The timber floor was assumed to be 19 mm ply flooring over an enclosed subfloor with ~11% framing and various levels of batts (often ceiling batts).

- Zone 1 – R1.9 – R1.8 batts, 140 mm joists
- Zone 2 – R2.2 – R2.2 batts, 140 mm joists
- Zone 3 – R2.5 – R2.6 snugfloor, 140 mm joists
- Zone 4 – R2.8 – R2.6 ceiling, 140 mm joists
- Zone 5 – R3.2 – R3.2 batts, 190 mm joists
- Zone 6 – R3.6 – R3.6 batts, 190 mm joists

Windows

Windows were assumed to be modern thermally broken aluminium/uPVC double-glazed windows with the frame estimated as ~26–31% of the area based on case studies of a typical house (Table 9). It should be noted that these are approximate, as window properties, frame U-values and frame sizes can vary significantly.

Table 9. Window constructions used to provide desired R-values in the models.

Zone	Frame	U_{cog}[12]	Target	Frame	Glazing	Air gap	Spacer
1	26%	1.9	0.39	Mid-range TB (U3.6)	Double, 4 mm clear low-E	12 mm air	Aluminium
2	26%	1.64	0.42	Mid-range TB (U3.6)	Double, 4 mm clear low-E	12 mm 90:10 argon/air	Thermal
3	26%	1.55	0.45	Mid-range TB (U3.6)	Double, 4 mm clear low-E	16 mm 90:10 argon/air	Thermal
4	26%	1.23	0.49	Mid-range TB (U3.6)	Double, 4 mm clear high-performance low-E	16 mm 90:10 argon/air	Thermal
5	31%	1.64	0.55	uPVC (U1.6)	Double, 4 mm clear low-E	12 mm 90:10 argon/air	Thermal
6	31%	1.31	0.62	uPVC (U1.6)	Double, 4 mm clear high-performance low-E	12 mm 90:10 argon/air	Thermal

Code constructions

For the NZBC Code H1 minimum constructions, we followed the BRANZ *House Insulation Guide, 5th edition* (BRANZ, 2014) – 2.2 or R2.6 batts in the walls, R3.2 or R3.6 batts in the ceiling, standard aluminium double glazing and an uninsulated concrete slab or R1.6 floor batts. This does mean that the construction R-values may not meet current minimum H1 construction R values in parts because 34% framing in the walls is assumed. However, the point is to reflect current practice.

3.2 Infiltration and ventilation

As per NZS 4218:2009, the baseline level of infiltration and ventilation to provide fresh air was assumed to be 0.5 ACH. The subfloor was assumed to have a constant infiltration/ventilation rate of 11 ACH based on BRANZ measurements (McNeil, Li, Cox-Smith & Marston, 2016). This represents the average level of a relatively poorly ventilated subfloor. From a heat loss standpoint, this is the best-case scenario for a timber floor. The comparison against the performance of the concrete slab is conservative as the slab has a lower heating load despite favourable assumptions for the timber floor. In real houses, these can vary significantly due to wind, the surrounding environment and how airtight the building construction is.

In a real house, ventilation can be highly variable depending on occupant behaviour, local conditions and individual rooms. Living spaces, for example, often have the highest potential ventilation with large sliding doors and cross-ventilation opportunity. At the same time, other rooms might only have a single small openable window. For these simple tests, with the house being approximated as a single zone, we have assumed a maximum overall ventilation rate of 15 ACH with windows being opened at 23°C. This could be achieved with two doors on either side of the house with a wind speed of ~2–2.5 m/s, which seems reasonable given the amount of openings and sliding doors commonly present in modern houses. This is intended to represent a reasonable level of ventilation that might plausibly be achieved by occupants who are

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[12] Centre of glass U-value.

making some effort to ventilate to provide comfort. Particularly well-ventilated spaces may achieve higher levels than this, while poorly ventilated houses or ones where the occupants fail to open windows may perform significantly worse.

3.3 Heating and cooling

Space conditioning was provided using an ideal loads system, which effectively has a COP of 1. The heating setpoint was 18°C to meet current WHO recommendations, while the cooling setpoint was 25°C following NZS 4218:2009. Note that these setpoints are operative temperature, an average of air and radiant temperature, which is considered to better align with human perceptions of temperature.[13] As the model was single zone, conditioning was applied to maintain the entire house at comfortable temperatures 24/7. It should be noted that this is not how New Zealanders typically heat their homes (Isaacs et al., 2010). Real energy use would be expected to be lower.

3.4 Ground modelling

The concrete slabs and ground were modelled using the GroundDomain model in EnergyPlus with a water table depth of 2 m. This is perhaps the worst-case scenario for concrete slab heat losses, and so our estimates of the relative advantage of concrete slabs should be conservative. Soil properties assumed are shown in Table 10.

Table 10. Soil properties used.

Property	Value	Source
Conductivity	1.2 W/m-K	BRANZ recommended value for New Zealand (Trethowen, 2000)
Density	1500 kg/m^3	ANSI/ASHRAE 140-2007 *Standard method of test for the evaluation of building energy analysis computer programs* Addendum B Table B18-1; NZS 4214:2006 *Methods of determining the total thermal resistance of parts of buildings* (clay soil)
Specific heat	800 J/kg-K	ANSI/ASHRAE 140-2007 Addendum B Table B18-1

To model the underslab insulation and account for the fact that the insulation does not go all the way to the edge of the slab (due to the slab thickenings at the foundations), the rough R-value of the slab insulation was taken as the difference between the R-value of an uninsulated slab and a slab with underslab insulation in the BRANZ *House Insulation Guide* (BRANZ, 2014). It was modelled as providing an additional R-value of ~R0.5 rather than R1.2.

3.5 Window modelling

The windows were modelled using the detailed window modelling methods in EnergyPlus rather than the simple glazing that is commonly used. This is because previous work had found that the simple modelling method appeared to have problems with accounting for the conductivity of aluminium frames as well as underestimating the benefits of low-E coatings. LBNL WINDOW8.0 was used to put together combinations of glass, air gap, spacer, and frame to meet the target R-values as described in the constructions. These were then exported into the EnergyPlus idf format and modelled.

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[13] https://designbuilder.co.uk/helpv2/Content/Calculation_Options.htm

To handle the need to parametrically vary window-to-wall ratio, one window was placed on each wall covering its full height. Their width could then be readily adjusted to produce any needed WWR. To maintain the same window frame proportion throughout, no vertical window frame elements were modelled. Instead, the frame was modelled entirely through four horizontal dividers breaking up the window into five panes. Adjustments to the width of the window thus had no effect on the framing ratio, while breaking the window up multiple times helped make sure there would still be a reasonable amount of frame-edge-glass in this abstraction (Figure 7).

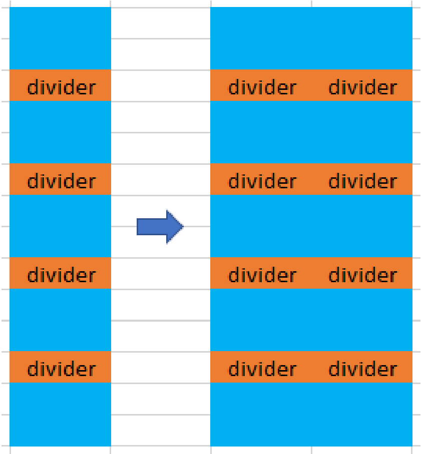

Figure 7. Modelling the frame through horizontal dividers allowed it to easily vary in size while keeping the frame ratio constant.

3.6 Internal gains

Internal gains assumptions can be problematic. NZS 4218:2009 as well as HEEP data and the schedules in AccuRateNZ derived from it are all based off old data dating back to the 1990s. They assume, for example, that all lighting is incandescent. Significant advances have been made in the areas of energy efficiency for many appliances – the move towards LED lighting being one example. At the same time, however, it may be argued that modern houses often have more electronics, which may work against that. As HEEP2[14] is yet to be completed, there is a lack of data on the equipment gains and loads in more modern houses.

An option would have been to use the significantly lower internal gains suggested in the Passive House Planning Package (PHPP).[15] However, this makes assumptions about users using very high-efficiency appliances and using far less energy than may be realistic for typical New Zealand households.

Instead, we opted to adjust some of the key loads in the HEEP data to try to account for what can be identified in known energy efficiency trends. We began with the basic schedules previously derived from HEEP data for AccuRateNZ covering lighting, heated towel rails, hot water cylinder losses, range (cooking) and other equipment. Our analysis, and resulting adjustments to the original HEEP data, are provided in the following sections.

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[14] https://www.branz.co.nz/environment-zero-carbon-research/heep2/

[15] https://passivehouse.nz/product/phpp-9-6/

3.6.1 Lighting

Lighting can be assumed to be LEDs in a modern house. One question is whether energy efficiency savings (~11 W LED versus ~100 W incandescent) are counteracted by modern houses having more lighting than older houses. Burgess, Camilleri and Saville-Smith (2010) found that lamp density was unchanged since an earlier study (2004) at ~0.15 lamps/m². However, that data is now over a decade old, and looking at the overall average in the housing stock could gloss over increases in new houses. Examination of a sample of 2016 house consents that include electrical plans suggests a rough average of 0.22 lamps/m². If we assume the lamps are common 11 W LEDs, this would give a lighting power density of ~2.4 W/m² compared to ~13.6 W/m² in Burgess et al. (2010) – a decrease of 82%. This is in line with common estimates that LEDs may use ~75–85% less energy than incandescents.[16] Based on this, reducing the HEEP lighting loads by ~80% would seem a reasonable approximation (Table 11).

Table 11. Lamp density.

	Floor area (m²)	Lamps	Lamp density (per m²)
House 1	168.4	46	0.27
House 2	120	21	0.18
House 3	127.3	37	0.29
House 4	194.1	41	0.21
House 5	139.8	28	0.20
House 6	237.1	48	0.20
House 7	170.9	27	0.16
House 8	222.7	58	0.26
		Average	0.22

3.6.2 Heated towel rails

Assuming that heated towel rails are common in modern bathrooms, we may estimate the use as follows. The average power rating of heated towel rails was noted to be around 70±10 W in HEEP (Isaacs et al., 2010, p. 201), a number that appears to still be valid today.[17] Assuming that a timer is used to save energy, running only 4 hours in the morning and evening, the resulting power use would be ~23 W per bathroom on average over the day.

3.6.3 Hot water cylinders

Hot water cylinder losses are traditionally assumed to be around 100 W in NZS 4218:2009. In practice, this will vary depending on how well the cylinder is insulated and how large it is, with HEEP measurements ranging between ~75–125 W for electric cylinders. EECA data[18] suggests that heat losses for an average new cylinder now are slightly higher than in 2002, providing little reason to assume that the typical modern

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[16] https://genless.govt.nz/for-everyone/at-home/use-led-lighting/; https://www.energy.gov/energysaver/led-lighting

[17] https://www.genesisenergy.co.nz/genesis-blog/saving-energy/energy-saving-during-winter#:~:text=Another%20appliance%20that%20is%20often,your%20towel%20several%20times%20over; https://www.consumer.org.nz/articles/appliance-running-costs

[18] https://figure.nz/chart/Rv0hdyRL9AX2YyMh-0NOarSpVQ6sZ2sH1

cylinder is any more efficient. In light of this, we have assumed the internal gains from the hot water cylinder is simply the traditional 100 W.

3.6.4 Range/cooking

It is difficult to find reliable information on range efficiency. Statements that induction stoves use 50% of the energy of ceramic resistive stoves are common,[19] yet generally lacking in supporting evidence. Consumer NZ noted that, when it compared stoves, it did not observe the induction stove to use any less energy,[20] while a report from Frontier Energy in the US measured several stoves and estimated that the induction type might use ~7% less energy than electric resistance coil stoves (Livchak, Hedrick & Young, 2019).

Similarly, we can find statements about how fan ovens use ~20–30% less energy than conventional ones but measurements of their energy use in practice are difficult to find. Mudgal et al. (2011) reported that oven energy use in the UK declined by 25% from 1980 to 2008 potentially because of more efficient appliances. Looking at the timeframe of HEEP (around 2000), the estimated decline is around 10% from ~1.2 kWh/cycle to ~1.1 kWh/cycle. More-recent EU work (Rodríguez Quintero et al., 2020) suggested that these numbers may be out of date and modern ovens might use ~0.7 kWh/cycle fan-forced and 0.9 kWh/cycle conventional. This would suggest the possibility of a ~25–40% reduction.

The total range load is an amalgamation of loads from multiple appliances. Beyond appliance efficiency, it can also be significantly affected by changes in user behaviour. For example, while Mudgal et al. (2011) estimated a 25% decline in consumption per use from 1980 to 2008, the estimate in overall energy use saw a 60% decline due to the oven being used significantly less. According to Statistics New Zealand,[21] the proportion of the average New Zealander's food budget spent on takeaways and restaurants has increased slightly from 22% in 2000 to 27% in 2020. This might suggest a decline in cooking energy use, but without specific measurements it is hard to confirm this.

Overall, looking at the potential efficiency gains in stoves (0–7%) and ovens (25–40%) and assuming that total cooking is a mixture of both, reducing the HEEP range loads by 10–20% might be reasonable. We have assumed the lower end of this (10%) to be conservative.

CIBSE (2015) and ASHRAE (2001) note that, in the presence of an effective hood, the internal heat gains from cooking should be ~15–45% of the actual energy use, with that energy all being radiant (because air/moisture is being vented so it is not going into space). Without a hood, the load should be the actual energy use – ~34% latent, 66% sensible.

To determine range loads (Table 12), we make the assumptions that:

- the load is half stove, half oven for simplicity
- the stove is hooded and the oven is not ventilating to outside
- the higher end of the hooded load for the stove is used to be conservative – >45%

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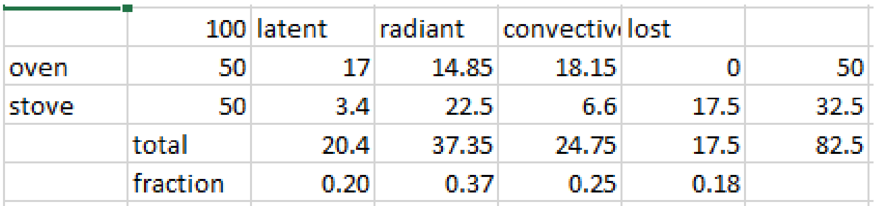
[19] https://www.smarterhomes.org.nz/smart-guides/power-lighting-and-energy-saving/stoves-ovens-and-dishwashers/

[20] https://www.consumer.org.nz/articles/cooktops-induction-cooktops

[21] https://www.stats.govt.nz/news/kiwis-growing-taste-for-takeaways-and-eating-out

- people do not always turn on extract fans or residential fans are not always strong enough, therefore creating inefficiencies – adding an extra ~20%.

Table 12. Assumed range loads.



	100	latent	radiant	convectiv	lost	
oven	50	17	14.85	18.15	0	50
stove	50	3.4	22.5	6.6	17.5	32.5
	total	20.4	37.35	24.75	17.5	82.5
	fraction	0.20	0.37	0.25	0.18	

If ~18% of the load is lost due to venting and another 20% is latent, this results in ~62% sensible heat gain instead of 66% if we just took the no hood assumptions. The main effect is on latent gains. Those should not affect heating energy use but could affect cooling somewhat. Therefore, the assumption is that the HEEP cooking loads are 10% lower than they were then (being conservative) and that 62% of that gain is sensible, with 18% lost and 20% latent.

3.6.5 Other equipment and refrigeration

The remaining equipment schedule comprises a wide range of appliances such as refrigeration, entertainment systems, computers, dishwashers, washing machines and kettles, which may be challenging to estimate due to the many potential factors acting on their energy use. For example, entertainment is a large portion of the energy use identified by HEEP, but potential increases in efficiency could be counteracted by increases in the number of appliances or their size (such as TVs).

EECA has collected data on the average energy consumption of a number of appliances sold in New Zealand over the years including refrigerators, dishwashers, TVs, washing machines, clothes dryers and computer monitors.[22] This may give some indication of potential load reductions over time.

The average refrigerator uses ~40% less energy now than in 2002.[23] This is particularly valuable as refrigeration was one of the largest loads in HEEP at 28% of the electric appliance load. Not counting lighting and range loads, as they are addressed as separate schedules in the model, it comprises ~43% of the equipment load. Assuming typical refrigerators now use ~40% less energy than in HEEP, the load is reduced by 17%.

TVs are harder to estimate, as the technology has changed significantly over time – from CRT to plasma to LCD to LED – and EECA's data only goes back to 2013. Batstone and Reeve (2014) made a very rough estimate of a ~10% reduction in TV energy consumption since 2003, with improvements to efficiency being counteracted by increases in size and number of TVs per household. EECA's data suggests the average energy consumption of new TVs has risen by almost 50% since 2014 along with significant increases in size.[24] Taking the rough estimate of an average 250 kWh for CRT/plasma TVs during HEEP from Batstone and Reeve and comparing it to EECA's numbers for new TVs, that is an increase of ~25% per TV. The number of TVs per household was ~1.5 in 2003, which may have risen to around 1.7 in more recent

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[22] https://www.eeca.govt.nz/insights/eeca-insights/e3-programme-sales-and-efficiency-data/
[23] https://figure.nz/chart/kNn2WAINP6RmR07V
[24] https://figure.nz/chart/xHu018n3AAEunFa4-JuWVyUx1xS9E14EA

times,[25] so the increase in TV load would be ~41%. HEEP did not explicitly provide TV energy use – it is part of entertainment. However, HEEP did estimate that the average TV used ~132 kWh/yr. Assuming that most of the TV use is the main TV, this would be about 5% of the equipment load – an approximate increase of ~2%.

Washing machine data suggests that the energy used for warm washes has declined by ~13% (463–404 kWh/yr), but the energy consumption for cold washes has increased significantly from 51 kWh/yr to 120 kWh/yr.[26] For simplicity and because they were not a significant part of the observed load (only 2%), we assume these roughly cancel out overall, leading to no significant change from HEEP.

Dishwashers may have around a ~35% reduction in energy use.[27] At 4% of the equipment load, this is a 1.4% reduction overall.

Average clothes dryer energy use has increased slightly since 2002 by ~13%.[28] At 5% of the equipment load, this translates to ~0.6% increase.

Over the years, there have been large pushes to minimise standby loads internationally. HEEP estimated standby loads to be ~57 W on average and that, if appliances other than refrigeration and set-top boxes were reduced to no more than 1 W standby, it would reduce standby power by ~60%. At ~13.5% of total equipment loads, reducing them by 60% would result in reductions of around 8% overall.

Combining all of the above, we estimate a reduction in the equipment load of ~24%.

3.6.6 Resulting loads and schedules

The question is then how to scale the HEEP-based schedules for an average house of 122 m² and 2.9 occupants. The sensible heat gains from hot water cylinders are traditionally assumed to be a static load, and in the interest of not overcomplicating matters, we will continue to do that. The heated towel rail should be applied on a per bathroom basis, which in this case requires an estimate of the number of bathrooms. We assume a typical ~150 m² house has two bathrooms – one most likely an ensuite.

The other equipment loads are slightly more problematic. It is common to simply use per square metre rates as in NZS 4218:2009. However, this means that load density will not change in larger or smaller houses. In reality, many appliances will exist regardless of the size of the house, and smaller houses should be expected to have higher internal gains per square metre.

To scale the internal gains for lighting, equipment and range loads, we have used the models developed for HEERA in HEEP to estimate energy use. These have then been normalised against the estimate for the average house. The baseline loads were derived to produce adjustment factors.

We can fit simple linear models to estimate these adjustment factors as follows:

$$F_{light} = -0.99 + 0.00765 * Area + 0.377 * N_{people}$$

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[25] https://thinktv.co.nz/wp-content/uploads/2018/05/Think_TV_-2017_PowerPoint_Fact_Pack.pptx.pdf

[26] https://figure.nz/chart/Vsy3m²OSYTA1Bcb6

[27] https://figure.nz/chart/spm3YXYX3lj9yxj7

[28] https://figure.nz/chart/6EY3qb6E6lXZAQIa

$$F_{equip} = 0.0862 + 0.000298 * Area + 0.035 * N_{people}$$

$$F_{range} = 0.685 + 0.236 * N_{people}$$

For some reason, the range energy model had a negative term for a floor area*people interaction, which results in people using less cooking energy in larger houses. This may reflect a behavioural trend in terms of how people tend to live in larger houses. However, it is questionable to build into our assumptions as there is no logical reason why house size should lead to a decrease in cooking. We have instead scaled the range loads according to the number of occupants, which makes more sense.

It should be noted that any assumption we make is highly uncertain. There is no such thing as an average house and people vary widely in how they live.

The people loads are taken from estimates made based off HEEP occupancy data to describe an average household for AccuRateNZ. For simplicity, we scale them to the desired number of occupants.

For a 150 m² house with 4 occupants and two bathrooms, this would produce the internal gains schedule shown in Figure 8.

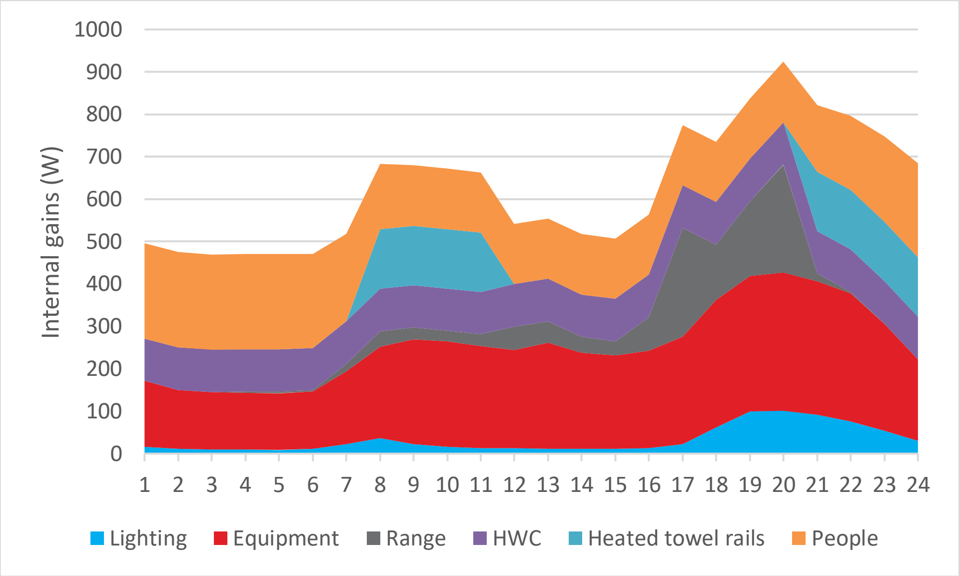

Figure 8. Internal gains schedule.

As a rough comparison of different load assumptions, we can calculate the average W/m² from different approaches, summarized in Table 13..

NZS 4218:2009 leads to the highest assumptions,[29] with the basic HEEP schedules being ~15% lower.[30] Our new adjusted schedules produce loads ~25% lower than

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[29] This is actually an underestimate due to manually assigning occupancy. NZS 4218:2009 assumes that occupancy gains are a minimum of 150 W + 3 W/m² past 50 m². This is roughly equivalent to 2 occupants for every 50 m² or 6 occupants in a 150 m² house.

[30] This depends on implementation. For example, here we have scaled the lighting loads over the year as observed in HEEP. The basic schedule that was devised did not do that, and, focusing on heating, was scaled to the rough winter average. This additional scaling reduces the overall lighting load by ~20%. Similarly, not accounting for the fraction of the cooking load that goes into latent heat instead of sensible and just taking the HEEP energy measurements, the numbers would be higher.

that. PHPP's assumptions are still ~35% lower, but that was to be expected given its assumptions.

Without HEEP2 to provide new measurements of modern houses, however, it is hard to do more than this.

Table 13. Comparison of different load assumptions.

Source	Area (m²)	Occupants	W/m²
NZS 4218:2009	150	4	6.38
NZS 4218:2009	150	3	5.98
HEEP	150	4	5.39
HEEP	150	3	4.71
New schedules	150	4	4.19
New schedules	150	3	3.72
PHPP	150	2.9	2.43

3.6.7 Plausibility checks

MBIE data on average household electricity use suggests it has declined by less than 10% since HEEP[31]. This may be affected by a wide range of factors pulling in multiple directions. Nevertheless, it does at least suggest that reductions in equipment energy use may not be extreme overall or any large effects would be counterbalanced by increases in space conditioning energy use.

The suggested changes here would lower electric equipment load by ~24% and by ~43% if lighting and range loads are added. Assuming they are roughly a third of the energy use, as estimated by HEEP, this reduction would lower overall energy use by roughly 14% if all else stays equal. Average household electricity use will encompass a mixture of both old and new houses covering a range of conditions. Space conditioning may have dropped in new houses with higher COP systems and better insulation, may have stayed the same with people simply spending the same amount of energy to be more comfortable or may have increased in areas with people now using air conditioning as well. Significant proportions of residential energy use are also not electricity, adding further complications to any comparisons here.

In the EU, however, it was noted that the energy demand for appliances and lighting had increased by about 50% over the past two decades, despite efficiency improvements (Elsland et al., 2014). Based on that, the suggestion that we are using less energy now may be optimistic.

Altogether, these data points suggest our estimates, although highly uncertain, are at least plausible. Additionally, they give reason to be cautious about dramatic reductions in energy use. It is not impossible that, for example, equipment energy use has dropped more dramatically in new houses than estimated here, but this would need to be counterbalanced by increases in other areas such as heating. Ultimately, with the limited available information, a wide range of plausible assumptions could be made.

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[31] https://figure.nz/chart/WYKrv65R1rBAfLzO

4. Cross-checking results

Several significant results were surprising. It was therefore considered important to check their soundness through comparisons with similar simulations using AccuRateNZ.

These included confirming that the:

- magnitude of the energy numbers was broadly consistent with other models once assumptions were accounted for, noting that these values are heavily dependent on assumptions around HVAC operation, which are often unrealistic – for example, assuming that people operate their houses to maintain a comfortable temperature of between 18 – 25°C year round.
- large effects of shape or area/perimeter ratio were reliable.
- strong performance of the exposed concrete slab was reliable.
- positive effects of increased WWR with exposed concrete slabs were reliable – this was uncertain, as AccuRateNZ and EnergyPlus seem to disagree on this and the effects seem related to how aggressive ventilation operation is.

These cross-checks were run at several different times throughout the project, and so the assumptions used varied. For example, curtains were initially included but were later dropped partly because the windows were performing better than expected and we wanted to be conservative. This is also particularly the case for internal gains and ventilation assumptions due to how AccuRateNZ manages those. Those will generally differ between the tools apart from where we went to significant lengths to make the AccuRateNZ model identical. (Note that this was not possible with ventilation as AccuRateNZ estimates natural ventilation from window openings and does not report its ventilation rates anywhere.) Most of the time this is not important, as checking the basic direction and general magnitude of an effect does not rely on these factors.

4.1 Cross-checking test cell against previous work

During initial test runs of the test cell the heating energy use seemed low in comparison to the earlier H1 study (Jaques et al., 2020) using the same construction R values. Of concern was that the heating use was almost *half* of what had been estimated previously (13.2 kWh/m² versus 25.2 kWh/m²).

The test cell used for comparison was a carpeted slab three-point model with windows mainly on the north, east and west and 20% WWR (Figure 9).

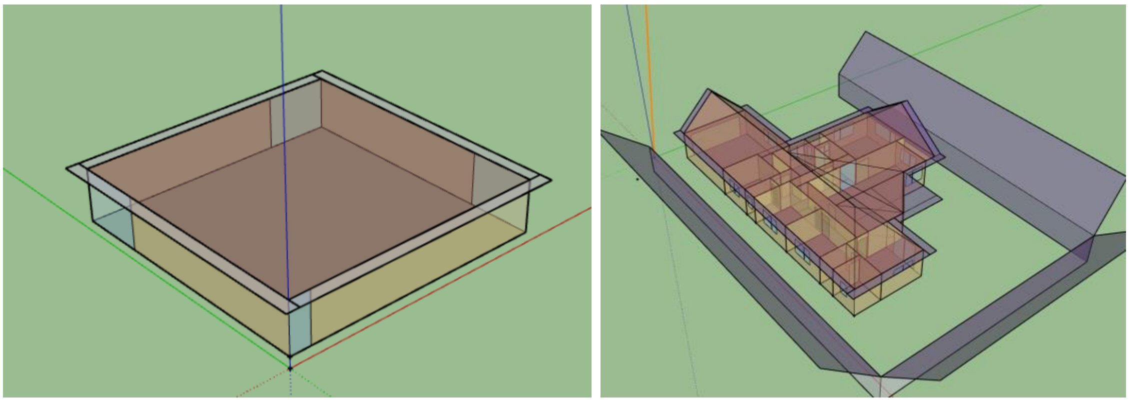


Figure 9. Test cell (left) and the single storey house from the earlier H1 study (4_M_SS, right).

There were several differences between the two models:

- Curtains were not used in the H1 study (at the time this cross checking was undertaken, they were included in this study).
- The hot water cylinder in 4_M_SS was in the garage so its load was outside of the thermal envelope and did not contribute to heating the house (whilst in this study, it was assumed that the hot water cylinder was in the house).
- The glazing construction in the H1 study (Jaques et al., 2020) used the simple method, which may underestimate the heat retention of higher-performance low-E glazing compared to the detailed method we are now using.
- The houses in the H1 study had surrounding site shading built roughly up to the allowed recession planes.
- 4_M_SS has relatively poor orientation, with its main face being more eastwards.

Addressing some of these differences – mostly the presence of curtains, site shading, and the placement of the hot water cylinder – can draw the models much closer together (Table 14).

Table 14. Model variations.

4_M_SS (H1 study)		**Selected test cell**	
Model variation	**Heating (kWh/m^2)**	**Model variation**	**Heating (kWh/m^2)**
Baseline	25.2	Baseline	13.2
Curtains added, site shading removed	18.9	Using simple glazing material	14.1
+ orientation improved	18.35	+ hot water load removed	16.2
		Curtains removed	14.5
		Simple glazing, no curtains, site shading	18.75
		Simple glazing + no curtains + site shading + hot water load removed	21.3

The curtains and site shading have a significant effect on the energy use of the house model from the previous study, with the addition of curtains and removal of site shading reducing its heating needs by ~25%. Similarly, using simple glazing material increases the heating load by about 7% compared to the newer detailed one, and the removal of the hot water load from the test cell significantly increases its heating energy use. Aligning these factors better means the test cell is only ~15% better, which is much more reasonable.

4.2 Shape effects

The shape analysis found that the compactness of the model had surprisingly large effects, with the least-compact model requiring around 40% more energy than the most compact square (Figure 10).

This was surprising, as the only variable that really changes, especially for the timber subfloor models, is the area of the external walls.

Simple heat loss calculations would suggest the effect should be much smaller – for example, if the walls are only 15% of the total heat loss of the dwelling, increasing the wall area by half would only increase the overall heat loss by ~7.5%.

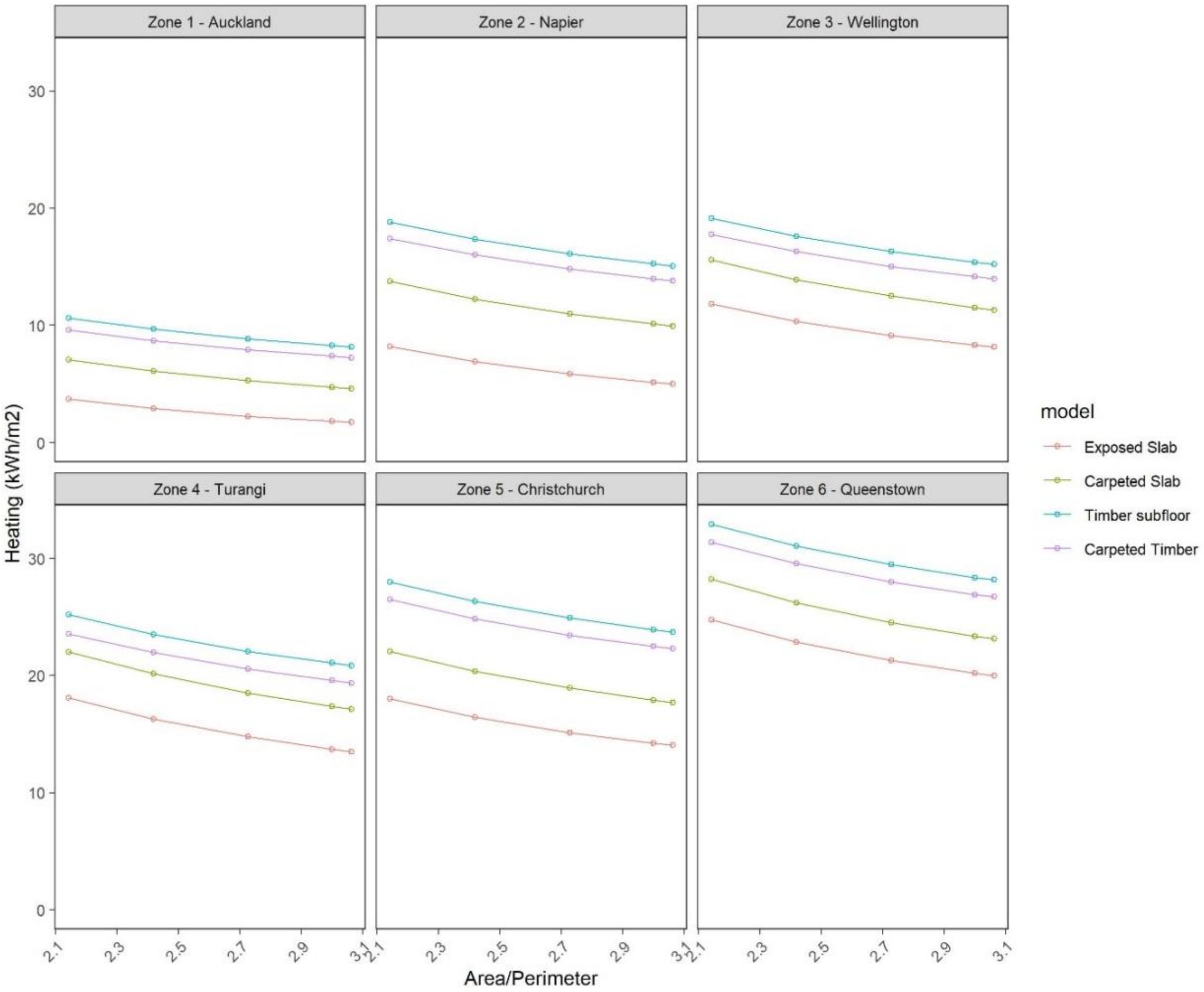


Figure 10. Results of the shape analysis on heating energy use.

A cross-check was run in AccuRateNZ to ensure there were no modelling errors or issues. A south-facing exposed concrete slab test cell of the same dimensions and R-values as the EnergyPlus models was run in Auckland. AccuRateNZ reported that the 30 x 5 m rectangle required ~50% more heating energy than the 12.25 x 12.25 m square, corroborating the results from the main EnergyPlus analysis.

4.3 Concrete slab versus timber over subfloor

In this study, the concrete slab models, especially when exposed, suggested that the thermal mass could have substantial effects on heating energy use. In theory, the equivalent R-values of the concrete slab and light timber floors should be roughly comparable, and they should have similar heat loss.

However, when a dynamic simulation tool such as EnergyPlus is used to account for the effects of thermal mass, high mass can have significant benefits by reducing heating energy use significantly as well as the well-established benefits for cooling from smoothing out temperature spikes. This is why Clause H1 has separate tables allowing for high-mass walls to have lower R-values than light timber-framed walls. High-mass walls with ~190 mm of exposed concrete and a total R-value of R2.0 could produce similar performance to light timber walls of R2.9.

The magnitude of the increased heating performance of a concrete slab compared to a light timber floor at roughly the same R-value was surprising. The results suggested that a badly oriented house with an exposed concrete slab could have similar or even better heating performance as a well-oriented house with a light timber floor.

Failing to provide good solar gains should substantially reduce any benefits the concrete slab can provide to store these and use them to smooth out the temperature fluctuations. Figure 11 shows that the exposed slab is particularly affected by how good the glazing distribution/orientation is. Despite this, a slab with no north glazing still appears to outperform a north-facing house with a light timber floor.

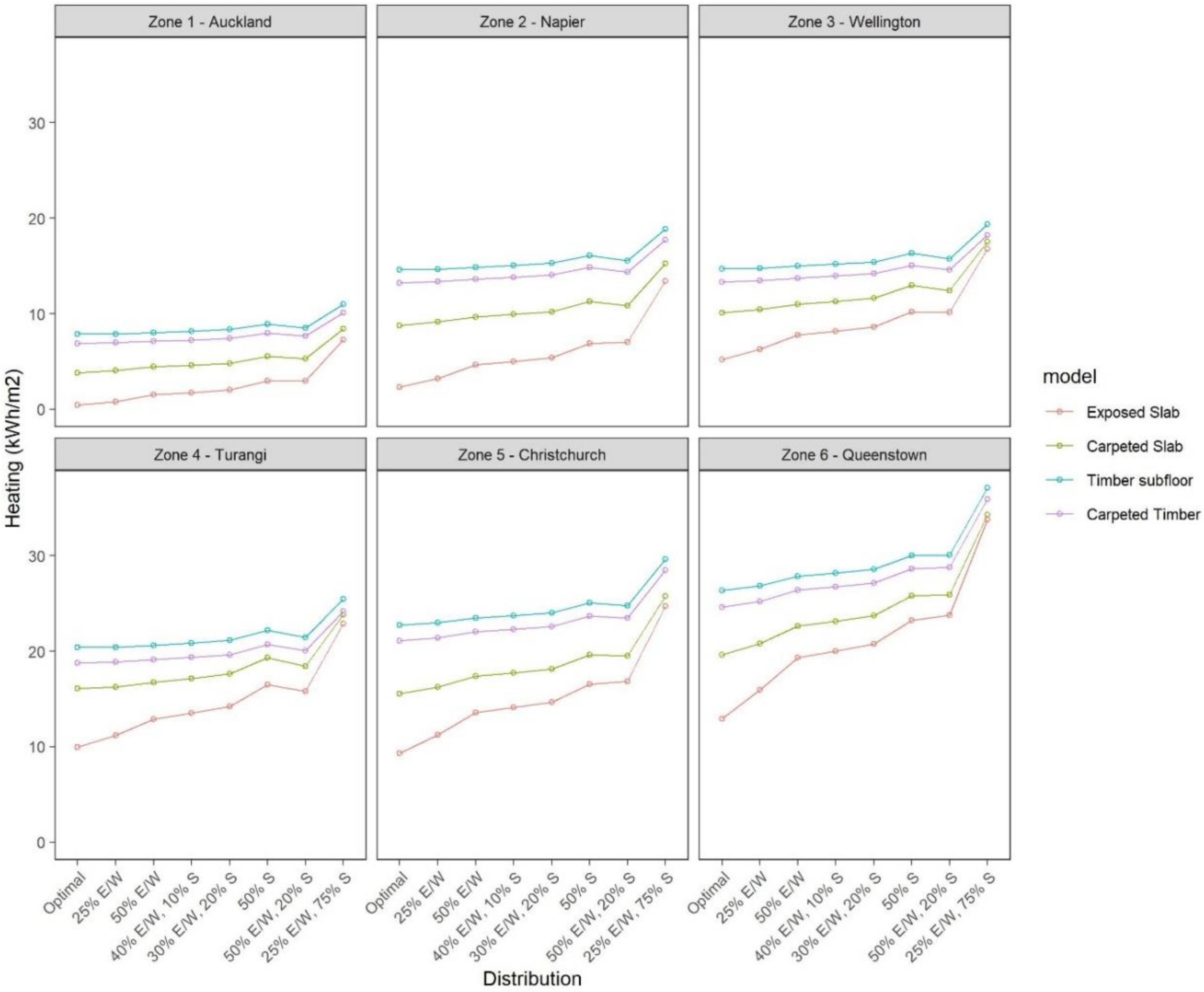


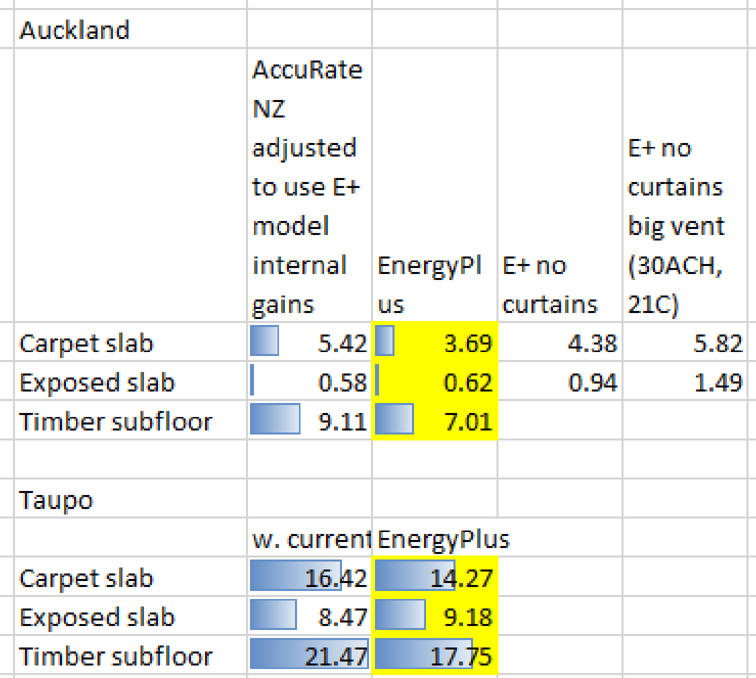
Figure 11. Results of the deopt analysis showing the effects on heating energy use of shifting glazing away from north.

Some comparisons were run in both AccuRateNZ and EnergyPlus using the 20% WWR even window distribution test cell (Figure 12).

Both tools agreed on the basic pattern and strong benefits from thermal mass – exposed concrete has the lowest heating energy use, followed by carpeted concrete slabs, followed by the carpeted timber subfloor. (Exposed timber was a later addition to the study and not examined here.)

Differences in assumptions between the tools in terms of internal gains, presence of curtains and ventilation significantly affect the magnitude of the estimates but not the basic pattern in terms of the benefits of mass. AccuRateNZ suggests that the relative difference between low and high mass is larger than in EnergyPlus, potentially making our estimates of the advantages here slightly conservative.

That being said, it should also be remembered that the heating schedule, by conditioning the entire house 24/7, is making the potential benefits of the concrete slab as large as possible. A more typical pattern of use would likely present smaller energy savings.



Auckland				
	AccuRate NZ adjusted to use E+ model internal gains	EnergyPlus	E+ no curtains	E+ no curtains big vent (30ACH, 21C)
Carpet slab	5.42	3.69	4.38	5.82
Exposed slab	0.58	0.62	0.94	1.49
Timber subfloor	9.11	7.01		
Taupo				
	w. current	EnergyPlus		
Carpet slab	16.42	14.27		
Exposed slab	8.47	9.18		
Timber subfloor	21.47	17.75		

Figure 12. Comparisons of heating energy use (kWh/m²) of different floor options of the test cell modelled in AccuRateNZ and EnergyPlus.

4.4 Effects of high window-to-wall ratios

The question of whether increasing the amount of glazing is good or bad for heating energy efficiency is not straightforward.

The initial runs of the WWR tests suggested that, while overall energy use went up in all cases as glazing increased (due mainly to increasing cooling loads), heating energy use actually decreased when there was a well-insulated exposed concrete slab to take advantage of the solar gains (Figure 13).

Even with an even glazing distribution, which is hardly optimal, the 80% WWR case was markedly better than the 20% WWR case in all climates, not just hot ones. This was surprising and merited cross-checking as prior experience using AccuRateNZ had suggested that windows were generally a net negative for energy efficiency. Moreover, the heating schedule is 24/7 and heating overnight with no curtains would generally be expected to make the windows a significant source of heat loss.

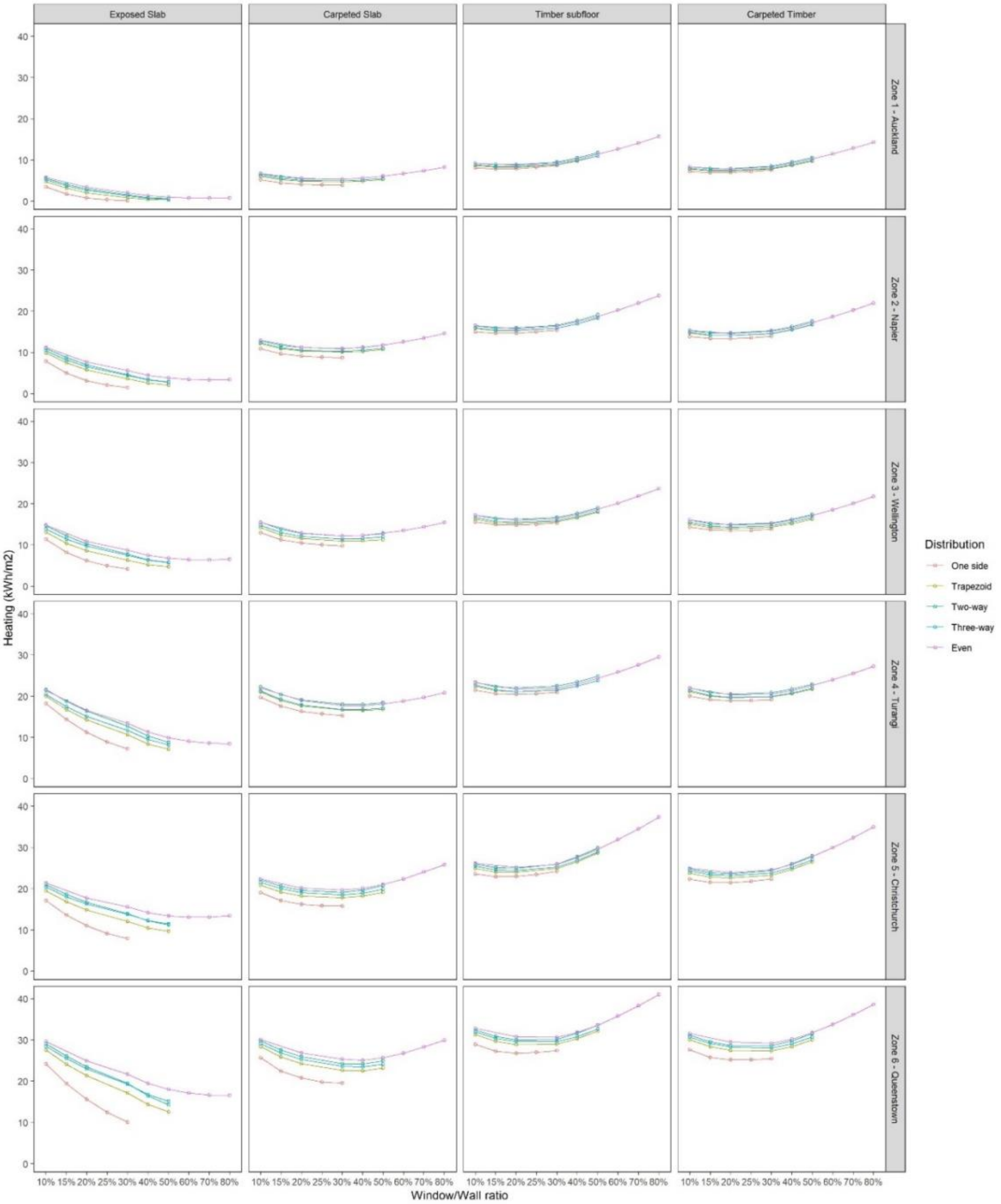


Figure 13. Results of the analysis of the effects of WWR on heating energy use.

A cross-check was run with AccuRateNZ comparing the 20% WWR test cell against the 80% WWR cell in Taupō.[32] Unfortunately, AccuRateNZ gave the opposite result. It showed that the 80% WWR case should require substantially more heating use than 20% WWR (Figure 14).

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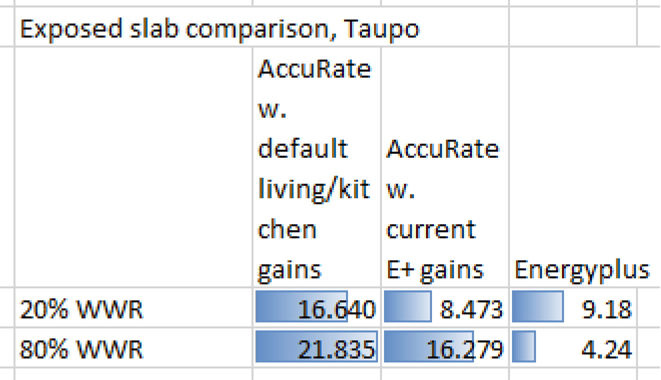
[32] Taupō was chosen as the coldest climate that we could easily model in AccuRateNZ with these constructions. AccuRateNZ's construction library does not include glazing that matched those we are using in Zones 5 and 6.

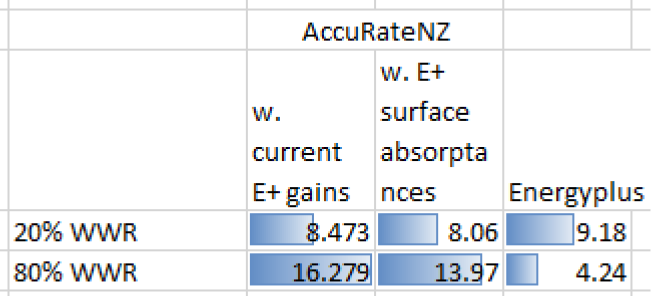


Exposed slab comparison, Taupo			
	AccuRate w. default living/kitchen gains	AccuRate w. current E+ gains	Energyplus
20% WWR	16.640	8.473	9.18
80% WWR	21.835	16.279	4.24

Figure 14. Comparison of the effects of WWR on heating energy use in Taupō with an exposed concrete slab in both AccuRateNZ and EnergyPlus

A range of parameters and factors that could potentially differ between the tools and affect the results were then examined to identify what could be causing the disagreement.

Tuning the material surface reflectances has some effect. If concrete is lighter, it will be less effective. Adjusting the surface absorptances in AccuRateNZ to match the ones used in the EnergyPlus model does bring its difference down slightly, although it still holds that more glazing increases heating energy use (Figure 16).

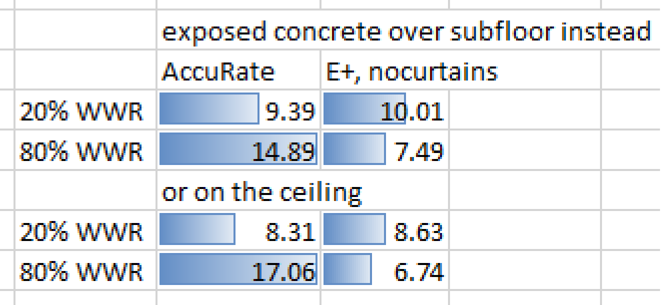


	AccuRateNZ		
	w. current E+ gains	w. E+ surface absorptances	Energyplus
20% WWR	8.473	8.06	9.18
80% WWR	16.279	13.97	4.24

Figure 15. Adjusting surface absorptances in AccuRateNZ.

Curtains are significant and removing them increases window heat loss. However, EnergyPlus still holds that more glazing reduces heating even without them.

While one might suspect the cause to be the different ground models used by the tools, this does not appear to be the case. Rather, the problem appears to be one of thermal mass. The same disagreement between the tools is found even when the concrete is separated from the ground and put over a subfloor or even on the ceiling.



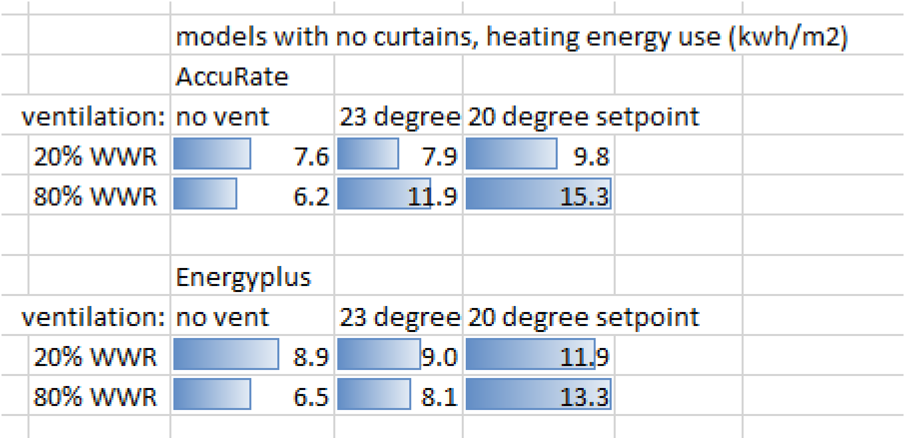
	exposed concrete over subfloor instead	
	AccuRate	E+, nocurtains
20% WWR	9.39	10.01
80% WWR	14.89	7.49
	or on the ceiling	
20% WWR	8.31	8.63
80% WWR	17.06	6.74

Figure 16. Comparison with the concrete mass separated from the ground, and curtains removed from the EnergyPlus model

Passively, both tools agree that having more windows makes the space less cold overall, although the difference is larger in EnergyPlus (4660–>2718 degree hours too cold in EnergyPlus, 3953–>3223 degree hours too cold in AccuRateNZ).

The heating schedule appears to have some effect. Using daytime heating rather than 24-hour heating can make AccuRateNZ agree that more windows = lower heating although this is not entirely reliable. While 7am–11pm lines up well with EnergyPlus, shifting it an hour back to 6am–10pm increases the heating load, and AccuRateNZ then says that both 20% WWR and 80% WWR should be similar, with 80% WWR requiring maybe 5% more heating.

The biggest factor appears to be ventilation. Removing ventilation from the models results in them agreeing that more windows reduces heating — though EnergyPlus still has a larger difference, mostly due to higher estimates in the 20% WWR case (Figure 17). Similarly, it is possible to make the EnergyPlus model say that increased glazing increases heating by lowering the ventilation setpoint to 20°C and increasing the ventilation rate to 30 ACH although the difference is not as large as the AccuRateNZ models. (It should be noted that AccuRateNZ's basic behaviour involves separate ventilation on and off setpoints – windows are opened at 23°C, say, and closed at 20°C. Also, because it involves opening windows and calculating the airflow, we cannot control the actual ACH as specifically and, while unknown, it may be quite high.)



	models with no curtains, heating energy use (kwh/m2)		
	AccuRate		
ventilation:	no vent	23 degree	20 degree setpoint
20% WWR	7.6	7.9	9.8
80% WWR	6.2	11.9	15.3
	Energyplus		
ventilation:	no vent	23 degree	20 degree setpoint
20% WWR	8.9	9.0	11.9
80% WWR	6.5	8.1	13.3

Figure 17. Comparison of the effects of ventilation settings on the effects of WWR on estimated heating energy use

While ventilation management appears to be significant, even when we try to align those, we still see EnergyPlus tending to be more positive about lower WWR than AccuRateNZ. It's not clear why the programs would be disagreeing in this way or why ventilation settings seem to have a more marked effect on the performance of the high WWR model in AccuRateNZ.

One possible hypothesis is that it relates to AccuRateNZ working on operative rather than air temperature. If we compare the temperature profiles of the programs with the problematic 23°C setpoint, we see that AccuRateNZ's temperatures line up with the air temperatures in EnergyPlus, which ends up lower than the setpoint (Figure 18). The operative temperature, however, is higher than that because opening the windows lowers the air temperature more rather than surface temperature. Could AccuRateNZ thus be overcooling the surfaces compared to EnergyPlus?

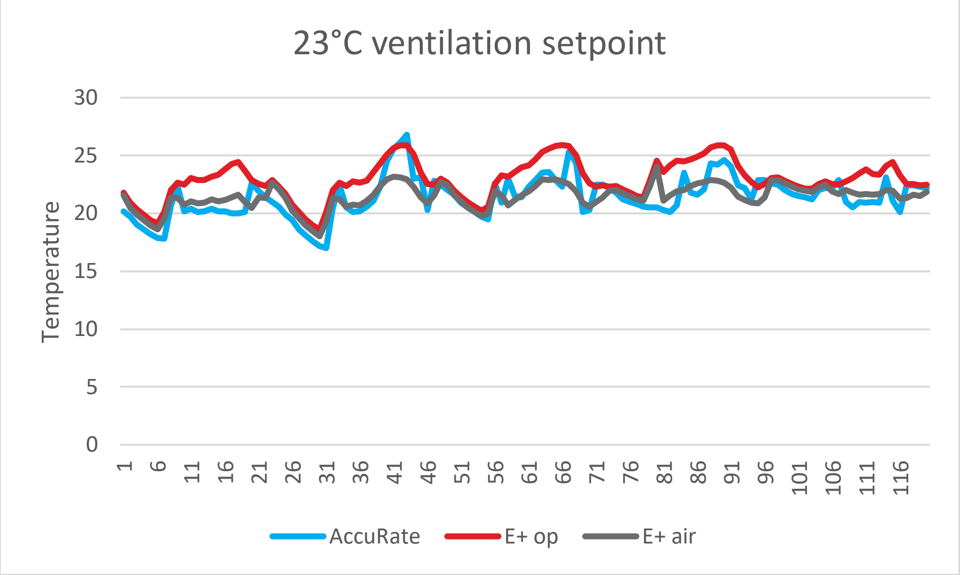


Figure 18. Comparing temperature profiles between AccuRateNZ and EnergyPlus (both operative and air temperature).

It may also be noted here that the BESTEST validation suite does not really test natural ventilation. The only ventilation scenarios involve constant forced ventilation for a period. These odd results may indicate a gap. That the programs do not agree exactly is also not something that should be surprising – comparison of the validation reports for both tools indicates that, even in controlled circumstances, they can disagree on energy use by ~20% (Delsante, 2014; GARD Analytics, 2013).

Overall, there does not seem to be a simple answer here. Ventilation operation is highly uncertain, so it is not ideal to have the results contingent on something highly sensitive. Multi-zone airflow is complicated, and how people operate the windows and doors in their house is very uncertain and may vary a lot. Any assumptions we make will only have limited ability to describe how any specific people will operate their house, which we generally just need to accept. Most of the time, this is not too problematic – it is simple enough to understand that the amount of overheating or cooling depends on how much ventilation there is. The interactions here, however, are much more complicated, and present not merely variation in the magnitude of the effect, but the potential to swap the effects from positive to negative. That different tools then disagree so significantly should instill further caution in the interpretation of the results.

That being said, while heating benefits are uncertain, the costs in terms of increased cooling and embodied carbon are less of an issue. It may be best to be conservative rather than jumping at the possibility of high WWR high mass designs having lower heating bills, especially when overall greenhouse gas emissions are less positive due to the impacts on cooling and materials.

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