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# The role of highly energy-efficient dwellings in enabling 100% renewable electricity

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ABSTRACT

One of the key challenges to achieving high-percentages of renewable electricity supply is the temporal mismatch between non-dispatchable renewable supply and peaks in electricity demand. These challenges become more pronounced as the timescale of this mismatch extends to seasons. Standard policies emphasise supply-side solutions that will result in underutilized supply, storage and transmission infrastructure, and significantly increased decarbonisation costs. Less attention has been placed on demand-side solutions and, in particular, the potential role of high-performance buildings in reducing the demand for electrical heating in winter, addressing the seasonal supply-demand mismatch. This paper quantifies the potential future reduction in winter electrical heating that could be achieved through widespread uptake of energy efficient dwellings in New Zealand - a country with a high percentage of renewable electricity. The results show that rapid uptake of currently achievable best-practice standards could reduce the winter-summer demand variation by 3/4 from business as usual by 2050. Therefore, New Zealand, and other countries with seasonal peaks in space heating/cooling demand, should urgently adjust policy settings to mandate highly energy-efficient housing for new-builds and retrofits in order to deliver a least cost low-carbon energy transition, which also captures the well-known social and health co-benefits of improved dwelling performance.

## 1. Introduction

A number of expert assessments have concluded that de-carbonizing global energy systems requires a combination of: (i) reduced demand via increased energy efficiency in all sectors; (ii) high percentages of renewable electricity generation from low cost options such as solar photovoltaics and wind and; (iii) greater electrification of heat and transport (Williams et al., 2012; Connolly et al., 2016; Jacobson et al., 2018). However, as future electricity systems approach 100% renewable, the lack of large-scale dispatchable generation significantly impacts the ability of these systems to cope with temporal mismatches between variable supply and demand over both daily and seasonal timeframes (Mason et al., 2010; Pereira et al., 2016; Deason, 2018; Shaner et al., 2018; Ringkjob et al., 2018).

Renewable energy supply varies on a range of timescales depending on the resource (IPCC, 2011). For example, hydro tends to vary by seasons, wind by minutes to days, and solar by day and season. Thus, supply does not necessarily coincide with demand, which also varies with its own daily and seasonal patterns. Temporal mismatch on a daily timescale can be dealt with at reasonable cost by demand management (Strbac, 2008; Dyson et al., 2014; Alham et al., 2017) and/or short-term storage in thermal, hydro or battery storage systems (Denholm and Hand, 2011; Lund et al., 2015; Weitemeyer et al., 2015; Muenzel et al., 2015; Le Dréau and Heiselberg, 2016). However, mismatches on a longer timescale, such as between increasingly electrified winter heating and plentiful spring (e.g. run of river hydro) and summer (e.g. solar PV) supply (which arise in many temperate and cold climates), are much more difficult to resolve using low-carbon approaches (Mason et al., 2010; Pereira et al., 2016; Deason, 2018; Shaner et al., 2018; Hansen et al., 2019).

Conventional low-carbon policy approaches to this seasonal supply-demand mismatch involve overbuilding renewable supply, which is then curtailed or stored long term when demand is low and supply is high. This approach is likely to lead to capital intensive yet underutilized generation, transmission and storage infrastructure and a much more costly energy transition (Denholm and Hand, 2011; Lund et al., 2015; Trainer, 2017a, 2017b; Heard et al., 2017; Dowling et al., 2020; ICCC, 2019). This continues to justify policies that argue against entirely eliminating fossil fuels from power systems (Pereira et al., 2016; ICCC,

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**Acronyms**

| | |
|---|---|
| BC | Building Code scenario |
| BPI | Building performance index |
| H | High efficiency scenario |
| HDD | Heating degree days |
| HDH | Heating degree hours |
| HDM | Heating degree months |
| M | Medium efficiency scenario |
| OECD | Organisation of Economic Cooperation and Development |
| P | Progressive scenario |
| SHD | Space heating demand |
| VH | Very High efficiency scenario |

*Roman Symbols*

| | |
|---|---|
| $A$ | Floor area ($m^2$) |
| $a$ | Floor area of individual house ($m^2$) |
| $E$ | Space heating demand of individual house (kWh/year) |
| $H$ | Parameter in BPI related to HDM (degree-months) |
| $h$ | Wall height (m) |
| $M$ | Monthly specific space heating demand (kWh/$m^2$ year) |
| $N_m$ | Number of days in each month |
| $Q$ | Heat loss or gain (W/$m^2$) |
| $S$ | Specific space heating demand (kWh/$m^2$ year) |
| $s$ | Short-side to long-side ratio |
| $T$ | Temperature (°C) |
| $t$ | Time (year) |
| $U$ | Specific heat-loss coefficient (W/$m^2$K) |
| $w$ | Area of walls and windows ($m^2$) |

*Superscripts*

| | |
|---|---|
| $\sigma$ | Scenario |
| base | Base temperature |
| ref | Reference temperature for HDD |
| set | Set temperature |

*Subscripts*

| | |
|---|---|
| $d$ | Days within a month |
| $m$ | Month |
| $n$ | Territorial authority |
| $r$ | New build ($r = N$) or retrofit ($r = R$) |

2019; CCC, 2021). Another potential approach is to use biomass for heat and power. However there are sustainability, emissions, and scale challenges with this option, and it is likely to be only a partial solution (Purkus et al., 2018). Recently, there has been an increasing interest in the role of energy efficiency in lighting and heating appliances in permanently reducing electricity demand during critical peak periods (Arteconi et al., 2013; Dortans et al., 2020).

If the majority of the problematic 'mismatch' is (or will be) due to heating/cooling, then reducing the need for active heating/cooling in the first place by adjusting policy settings to radically improve building performance could offer significant advantages. In particular, it could enable a much lower cost low-carbon electricity system transition, by avoiding the need for costly supply-side over-build.

Studies have shown that the annual space heating demand and associated greenhouse gas emissions can be significantly reduced (up to 90%) through high-performance mew-build and retrofit in almost any climate (Ürge-Vorsatz and Metz, 2009). This has lead to many countries introducing higher standards for building energy use (GABC, IEA & UNEP, 2019). Further, high-performance buildings can both reduce energy poverty (through removing the need for costly energy inputs for heating/cooling) and improve associated health outcomes by providing a high-quality indoor environment (Howden-Chapman et al., 2009a, 2017; Ürge-Vorsatz and Herrero, 2012; Buonocore et al., 2016). The need for long-term thinking about building energy efficiency has also been emphasised as part of net-zero solutions (GABC, IEA & UNEP, 2019; Ürge-Vorsatz et al., 2013). It is estimated that by 2050, population growth, growing affluence, and increasing demands for improved thermal comfort levels will lead to more than a doubling of global building floor area, and, based on current building standards, a 50% increase in energy use for space heating and cooling (Urge-Vorsatz et al., 2012). Given that this growth largely occurs in developing countries, it is likely to have a significant impact, despite predicted improvements in efficiency of renewable heating in developed countries (Drysdale et al., 2019; David et al., 2017; Möller et al., 2019). In contrast, aggressive uptake of high performance buildings could reduce global demand for space heating and cooling by more than 30% (Ürge-Vorsatz et al., 2013). On the other hand, slower adoption could suffer from a lock-in effect, whereby it is uneconomic to bring buildings up to high performance levels until the next retrofit/construction cycle leading to a significant delay in potential benefits (Ürge-Vorsatz et al., 2013; CCC-UK, 2019).

Given the evidence that high performance buildings can significantly reduce heating demand, it seems likely that they could be recruited to address the seasonal supply-demand mismatch of highly renewable electricity systems (AECOM, 2019) in countries pursuing greater electrification as a pathway to decarbonizing space heating (Williams et al., 2012; Connolly et al., 2016; Jacobson et al., 2018; ICCC, 2019; CCC, 2021). However, with the exception of (Seljom et al., 2017), there have been very few studies quantifying the temporal patterns of electricity demand in ultra-low energy buildings and of their consequential utility in reducing seasonal peaks heating/cooling demand. As a result, the value of more or less stringent building energy efficiency standards in enabling greater integration of renewables into the electricity system at least cost is not well understood, and there is very little evidence on which to base policy. Estimating this value in an energy system where heating and cooling is already predominantly electric and up to 80% renewable (such as in New Zealand) would therefore provide crucial insights - not just for New Zealand, but for other nations that wish to follow the same path to a low-carbon energy system.

In response, this paper explores the potential role that different levels of energy efficiency improvements in dwellings might have in addressing seasonal supply and demand mismatches by permanently reducing electricity demand in winter in New Zealand. To do this, we consider long-term future scenarios of high-performance residential building uptake to quantify the opportunity and to develop a modelling framework that can be applied in other nations where electricity is intended to be the main energy source for domestic heating (and cooling). We acknowledge that this is not necessarily the case in all energy system contexts with mixed-fuel strategies and other sources of heat proposed for higher density urban heat networks, or for countries with well-established biomass-fueled district heating schemes which can deliver heat at higher efficiency (Drysdale et al., 2019; David et al., 2017; Möller et al., 2019) than individual building level provision can attain. However, as discussed below, for energy resource (availability of renewable electricity) and historical infrastructural reasons (energy distribution network already exists and relatively low density built form), these solutions are less relevant to countries such as New Zealand. Further, the need to mitigate the likely demand consequences of using electricity as part of a future heating or cooling strategy (e.g. heat pumps) means that modelling the effects of greater dwelling fabric efficiency will still have value, even where that part is relatively minor.

We focus on residential dwellings due to their significant impact on peak electricity demand in New Zealand and in many other countries where electricity constitutes, or will constitute, the main source of energy for heat (Alham et al., 2017; Muenzel et al., 2015). New Zealand represents an excellent case study in this regard, as (i) residential space heating is predominantly provided by electricity - with future policy resolutely focused on the increased use of electricity to decarbonize space heating, (ICCC, 2019; CCC, 2021) and (ii) its electricity generation mix has already reached very high percentages of renewable supply (MBIE, 2020), aspiring to reach 100% in the face of a presumed doubling of demand by 2050 (Transpower, 2018), while overcoming a significant seasonal supply-demand mismatch (ICCC, 2019). It also (iii) has a relatively low-performing building stock lacking high energy efficiency building standards (Leardini and Manfredini, 2015) with likely growth in floor area, and (iv) has a large variation in climatic conditions, so the results can be easily translated to other climate zones.

The paper is organised as follows: Section 2 provides further context on the New Zealand energy and electricity supply system, and relates residential space heating to its 100% renewable energy political ambitions. Section 3 introduces the data and methods used to estimate the potential for high performance buildings to reduce peak demand at different seasons of the year in New Zealand. Section 4 presents the findings of the analysis. Section 5 draws implications for policy both in New Zealand and internationally, and concludes by identifying areas of further work.

## 2. New Zealand context

New Zealand is a particularly informative case study because 66% of New Zealand's residential space heating is already supplied by electricity (see Fig. 1) (EECA, 2020)), electricity has recently reached > 80% renewable (MBIE, 2020) generation, and the government has a target of achieving 100% renewable electricity under normal conditions by 2035 (ICCC, 2019). Despite the lack of policy or regulatory incentives, the percentage of renewable supply in New Zealand is likely to climb to > 95% under business as usual (ICCC, 2019), as renewable options now have the lowest cost. New Zealand's current electricity system therefore reflects the future aspirations of many other countries, and is already facing some of the challenges they will face in the near future.

New Zealand's renewable generation is dominated by hydro (~ 60%), with wind (~5%) and geothermal (~18%) also contributing (MBIE, 2020). Hydro is generally used to meet daily demand peaks, but hydro reservoirs often lack the buffering (storage) capacity to meet the winter increase in demand, which is currently met by coal and natural gas (Khan et al., 2018). Building on this base, future proposals for decarbonisation of the full energy system (MfE, 2019) inevitably presume increased supply from wind and solar to meet new demand from greater electrification of process heat and transport (ICCC, 2019; Transpower, 2018). This is explicitly captured in the New Zealand Climate Change Commission's first package of Advice to government (CCC, 2021), which clearly assumes supply side (over) investment and relatively underplays the role of permanent demand reduction.

As the Commission notes, a significant challenge for this decarbonisation strategy is the seasonal supply-demand mismatch. An extreme example is the so-called'dry-year problem' which arises in years when hydro lakes are low and wind generation is minimal (ICCC, 2019). This problem currently amounts to a shortfall of approximately 2 TWh of electricity supply during winter in New Zealand. Meeting this shortfall with zero carbon supply would require significant overbuild of renewable generation capacity and/or large inter-seasonal storage, such as pumped hydro, giving rise to arguments against entirely eliminating fossil fuel-based generation (ICCC, 2019).

To make the problem clear, we have used estimates of the seasonal distribution of space heating (Isaacs et al., 2010) and the annual proportion of electricity used for space heating (EECA, 2020) to estimate the seasonal variation of electrical heating. Fig. 2 compares this variation with the seasonal variation of total residential and national electricity demand (Electricity Authority, 2020) and demonstrates that the national seasonal variation in demand is largely driven by residential demand variation, to which space heating is the main contributor.

Although residential heating dominates the seasonal variation in demand, to date, a detailed analysis of the energy demand implications of potential changes in residential heating in New Zealand does not exist. This is surprising, as all trends point to further growth in total

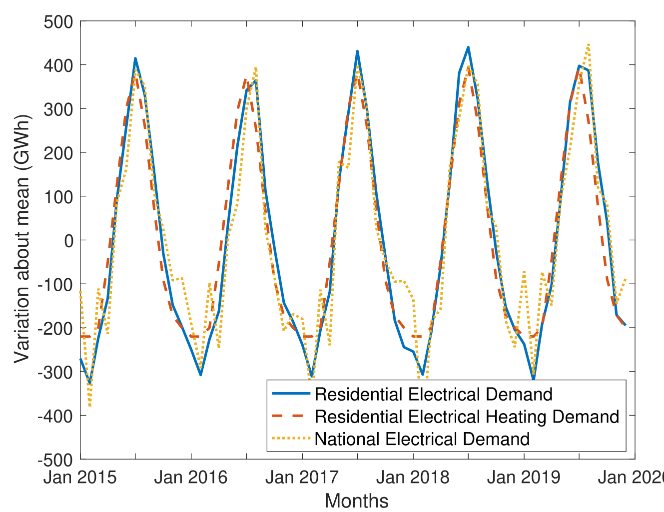


**Fig. 2.** Variation in national electricity demand, residential electricity demand and residential space heating electricity demand about their means.

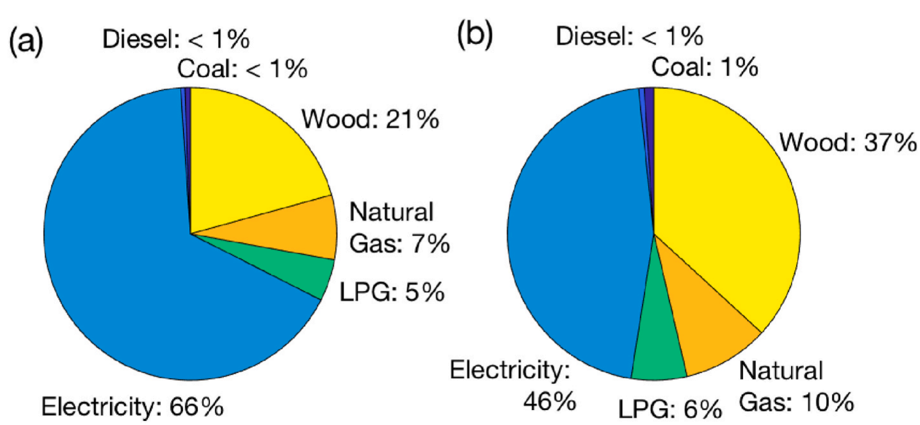


**Fig. 1.** Proportion of end-use (a) and delivered (b) energy for space heating in 2019 by fuel type (EECA, 2020). End-use numbers are estimated from delivered energy by assuming the conversion efficiencies: Wood/Coal:70%, Heat pumps:200%, LPG/Natural Gas/Diesel:85%.

residential floor area and therefore increased demand. New Zealand currently has almost 1.9 million private dwellings and over the past decade the housing stock has grown at an average annual rate of 1.1% (StatsNZ, 2020), mostly driven by population growth. The population is currently growing at 1.2%/year (2019), with long term projections showing a growth rate of 0.5%/year to 2050 (StatsNZ, 2016). Although there is a growing trend towards the construction of apartments and townhouses in the face of population growth pressures on urban land area (from ~ 10% to ~ 30% of the consents for new dwellings (StatsNZ, 2020)), energy demand from detached houses is expected to dominate residential space heating demand for the next few decades as they represent 80% of the existing dwelling stock, 85% of all new dwellings (StatsNZ, 2020) by number, and > 90% by floor area.

While recent trends in residential electricity intensity seem to suggest otherwise (MBIE, 2019), it is likely that New Zealand's space heating intensity will also increase in the future. This is because New Zealand's space heating intensity currently falls well below that of other OECD countries, even when adjusted for heating degree days (HDD). Fig. 3 shows the space heating intensity for selected countries (IEA, 2020) divided by their respective HDD ($T_{ref}$ = 18 °C) (Atalla et al., 2018). New Zealand's intensity is half the average of the other countries in this group. This shortfall is not due to energy efficiency (which may be the case for apartment-style housing in Japan), but rather to inadequate space heating in New Zealand homes, which are currently heated to well below the temperature standards recommended by the World Health Organisation (Johnson et al., 2018).

For example, the 2015 BRANZ House Condition Survey found that bedrooms in 46% of dwellings were not usually heated in winter, just 1/3 of the houses regularly heated all bedrooms at some point during the day, and almost half of children's bedrooms were not heated at all (White and Jones, 2017). In addition, there was visible mould in almost half of houses surveyed (White and Jones, 2017). These conditions have been shown to have significant negative health impacts, especially on lower socio-economic households (Howden-Chapman et al., 2009a; Ingham et al., 2019). Due to historically lower building standards, the indoor conditions of older buildings are significantly worse and energy poverty is a known problem (Lloyd, 2006; Howden-Chapman et al., 2012; StatsNZ, 2017). While there have been a number of local (e.g. Wellington's Healthy Housing Initiative (Chisholm et al., 2020)) and national responses (e.g. 'Warmer Kiwi Homes' (NZ Government, 2020)) to these problems, they have tended to focus solely on lower income owner-occupiers and on improving insulation, alongside installing heat pumps to essentially push low-carbon heat into old and non-airtight dwellings. Only rarely have whole-dwelling deep retrofits to more stringent standards been attempted (Leardini and Manfredini, 2015).

Unfortunately, New Zealand's current Building Code is deficient

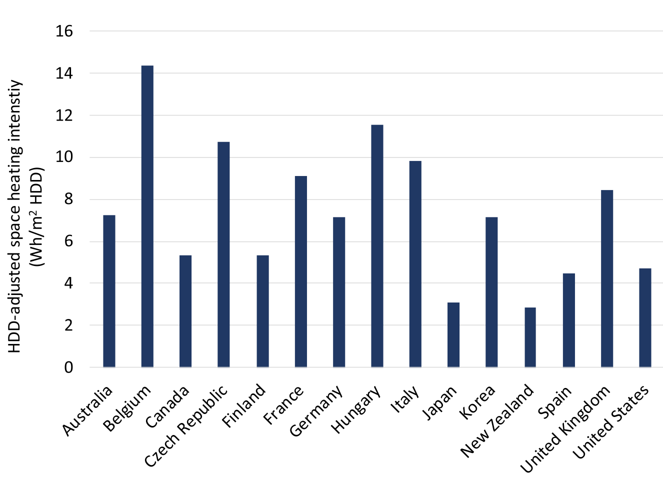


**Fig. 3.** HDD adjusted ($T_{ref}$ = 18°C) space heating intensity of selected countries.

compared to standards in other countries, offering little guidance to renovations (Leardini and Manfredini, 2015), not specifying sufficiently high insulation values in colder areas of the country (McChesney et al., 2008) or in modern complex houses (Viggers et al., 2017), and has inadequate specifications regarding ventilation and air tightness (Leardini et al., 2012). As a result, addressing current under-heating levels under the current Building Code will almost certainly lead to increased residential electricity intensity as more and more energy is pumped into very inefficient housing. This is likely to further increase the seasonal supply-demand mismatch and to our knowledge, this has not been identified as a significant risk in previous New Zealand research (ICCC, 2019).

Finally, the large variation in climatic conditions in New Zealand means that 'average' values mask substantial and significant inter-regional variation. For example, average monthly temperatures can vary between 20°C in the north in summer to 2°C in the south in winter. Average monthly temperatures for the coldest and warmest months in each region are given in Table A4. Due to the large variation in climatic conditions, studies have found that on average houses in the lower South Island require more than twice the amount of energy for space heating as houses in Auckland (Lloyd, 2006; McChesney et al., 2008). Even in a country as small as New Zealand, this means that analysis must be carried out at a sub-national (regional) level - not only to provide appropriate insights for New Zealand's climatic regions, but also to provide insights for other countries whose climatic zones match (some of) the regions of New Zealand.

## 3. Methodology

To evaluate the potential impact of high-performance buildings on seasonal energy demand, we consider a range of scenarios of energy-efficiency standards for new and retrofit residential buildings. In line with their dominance (see above), we focus only on detached dwellings, and model these scenarios from 2020 to 2050 to align with New Zealand's net-zero greenhouse gas emissions targets (MfE, 2019). Our simple housing stock model includes new builds, but also energy-efficiency retrofits to existing dwellings, as a large percentage of the current building stock are likely to still be in use in 2050 (Ürge-Vorsatz et al., 2013).

The five scenarios considered are: Building Code (BC), Medium (M), High (H), Very High (VH), and Progressive (P). The Building Code scenario is based on the assumption that all new and retrofitted houses are constructed to the current New Zealand Building Code standard (MBIE, 2019), and represents the business-as-usual case. The Medium and High scenarios assume that all new and retrofitted houses meet the heating demand requirements of the Homestar 6 and 7 rating schemes, respectively (NZGBC, 2020). The Very High scenario assumes all new and retrofitted dwellings are built to meet the heating demand requirements of the Passive House standard (Passive House Institute, 2016). Finally, the Progressive scenario assumes a model where in 2020, 10% of all new-builds and retrofits are built to Passive House standard and the rest meet the current Building Code. The proportion built to Passive House standard then increases linearly (by 3% each year) to reach 100% by 2050. Table 2 provides a summary of the scenarios and underpinning assumptions. In all scenarios, the respective standards are assumed to be met exactly, although we acknowledge that this may not be true in all

**Table 1**
Specific space heating demand (in kWh/m$^2$year) for new builds and retrofits in the Medium (M) and High (H) scenarios for each Homestar climate zone.

| Homestar zone | $S^M_{n,r}$ | $S^H_{n,r}$ |
|---|---|---|
| 1 | 35 | 20 |
| 2 | 60 | 40 |
| 3A | 70 | 50 |
| 3B | 80 | 60 |

**Table 2**
Summary of key assumptions for each scenario. In all scenarios buildings are assumed to be heated to 20°C. Details are provided in Sec.3.

| | Key Assumptions | |
|---|---|---|
| Scenario | Specific heat demand | Area |
| Building Code (BC) | All new builds and retrofits achieve current building code standards. Depends on climate. | Pre-existing floor area: 1.6 M × 150 $m^2$. Demolition rate 0.7%/year. |
| Medium (M) | All new builds and retrofits achieve the Homestar 6 standard. Depends on climate. | Retrofit floor area is 4.5 M $m^2$/year, apportioned to territorial authority based on |
| High (H) | All new builds and retrofits achieve the Homestar 7 standard (based on BRANZ ALF tool). Depends on climate. | number of renovation consents. Floor area of new builds increases linearly based on recent building consents, then slows to |
| Very High (VH) | All new builds and retrofits achieve the Passive House standard (e.g. 15 kWh/$m^2$ year for new builds). Largely independent of climate. | 60% of these rates by 2050. |
| Progressive (P) | A proportion of the new builds and retrofits built to Passive House standard and the rest to Building Code. | In 2020, proportion of new builds and retrofits built to Passive House standard (by floor area) is 10% and this proportion increases by 3% per year. |

cases due to potential energy performance gap effects (Delzendeh et al., 2017; Johnston et al., 2020).

To provide a baseline for comparison, we assume that under all scenarios new and retrofitted houses are heated to healthy temperatures (20°C). This assumption is used by both the Passive House standard (Passive House Institute, 2016) and modeling tools used to implement the New Zealand Building Code (MBIE, 2019). Note that this is not currently the case, with indoor temperatures in New Zealand dwellings on average falling far short of these temperatures as discussed in Sec.2 above. In this respect, this study is not attempting to predict future energy demand, but rather estimate the potential future energy savings that can be achieved through different building standards under optimum theoretical performance.

### 3.1. Floor area model

The first step in the modelling process is to forecast floor area for each of the scenarios. In the following, we assume the floor area used for heating calculations to be equal to the gross floor area, making our calculated floor area an upper bound.

The housing floor area in future years can be considered to have three components: pre-existing, retrofits and new. We define the pre-existing component to be the floor area of detached houses existing in 2019. This is estimated to be ~1.6 million houses × 150 $m^2$ (StatsNZ, 2020). We model the pre-existing baseline from 2020 and new-builds from that date. Energy-efficiency retrofits take place on the pre-existing houses (at rates specified below), and we allow for demolition of pre-existing dwellings at a rate of 0.7% per year (Coleman and Karagedikli, 2018).

The total floor area (in $m^2$) of new and retrofit houses in year $t$ in each territorial authority is denoted by $A_{n,r}(t)$, where the subscript $n$ denotes the territorial authority and $r$ the retrofits ($r = R$) or new builds ($r = N$). The floor area for new builds in each territory is assumed to increase linearly each year from 2020:

$$A_{n,N}(t+1) = A_{n,N}(t) + \beta_n(t) \tag{1}$$

where $\beta_n$ ($m^2$) is given by

$$\beta_n(t) = \kappa_n \left\{ 1 + \frac{(\omega - 1)}{1 + \exp[-\lambda(t - 2035)]} \right\}. \tag{2}$$

In Eq. (2), the initial growth rate $\kappa_n$ is determined from linear projections of approved building consents by region (StatsNZ, 2020) (assuming 95% of consents are constructed (Coleman and Karagedikli, 2018)). $\lambda = 1/4$, such that, growth rate per year transitions smoothly between $\kappa_n$ in 2020 and a reduced value $\omega\kappa_n$ ($\omega < 1$) in 2050. The value of $\omega = 0.4$ is chosen to reflect slowing population growth (StatsNZ, 2016), future trends towards smaller houses, and the slow trend away from detached houses, that is reflected in new building consent statistics (StatsNZ, 2020). A similar building stock model was used in Chandrakumar et al. (2020) to assess the long term GHG emissions of New Zealand houses. The rate of new builds in our model is similar to Chandrakumar et al. (2020), but the rate of demolition in our model (taken from Coleman and Karagedikli (2018)) is much more rapid. However, it aligns better with the average age of New Zealand houses (Johnstone, 2001).

We also assume that the retrofit area, $A_{n,R}(t)$, increases linearly in each territorial authority. The number of houses undergoing retrofits nationwide is approximately 30000/year (Page and Fung, 2009). Assuming an average floor area of 149 $m^2$ (StatsNZ, 2020), the national increase in floor area of retrofitted houses per year is approximately $\Delta_R = 4470000$ $m^2$/year. This is apportioned by territorial authority based on number of consents for renovations (StatsNZ, 2020).

Since houses built since 2011 tend to be larger than 149 $m^2$ (StatsNZ, 2020), this is almost certainly an underestimate of the current average house floor area. However, the houses requiring energy-efficient retrofits are also more likely to be older, suggesting that this is a reasonable floor area assumption.

The estimated change in area in each of these three categories is shown in Fig. 4. Note that we assume no change in the specific heating demand, ~ 27 kWh/$m^2$ (based on estimates of space heating end use energy, c.f. Fig. 1), for pre-existing buildings that are neither retrofitted nor demolished, and thus the heat demand of the pre-existing buildings will be the same for each scenario.

For the Progressive scenario, we assume that the proportion of houses built or retrofitted to Very High standard increases linearly over time via:

$$A_{n,r}^{\mathrm{VH}}(t) = [\alpha_1 + \alpha_2(t - 2020)]A_{n,r}(t), \tag{3}$$

$$A_{n,r}^{\mathrm{BC}}(t) = A_{n,r}(t) - A_{n,r}^{\mathrm{VH}}(t), \tag{4}$$

where $\alpha_1$ is the initial proportion of new and retrofit houses that are constructed to the Very High standard, and $\alpha_2$ is the rate that this proportion increases each year. We chose $\alpha_1 = 0.1$ and $\alpha_2 = 0.03$, which ensures that all houses are built or retrofit to Very High standard by 2050.

### 3.2. Modelling specific space heating demand

The second step in the method is to calculate the specific space heating demand (in kWh/$m^2$ year) for each scenario. The specific space heating demand is assumed to depend on territorial authority (to take account for climate differences), and whether the dwelling is a new build or a retrofit. The specific space heating demand is denoted by $S_{n,r}^{\sigma}$, where $\sigma$ is one of {BC, M, H, VH}, corresponding to the scenario Building Code, Medium, High and Very High efficiency scenarios, respectively. For simplicity, we assume that houses have the same heating demand in subsequent years as when they were built or retrofitted, i.e. $S_{n,r}^{\sigma}$, does not change by year.

Total allowed energy demand in the New Zealand Building Code depends on local historical temperature data (MBIE, 2019). The

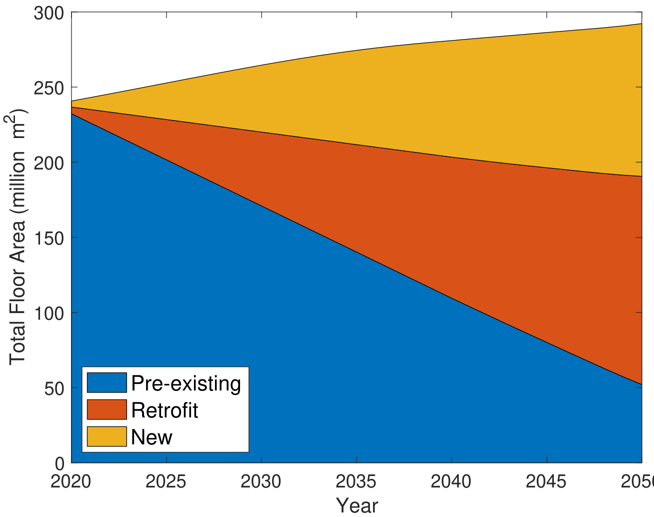


**Fig. 4.** Forecasted total floor area of the detached housing sector in New Zealand. In these figures we have plotted: $A_R(t) = \sum_n A_{n,R}(t)$ and $A_N(t) = \sum_n A_{n,N}(t)$, where the sum is over all territorial authorities.

Homestar rating schemes have fixed specific space heating demand depending on location (NZGBC, 2020). The Passive House specific space heating demand for new buildings is independent of both temperature and location, but for retrofits, it depends on location. For consistency across the scenarios, we have used the Passive House climate zones (Quinn, 2015) to provide a consistent set of zones and weather data for the calculation of specific heating demand for all the scenarios. The mapping between the different climate zones, territorial authorities and the usual climate zone classification of other scenarios are shown in Table A4.

*3.2.1. Building code efficiency scenario: specific space heating demand*

The Building Code scenario is loosely based on assuming that all new builds and retrofits are carried out to the New Zealand Building Code standard. The New Zealand Building Code does not specify a specific space heating demand for new buildings - instead, it requires houses to be constructed so that their building performance index (BPI) does not exceed 1.55 (MBIE, 2019). The BPI of an individual house is defined as

$$\mathrm{BPI} = \frac{E}{H(w+a)}, \tag{5}$$

where $E$ is space heating demand in kWh/year, $w$ is total wall area (walls + windows) in m$^2$, $a$ is floor area in m$^2$ and $H$ is a parameter related to the heating degree months (see Appendix B). Rearranging Eq. (5) for $E$ and assuming the building exactly meets the Building Code requirement, the space heating demand is therefore

$$E = 1.55H(w+a). \tag{6}$$

Note that this approach may result in an overestimate of the specific space heating demand due to the specific assumptions required for estimating space heating energy demand as part of the BPI calculation [see Eq. (5)] in the New Zealand building Code (MBIE, 2019), including: 40% shading of windows, one air change per hour and no consideration of floor coverings. For transparency, we have chosen not to attempt to correct for these here.

Equation (6) can be further simplified as follows. Let us consider houses to have perimeter and floor area equivalent to a notional rectangle, and let the short-side to long-side ratio be $s$: 1. We can then write

$$E = 1.55H\left(\frac{2+2s}{\sqrt{s}}h\sqrt{a} + a\right), \tag{7}$$

where $h$ is wall height (see Appendix B for the detailed derivation). Based on this analysis, we can write the specific space heating demand for new builds and retrofits in the Building Code scenario as:

$$S^{\mathrm{BC}}_{n,r} = 1.55H_n\left(\frac{2+2s_r}{\sqrt{s_r}}\frac{h}{\sqrt{a_r}} + 1\right) \tag{8}$$

in units of kWh/(m$^2$year), where we have assumed the heating degree days, $H_n$, depend on the temperature data in each territorial authority (see Appendix B). We assume that new builds and retrofits differ in floor area and short-side to long-side ratio, such that the area is given by $a_N =$ 198 m$^2$ (Chandrakumar et al., 2020) and $a_R = 149$ m$^2$ (StatsNZ, 2020). Interpolating the results in Viggers et al. (2017), we further assume that the short-side to long-side ratio is given by $s_N = 0.235$ and $s_R = 0.272$. We assume these values of $a_r$ and $s_r$ to not change by year (see Appendix B for justification). For our scenarios we assume $h = 2.5$ m.

*3.2.2. Medium and High efficiency scenarios: specific space heating demand*

The Medium and High scenarios assume that houses meet the requirements of Homestar 6 and 7, respectively, using the BRANZ ALF tool (BRANZ, 2018). The specific space heating demands associated with each of these standards are shown in Table 1, based on Homestar climate zones. The mapping between the Homestar climate zones and the territorial authorities used for floor area estimates are given in Table A.4.

*3.2.3. Very high efficiency scenario: specific space heating demand*

The Very High scenario assumes that all new houses are built to achieve the Passive House standard (Passive House Institute, 2016), which represents the current state of the art in high performance housing (AECOM, 2019; Mihai et al., 2017). Although originally developed in Northern Europe, the standard has since been extended to non-European climates, including the Southern Hemisphere (Schnieders et al., 2017; Badescu et al., 2015) and New Zealand (Quinn, 2015; Besen et al., 2015), using appropriately specified climate zones. The Passive House standard is specified in terms of either a total energy consumption requirement, or a demand load less than 10 W/m$^2$. In this work, following standard New Zealand practice (Quinn, 2015), we consider only the total energy consumption, and set the specific space heating demand for new builds in the Very High scenario to be the Passive House standard:

$$S^{\mathrm{VH}}_{n,N} = 15\ \mathrm{kWh/m^2 year}. \tag{9}$$

This value holds for new builds across all territorial regions or climate zones, $n$, since it is a requirement of the Passive House standard.

Retrofits under this scenario are assumed to achieve the EnerPHit standard (Passive House Institute, 2016), where the required specific heat demand is set according to the relevant EnerPHit climate zone. The climate zones appropriate to each region of New Zealand are specified in Table A.4 of Appendix A. As can be seen, the 'cool-temperate' zone of the EnerPHit standard includes all of the South Island plus the Taupo and Ruapehu districts, and the 'warm-temperate' includes the rest of the North Island (see Table A.4) (Leardini and Manfredini, 2015). The specific heating demand for retrofits in the Very High scenario is therefore set to:

$$S^{\mathrm{VH}}_{n,R} = \begin{cases} 25\ \mathrm{kWh/m^2/year}, & \text{'cool − temperate'} \\ 20\ \mathrm{kWh/m^2/year}, & \text{'warm − temperate'}. \end{cases} \tag{10}$$

*3.3. Total energy model*

We now calculate the total energy demand for a given scenario by multiplying the floor area of houses in a particular category with the specific heating demand of that category of houses. For each scenario except the Progressive, the total energy demand in year $t$ is given by

$$\text{SHD}_\sigma(t) = \sum_{n,r} A_{n,r}(t), S^\sigma_{n,r} \,, \tag{11}$$

where $\text{SHD}_\sigma$ is end-use space heating demand (kWh/year) for a specific scenario $\sigma$.

For the Progressive scenario, as only a proportion of the new builds or retrofits are built to Passive House standard (and the rest to Building Code) and this proportion progressively increases over time, the demand is given by

$$\text{SHD}_\text{P}(t) = \sum_{n,r} A^{\text{BC}}_{n,r}(t) S^{\text{BC}}_{n,r} + A^{\text{VH}}_{n,r}(t) S^{\text{VH}}_{n,r}, \tag{12}$$

where $A^{\text{BC}}_{n,r}(t)$ and $A^{\text{VH}}_{n,r}(t)$ are the areas of new and retrofits in each territorial authority that are built to Building code or Passive House (Very High) standard, respectively.

A summary of the key assumptions for each scenario is provided in Table 2.

### 3.4. Seasonal breakdown

A key element of this paper is a seasonal breakdown of the specific space heating demand. The monthly specific space heating demand, $M^\sigma_{n,r,m}$, is defined by

$$S^\sigma_{n,r} = \sum_{m=1}^{12} M^\sigma_{n,r,m}, \tag{13}$$

where the sum is over the months denoted by the index $m$.

In this paper, we use the method described by CIBSE (CIBSE, 2006) to calculate the monthly specific space heating demand, $M^\sigma_{n,r,m}$. In this approach, $M^\sigma_{n,r,m}$ can be estimated in terms of the heat loss and heating degree hours (HDH) by:

$$M^\sigma_{n,r,m} = 10^{-3} U^\sigma_{n,r} \text{HDH}_{m,n} \tag{14}$$

where $U^\sigma_{n,r}$ is the overall specific heat-loss coefficient of the building in units of W/(m$^2$K) and $\text{HDH}_{m,n}$ is the degree-hours for the month for the $n$th region defined by

$$\text{HDH}_{m,n} = \sum_{d=1}^{N_m} \sum_{h=1}^{24} \left(T^{\text{base}}_{m,n} - T_{h,d,m,n}\right)^+ \tag{15}$$

where $h$ denotes the hours within a day, $d$ denotes the days within a month, $N_m$ is the number of days per month, and the $^+$ notation means: $(x)^+ = \max(x, 0)$. In Eq. (15), $T_{h,d,m,n}$ is the mean hourly outdoor temperature and $T^{\text{base}}_{m,n}$ is the base temperature for the month in each region. $T^{\text{base}}_{m,n}$ depends on a number of factors, including internal and solar gains, heat loss, and thermal mass (CIBSE, 2006). We can interpret $T^{\text{base}}_{m,n}$ as the effective temperature (given passive gains etc..) below which active heating is required to maintain the indoor temperature at $T_{\text{set}} = 20°$C.

Equation (14) thus provides a method of determining the monthly heat demand from $U^\sigma_{n,r}$. In our case, $U^\sigma_{n,r}$ is not specified for our buildings. However, since our annual specific space heating demand is fixed by the scenarios from Eqs. (13) and (14), we can write

$$S^\sigma_{n,r} = 10^{-3} U^\sigma_{n,r} \sum_{m=1}^{12} \sum_{d=1}^{N_m} \sum_{h=1}^{24} \left(T^{m,n}_{\text{base}} - T_{h,d,m,n}\right)^+ , \tag{16}$$

which provides an implicit equation for $U^\sigma_{n,r}$ in terms of known quantities. As $T^{m,n}_{\text{base}}$ also depends on $U^\sigma_{n,r}$, this is a rather complicated implicit equation. However, it is straightforward to solve numerically using standard iterative techniques. Further details of this calculation are presented in Appendix C.

Once we have determined $U^\sigma_{n,r}$, we can calculate monthly specific demand using Eq. (14). This is used to determine seasonal demand variations for each of the scenarios in Sec.4.

## 4. Results

### 4.1. Specific heat demand by scenario

The specific heating demand for each scenario for selected climate zones (see Table 3) is shown in Fig. 5. In comparison, the current average specific heat demand in New Zealand is ~27 kWh/m$^2$ (based on estimates of space heating end use energy, c.f. Fig. 1).

Fig. 5 shows that there is a large variation in specific heat demand for the Building Code and the Medium and High scenarios across these climate zones. In contrast, the specific heat demand for the Very High scenarios are relatively constant. The specific heat demand for the Building Code scenario is double that of the Very High scenario in AK and six times that of the Very High scenario in CC and DN climate zones. The specific heating demand for all climate zones is given in Table B.5 in the Appendix. Our approach (outlined in Sec.3.2.1), of strictly conforming to the Building Code specifications, such as shading and air change assumptions, has resulted in higher specific heating demand for Building Code houses than reported elsewhere (Jaques, 2015, 2019). However, this approach provides us with a transparent baseline for comparison against other potential building standards.

### 4.2. Projected residential heat demand

Combining the specific heating demand for each scenario with the future floor area scenarios (see Fig. 4) for each region enables us to

**Table 3**
Selected climate zones with associated territorial authorities. Table also shows mean monthly temperatures in July and January (°C) for each zone. This is a subset of Table A.4 .

| Zone | $\bar{T}_{\text{July}}$ | $\bar{T}_{\text{Jan}}$ | Territorial authority |
|---|---|---|---|
| AK | 11.3 | 19.2 | Thames-Coromandel District, Auckland |
| WN | 9.0 | 17.0 | Porirua City, Lower Hutt City, Wellington City |
| CC | 5.1 | 16.2 | Hurunui District, Waimakariri District, Christchurch City, Selwyn District, Ashburton District, Timaru District, Waimate District |
| DN | 7.0 | 14.2 | Waitaki District, Dunedin City, Clutha District |

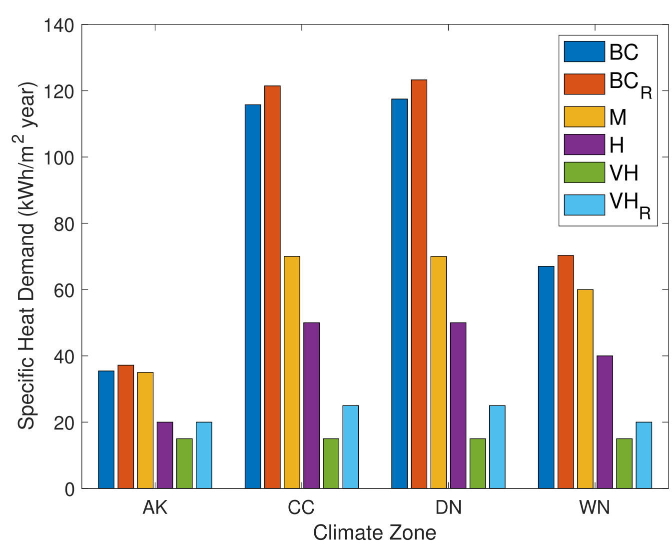


**Fig. 5.** Specific heating demand for each scenario in the selected climate zones given in Table 3. The scenarios shown are Building Code (BC), Medium (M), High (H) and Very High (VH),. The R subscript corresponds to the retrofit version of the scenario.

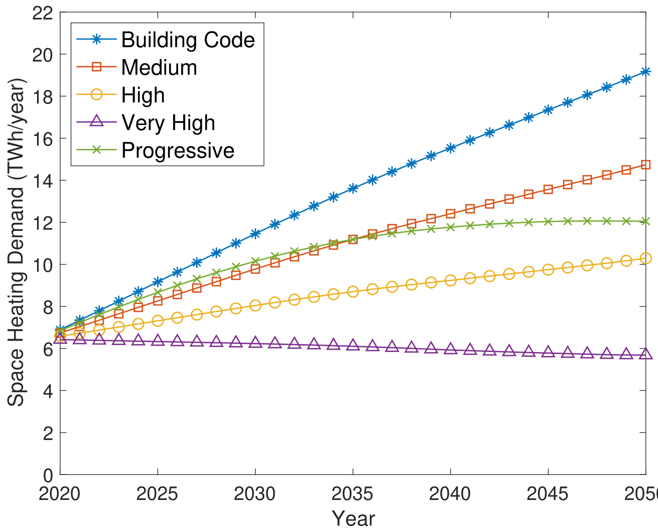


**Fig. 6.** Total space heating demand per year for each scenario.

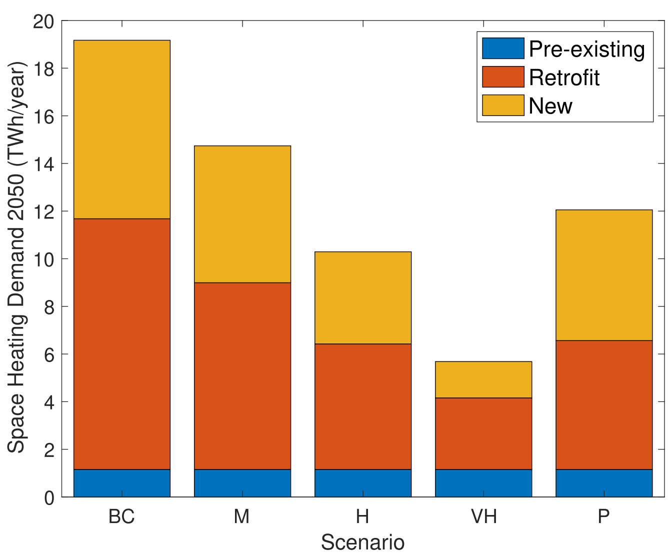


**Fig. 7.** Total space heating demand in 2050 showing split between new builds, retrofitted and pre-existing houses. The scenarios shown are Building Code (BC), Medium (M), High (H), Very High (VH) and Progressive (P).

calculate the space heating demand to 2050. Fig. 6 shows the yearly space heating demand required for each scenario from 2020 for both new and retrofitted houses. In each case, except for the Progressive scenario, the increase is approximately linear. There are substantial differences between the scenarios. For example, the annual increase is Building Code scenario is 0.4 TWh/year, but in the Very High scenario, it is negative. In 2050, the Very High scenario is less than 30% of the Building Code scenario and, in fact, is lower than current space heating demand.

The annual space heating demand in 2050 is shown in Fig. 7. This figure also shows the breakdown of energy into new, retrofit and pre-existing houses. Notably, the Very High scenario implies the need for $\sim$ 2/3 less energy input than the Building Code case. Clearly, the Progressive and other scenarios show a much less substantial reduction in energy use than that possible under the more aggressive Very High scenario.

### 4.3. *Projected seasonal variation in heating demand*

Using the methods outlined in Sec.3.4, we can evaluate the seasonal breakdown of the annual space heating demand under each scenario. Fig. 8 shows how the national space heating demand in 2050 is distributed across the months of the year under each scenario. All scenarios show a peak demand in the winter months, as expected. The peak-to-trough range in the Building Code scenario is approximately 2.5 TWh/month, while the same ratio in the Very High standard, is less than 0.8 TWh/month or $\sim$ 1/3 of the Building Code scenario reducing peak demand below that of current space heating.

An alternative measure of the seasonal mismatch is the sum of annual space heating demand greater than the month with the lowest demand (i.e. the area under the peak in Fig. 8). For the 2019 space heating demand the area under the peak is $\sim$ 6 TWh, for the Building Code scenario it is $\sim$ 13 TWh, but the Very High scenario reduces this by a factor of $>4$ to $\sim$ 3 TWh - half the current 2019 value. These results imply that the Very High scenario will act to substantially reduce the mismatch between winter peak heat demand and winter energy resource unavailability. Note that less aggressive scenarios, such as the Progressive scenario, achieve substantially less than 50% reduction in peak winter demand compared to business as usual.

Of course, the impact of the seasonal variation in space heating energy scenarios on the electricity system depends on the efficiency of electrical heating in the future. Fig. 9 shows the peak-to-trough range of monthly electricity demand in 2050 for the Building Code and Very High scenarios as a function of the national average Measured Heating Performance Factor (MHPF) of the electrical heating technology (Burrough et al., 2015). The current peak-to-trough range of the national electricity demand and the estimated residential electricity demand are also shown for reference. The national average MHPF represents the real world performance of all implemented heating technologies over the whole heating season. The current national average MHPF is $\sim$1.5, based on heat pump performance (Burrough et al., 2015), and the proportion of resistance heaters (EECA, 2020). The figure shows that under the current Building Code the winter electricity heating demand peak could increase to double its current value by 2050 for a national average MHPF below $\sim$2. In contrast, the Very High scenario could reduce space heating winter demand to below 2/3 of the current values for the same national average MHPF.

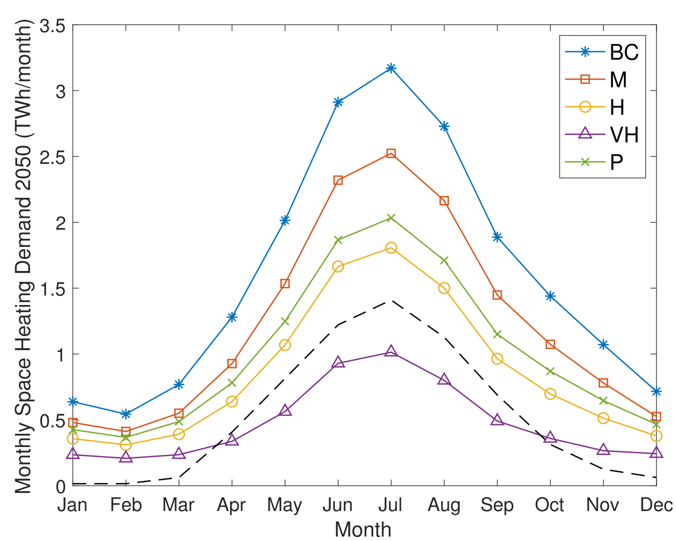


**Fig. 8.** Monthly space heating demand in 2050 under each scenario. The scenarios shown are Building Code (BC), Medium (M), High (H), Very High (VH) and Progressive (P). For reference we also show the current space heating demand (black dashed line).

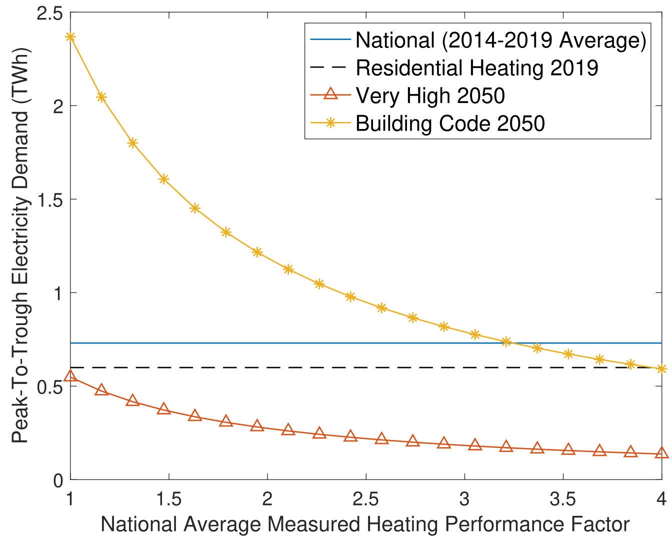


**Fig. 9.** Peak to trough variation of electrical demand as a function of national average Measured Heating Performance Factor for: current National Electricity Demand (Average of Last 5 years), estimated residential electricity demand for space heating in 2019, projected demand for the Building Code and Very High scenarios assuming all new demand is met by electricity.

### 4.4. *Projected regional residential heat demand*

To give an indication of the effect of outdoor temperatures (c.f. Table 1) on the space heating scenarios, the monthly demand for four selected climate zones spanning New Zealand (see Table 3) is shown in Fig. 10. Note that, in this plot, we have apportioned the space heating demand of the pre-existing houses to the regions based on both fraction of dwellings and heating degree days in each region. Fig. 10 shows that the business-as-usual scenario leads to very large monthly demand in winter in cold climate zones (CC and DN versus AK and WN). For example, the peak demand in the Building Code scenario in CH is similar to AK, even though this region has $\sim 1/4$ the population. In addition, this plot shows that the Medium, High and Very High scenarios result in a much greater reduction in the mid winter peak in colder climate zones.

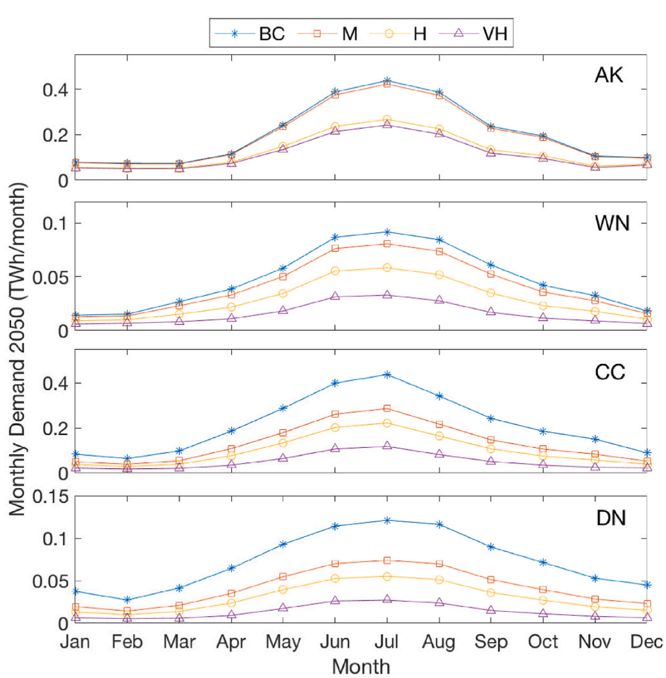


**Fig. 10.** Monthly space heating demand in 2050 for four selected climate zones: AK, WN, CC and DN. (see Table 3 for climate zone definitions). The symbols in these subplots correspond to the different scenarios: Building Code (BC-asterisk), Medium (M-square), High (H-circle), Very High (VH-triangle).

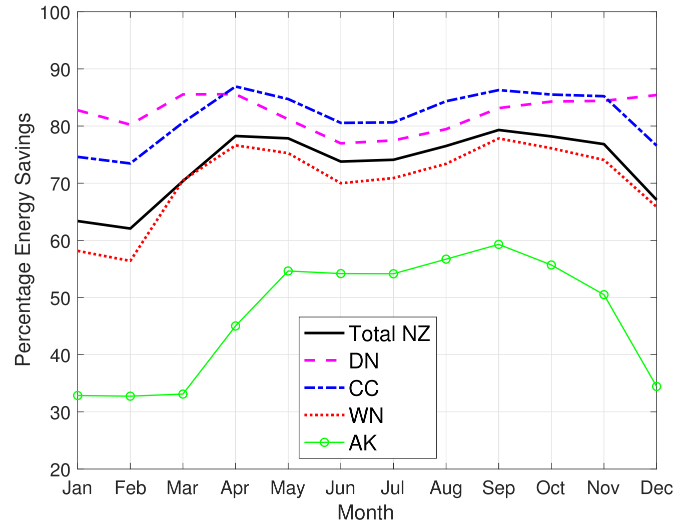


**Fig. 11.** Percentage monthly energy savings in 2050 by implementing the Very High instead of Building Code scenario. Shown for National total and selected regions (see Table 3).

In Fig. 11, we show the percentage energy saving of the Very High scenario compared to the Building Code scenario across the months. This shows that for most regions of New Zealand there is $> 70\%$ saving in energy across at least 9 months of the year. Interestingly, although Auckland (AK) is considered a mild climate, it still experiences $> 30\%$ energy savings even over the summer months under the Very High scenario.

## 5. Discussion

The analysis reported in this paper shows that attempting to reach 'healthy temperatures' in the New Zealand dwelling stock under the current building code would triple total annual space heating consumption by 2050 - this growth would double peak winter energy demand. Given that New Zealand is unlikely to continue to accept the health consequences and costs of substantial under-heating, this would make a 100% renewable electricity system even harder to achieve.

In contrast, the results show that higher building standards can dramatically reduce total annual space heating demand. In particular, implementing currently achievable best practice energy efficiency standards could reduce space heating energy demand *below* current levels, while still achieving healthy indoor temperatures. Perhaps more importantly, these higher standards can significantly reduce future growth in winter peaks. For example, very high efficiency standards can actually lead to a smaller winter peak and less seasonal variation than current space heating demand, despite significant additional population and dwelling growth and healthier indoor temperatures.

As expected, the results show significant climate variation, with colder climates driving higher winter heat demand, and therefore having much more to gain from energy efficient buildings. As an example, the Very High scenario could reduce overall space heating demand in New Zealand's colder climate zones by 70% in winter months. However, our results show that even in subtropical/temperate climates the Very High scenario can reduce winter energy demand by 50% from business as usual. In addition, although not evaluated here, warmer climates are likely to also benefit from reduced cooling in summer due to energy efficient buildings (Badescu et al., 2015).

### 5.1. Implications for New Zealand's future energy and climate change response policies

Most approaches to achieving high levels of renewable electricity in New Zealand have focused on supply options 'required' by increases in electricity demand from process heat and transport (ICCC, 2019), which are unlikely to vary by season. However, the seasonal mismatch between renewable supply and demand caused by residential space heating is currently a significant barrier to 100% electricity goals (ICCC, 2019). This paper shows that under the business-as-usual Building Code, and assuming that homes are heated to healthy temperatures, space heating demand is likely to more than triple by 2050, potentially making the goal of a 100% electricity system impossible to achieve.

One low-carbon option to deal with the seasonal variation in space heating demand is to have this space heating demand met by increased use of wood fuels from sustainable plantation forests (BANZ, 2010), although this option may be limited in many jurisdictions due to air quality issues. However, given that wood fuel currently only provides 21% of heating end-use energy in New Zealand (see Fig. 1), this would represent a 15 × increase in wood fuel for heating. As a result, this is likely to only be a partial solution, and most projections assume that heating will be increasingly met by renewable electricity (ICCC, 2019).

In this context, the paper's results show that under the current Building Code the winter electricity demand peak could more than double for realistic future heat pump efficiencies (e.g. MHPF $\sim$ 2, see Fig. 9). This increase would significantly exacerbate the existing seasonal supply-demand mismatch. However, the results also show that implementation of much higher building code standards could alleviate this issue. For example - implementing currently achievable best practice efficiency standards could reduce space heating winter demand to below current values (see Fig. 9). If we compare this with other proposed options to the 'dry year problem' such as a proposed \$400 M/TWh (ICCC, 2019) pumped hydro solution, the reduction in winter demand provided by the Very High scenario has an economic value of > \$3 Bn.

The reduction in winter electricity demand from ultra-efficient housing could also provide benefits to regional distribution networks, whose network congestion periods occur mostly on cold winter days. These are likely to be exacerbated with greater electrical heating. Significant reduction in winter demand could avoid costly investment in underutilized distribution capacity and reinforcement of constrained lines, and, as Fig. 10 shows, this effect is likely to be regionally distributed. It could also enable shorter term demand flexibility options by increasing thermal storage and mass (Le Dréau and Heiselberg, 2016). In contrast, there is currently very little possibility of short-term demand management of heating in New Zealand houses due to their very short thermal heat retention times.

The simplest and most effective method of achieving greater uptake of high-performance housing in New Zealand and elsewhere is to modify the building code for new builds and retrofits to align with achievable best practice energy efficiency standards (Leardini and Manfredini, 2015). Studies have shown that building to these standards leads to relatively minor 3–5% increases in the capital costs (AECOM, 2019), and that building to less stringent efficiency standards is less cost effective due to the additional capital cost of large heating systems (AECOM, 2019). These studies also show that most of the additional capital costs of implementing more stringent standards can be rapidly recouped through energy savings alone. For instance, in the DN and CC climate zones (see Table 3), the Net Present Value of future energy savings in the Very High scenario is approximately 7–10% ($\sim$\$300/m$^2$) of current building costs (\$3000/m$^2$) (assuming a 30 year project lifetime, interest rate of 3–6%, and heating costs of 15c/kWh). These energy savings vary significantly by region, dropping to between 2 and 5% in AK and WN (see Table 3) under the same assumptions. However, building houses to the Very High standard will also be much easier in these locations.

Current government policy signals suggest that modifications to the current building code to radically reduce energy intensity in kWh/m$^2$ are pending (MBIE, 2020). However, these signals explicitly exclude actions to reduce energy intensity in the existing housing stock, as they focus only on standards for new-builds. As this paper has shown, ignoring the larger problem of the existing dwelling stock (see Fig. 7) means that these potential building code settings will fail to significantly reduce the winter peak in demand. Thus, we argue that ultra-high energy efficient retrofits should be carried out in parallel to re-setting the standards for new-builds to realize the scale of estimated benefits. Further, the draft proposals imply a staged approach to increasing efficiency levels, despite evidence that attempting to achieve high levels of efficiency improvement during a retrofit to upgrade a lower standard recent 'new' build could be more expensive (AECOM, 2019). This is supported by the differences in outcome for the aggressive Very High scenario compared to the Progressive scenarios modelled in this paper, which show that any delay to implementing higher standards results in much smaller benefits by 2050.

The potential role for an energy-efficient dwelling stock to enable greater renewable energy supply by reducing the winter demand is also absent from the New Zealand Climate Change Commission's initial Advice to government (CCC, 2021). Given the high capital cost and economic inefficiency of alternative policy settings, the results reported in this paper suggest that the Commission's advice should urge the New Zealand government to adjust policy settings to mandate highly energy-efficient housing for both new-build and retrofit. This will enable a low-cost electricity system transition that complies with the New Zealand Climate Change Commission's "Principle 4: Avoid unnecessary cost" (CCC, 2021).

From a implementation perspective, given the current relative rarity of such buildings in New Zealand and the consequential lack of skills and supply chain capacity to deliver them, both government regulation *and* stimulation of the market through enhanced forms of the 'Warmer Kiwi Homes' programme (NZ Government, 2020) may be required. Given the ongoing savings, benefit to the electricity system and the substantial health co-benefits that derive from raising indoor temperatures (Howden-Chapman et al., 2009b), such investment would produce multiple benefits.

### 5.2. Implications for international 100% renewable energy policies

The seasonal mismatch between renewable supply and demand is a significant barrier to many countries achieving 100% renewable energy (Mason et al., 2010; Pereira et al., 2016; Deason, 2018; Shaner et al., 2018). Decarbonisation policies tend to focus mostly on renewable supply options, or if they do consider the demand side, it is mainly short term demand side management or reductions in overall annual consumption (Hansen et al., 2019). However, the results in this paper show that demand could play a huge role in either hindering or enabling this transition. In particular, for cold or temperate climates (c.f. Fig. 11) with winter peaks in energy demand, high performance buildings could play an important role in reducing the seasonal mismatch between supply and demand. This would provide an alternative to investing in potentially underutilized distribution and storage infrastructure, over-building renewable supply or backup fossil fuel plants (Denholm and Hand, 2011; Lund et al., 2015; Trainer, 2017a, 2017b; Heard et al., 2017).

Clearly, the challenge of inter-seasonal demand-supply mis-match could be mitigated by integrating across energy sectors (Mathiesen et al., 2015) or approaches to delivering heat at a significantly higher efficiency (i.e. MHPFs at the higher end of those depicted in Fig. 9). This is particularly relevant for a number of European countries with well-established biomass-fueled district heating schemes (Drysdale et al., 2019; David et al., 2017; Möller et al., 2019) that are often much more efficient at providing space heating than those at the individual building level. However, individual building heating/cooling is overwhelmingly the most common approach in New Zealand, and district level or biomass-fueled heating schemes are likely to be substantially less relevant. Indeed, even in countries such as the UK with higher density urban forms and some history of residential heat networks, electrically-fueled heating and cooling is projected to form at least 65 percent of future residential heat (Element Energy (2021) and De, 2021), and so the results discussed in this paper pertain to the UK and many other 'mixed energy' heat systems.

The results from this study are therefore directly applicable to many other countries with a high proportion of renewables and a high prevalence of electric heating, or who wish to attain that state. However, we have also provided a method for reproducing the analysis and useful indications of the magnitude of the effect for those who are yet to reach this point. New Zealand could be considered an extreme case, due to its already highly renewable electricity system and poorly performing housing stock. As a result, the impact of high performance buildings on seasonal electricity demand may be less dramatic in other countries due to the higher existing building standards, and more efficient approaches to space heating (Drysdale et al., 2019; David et al., 2017; Möller et al., 2019). However heating requirements are also often significantly higher (IEA, 2020). In contrast to New Zealand, where solar currently only makes up < 1% of electricity supply, many countries are pursuing high percentages of solar photovoltaic generation (REN21, 2020). This includes grid scale installations, rooftop solar, and (nearly) net-zero housing initiatives, where solar is the main generation method proposed (Salom et al., 2014; Sartori et al., 2012). Due the seasonal nature of solar resources, this will tend to increase the seasonal mismatch between summer supply and winter demand in locations with a significant winter space heating demand, unless high performance buildings have widespread uptake to mitigate some of this mismatch.

While this paper provides an example of the role of energy efficiency in permanently reducing heat demand, other work has shown the potential of energy efficient lighting to play a similar role (Arteconi et al., 2013; Dortans et al., 2020). As more countries adopt higher standards for space heating, the next large opportunity for advances in energy efficiency is likely to be in electrically heated domestic hot water (Pomianowski et al., 2020). Because heating water from lower temperatures in winter will likely lead to a seasonal variance in demand, the potential of these advances to permanently reduce demand during critical peak periods should be investigated further.

In common with previous studies of the reduction of annual energy consumption (Ürge-Vorsatz et al., 2013), our results show that the benefits of reduction in seasonal variation of energy demand due to high performance buildings are pushed back well beyond 2050 if implementation is delayed, gradual, or initially restricted only to new builds. Therefore, rapid implementation of these standards for new builds *and* the existing dwellings that will make up a large proportion of houses in 2050 is recommended. This will ensure that costs are reduced by avoiding the need for future retrofits and ensuring that lock-in effects are evaded (Ürge-Vorsatz et al., 2013).

Finally, it is important to note that reducing (winter) peak demand is just one additional benefit of energy-efficiency housing among the many previously identified (GABC, IEA & UNEP, 2019; Howden-Chapman et al., 2009a; Buonocore et al., 2016; Howden-Chapman et al., 2017). This suggests a more compelling case for energy efficient housing can be made by a cross-sectorial approach that aligns the goals of decarbonisation, improving health and reducing energy poverty (Ürge-Vorsatz and Herrero, 2012). This is especially relevant for countries that currently have relatively poor housing stock and have limited support for energy efficient housing (GABC, IEA & UNEP, 2019).

### 5.3. Limitations and further work

As with any scenario modelling work of this nature, there are a number of areas that would benefit from further refinement. First, the results presented here are based on a transparent but simplistic residential building stock model. This could be expanded to encompass a wider range of residential building types, commercial buildings, and to utilise more sophisticated approaches (Johnstone, 2001; Kavgic et al., 2010).

Second, we have used a simplified approach to estimating specific space heating demand. For the Building Code scenario, this has resulted in space heating demand that is higher than reported elsewhere (Jaques, 2015, 2019) due to our strict adherence to the New Zealand building code methodology (see Sec.3.2.1) and the need to provide a baseline for comparison. For other scenarios, this simplified approach has ignored the variation in specific spacing heating demand between different housing designs (Jaques, 2019). Future work should consider a range of specific housing designs and the resulting space heating demand. This would enable more accurate estimates of future demand under different building codes, exploration of the impact of internal temperature, and estimates of space heating demand variation on a daily or within-day timescale.

Thirdly, our approach has not accounted for embodied energy (Chandrakumar et al., 2020). Embodied energy may be significantly higher in energy efficient and low-carbon buildings, due to utilization of additional technologies and materials resulting in a trade off in embodied vs operational energy. In addition, in a scenario where the proportion of renewable supply is increasing over time, the greenhouse gas emissions intensity of the up-front embodied energy may be higher than that of that of the longer-term operational energy. Conversely, houses built from wood can act as long term carbon sinks (Churkina et al., 2020) and, in combination, these factors would have implications for the emissions-reduction value of the approach - although they will leave the specific implications for the electricity system unchanged.

Finally, given emerging evidence of the capital costs required to build or retrofit to high energy efficiency standards at scale (AECOM, 2019), an economic comparison of an ultra high efficiency building scenario vs other electricity supply side options to address the seasonal supply-demand mismatch should be carried out. Ideally, such an assessment would take into account the full co-benefits of investing in energy efficient buildings (Johnson et al., 2018).

## 6. Conclusions and policy implications

As countries increase the percentage of renewable energy in electricity supply and move to electrify heat and transport, seasonal mismatches between supply and demand will become an increasingly important issue. For example, in New Zealand (with > 80% renewable electricity) this issue potentially restricts the removal of the last 5–10% of fossil fuel-based generation from national electricity supply. Conventional low-carbon policy settings emphasise capital intensive supply-side or long-term storage solutions. In contrast, we have presented an example of a potential demand-reduction solution that aligns to health, comfort, and cost reduction drivers.

In this paper, we used scenarios of future residential building energy use to quantify the potential for energy efficient buildings to reduce the seasonal variation in electricity demand in New Zealand. The results show that rapid uptake of currently achievable best-practice standards could reduce the winter-summer demand variation by 3/4 from business as usual (or to below its current value) by 2050, even with a significant growth in housing area and increasing indoor temperatures to healthy levels.

While New Zealand's specific context means that the results may not (yet) be directly applicable to many other countries, they indicate that the impact of high-performance buildings on lessening the seasonal supply-demand mismatch is likely to be even more significant in countries which experience more severe winters, and also where there has been rapid growth of solar photo-voltaic supply in summer.

Based on these results, this paper argues that high-performance housing is likely to have a crucial role to play in enabling highly-renewable electricity systems in many countries. This is not limited to those such as New Zealand, where policy is resolutely focused on electricity as the fuel for heating or cooling, but also for those such as the UK where electricity, through heat pumps, is likely to form a major component of the heating mix. This is especially the case where there is a seasonal mis-match between demand and renewable electricity supply.

More importantly, the results provide a strong argument for the urgent implementation of policy settings that ensure new build construction and wide-scale and rapid retrofit to high-performance building standards. This will deliver wide-ranging health, efficiency, and greenhouse gas emission reduction benefits, help to alleviate energy poverty, *and* enable the transition to a 100% renewable electricity system at least cost.

### CRediT authorship contribution statement

**M.W. Jack:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **A. Mirfin:** Methodology, Software, Validation, Investigation, Visualization. **B. Anderson:** Conceptualization, Writing – review & editing, Supervision.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Climate zones

Table A.4 shows how climate zones assumed in this paper relate to territorial authorities and other climate zone definitions.

**Table A.4**
Climate zones and associated territorial authorities assumed in this paper (Quinn, 2015). Table also shows mean monthly temperatures in July and January (°C) for each zone and corresponding Homestar and EnerPHit zone, where WT is 'warm-temperate' and CT is 'cool-temperate'.

| Climate zone | $\bar{T}_{\text{July}}$ | $\bar{T}_{\text{Jan}}$ | Territorial authority | Homestar zone | EnerPHit zone |
|---|---|---|---|---|---|
| NL | 12.1 | 19.0 | Far North District, Whangarei District, Kaipara District | 1 | WT |
| AK | 11.3 | 19.2 | Thames-Coromandel District, Auckland | 1 | WT |
| HN | 8.6 | 17.5 | Hauraki District, Waikato District, Matamata-Piako District, Hamilton City, Waipa District, Otorohanga District, South Waikato District, Waitomo District | 2 | WT |
| BP | 10.4 | 19.6 | Western Bay of Plenty District, Tauranga City, Whakatane District, Kawerau District, Opotiki District | 2 | WT |
| RR | 7.6 | 17.0 | Rotorua District | 2 | WT |
| EC | 10.1 | 18.3 | Gisborne District, Wairoa District, Hastings District, Napier City, Central Hawke's Bay District | 2 | WT |
| WI | 7.6 | 17.7 | Tararua District, Upper Hutt City, Masterton District, Carterton District, South Wairarapa District | 2 | WT |
| WN | 9.0 | 17.0 | Porirua City, Lower Hutt City, Wellington City | 2 | WT |
| MW | 8.6 | 17.2 | Rangitikei District, Manawatu District, Palmerston North City, Horowhenua District, Kapiti Coast District | 2 | WT |
| NP | 10.2 | 17.3 | New Plymouth District, Stratford District, South Taranaki District, Whanganui District | 2 | WT |
| TP | 6.8 | 17.3 | Taupo District, Ruapehu District | 3A | CT |
| NM | 8.1 | 17.7 | Tasman District, Nelson City, Marlborough District, Kaikoura District | 3A | CT |
| WC | 6.4 | 16.6 | Buller District, Grey District, Westland District | 3A | CT |
| CC | 5.1 | 16.2 | Hurunui District, Waimakariri District, Christchurch City, Selwyn District, Ashburton District, Timaru District, Waimate District | 3A | CT |
| OC | 2.7 | 16.1 | Mackenzie District, Central Otago District | 3B | CT |
| DN | 7.0 | 14.2 | Waitaki District, Dunedin City, Clutha District | 3A | CT |
| QL | 2.3 | 15.2 | Queenstown-Lakes District | 3B | CT |
| IN | 5.4 | 14.0 | Southland District, Gore District, Invercargill City | 3A | CT |

## Appendix B. Building Code Calculations

In this appendix we provide some details of calculations used to justify the assumptions made in Sec.3.2.1. In Eq. (7) we gave an approximation for the wall area of a house in terms of the short side to long side ratio of $s$: 1, the floor area and the height. This approximation is based on assuming a notional rectangular shaped house (Viggers et al., 2017). If the long side is given by $L$ then the perimeter is given by

$$p = 2L + 2sL = L(2 + 2s) \tag{B.1}$$

and its area by

$$a = sL^2 \tag{B.2}$$

Rearranging we have

$$L = \sqrt{\frac{a}{s}} \tag{B.3}$$

Substituting into Eq. (B.1) we find

$$p = \frac{2+2s}{\sqrt{s}}\sqrt{a} \tag{B.4}$$

Thus the total wall area is

$$w = \frac{2+2s}{\sqrt{s}}h\sqrt{a} \tag{B.5}$$

where $h$ is the wall height.

In Sec.3.1 we used values for the floor area $a$ that do not change over time for new and retrofit houses. In many territorial authorities, the average area of new houses is forecast to increase, which would reduce the Building Code specific space heating demand. However according to Ref. (Viggers et al., 2017), larger houses tend to be less square. This increases the wall area to floor area ratio, increasing the specific space heating demand. The two effects are illustrated in Fig. B.12. As these two minor effects largely offset each other we take $a$ to be fixed in Eq. (8) despite the fact that the actual average floor areas of new houses is likely to increase over time.

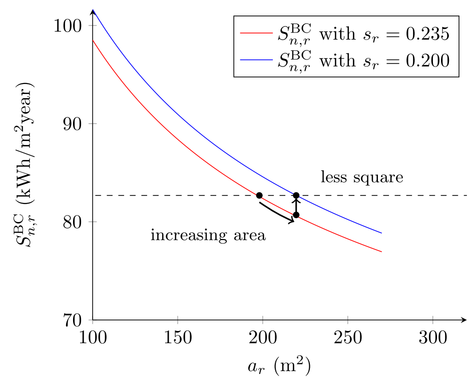


**Fig. B.12.** Dependence of $S^{BC}_{n,r}$ on $a_r$ and $s_r$.

The temperature data used by the BRANZ ALF tool (BRANZ, 2018), which assists with meeting the requirements of the New Zealand Building Code, consists of the mean temperature each month at 178 locations throughout New Zealand. For consistency with other scenarios we have instead used the monthly average temperatures corresponding to the Passive House climate zones given in Table A.4 for each territorial authority. Following the New Zealand Building Code (MBIE, 2019), the heating degrees (HDM) of each month (in units of degree-months) for each climate zone was calculated by

$$\text{HDM}_{n,m} = (14 - T^{m,n}_{\text{mean}})^{+} \tag{B.6}$$

**where $n$ denotes the territorial authority and $m$ the month. The heating degree total for each climate zone used in Eq. (8) is then given by**

$$H_n = \max\left(\sum_m \text{HDM}_{n,m}, 12\right). \tag{B.7}$$

**Table B.5**

Table of specific heating demand, $S^{\sigma}_{n,r}$, in kW/m$^2$and in brackets $U$-values, $U^{\sigma}_{n,r}$, in W/(m$^2$ K) for each climate zone and scenario. The R subscript corresponds to the retrofit version of the scenario. Retrofit specific heating demand and $U$-values for the M and H scenarios are the same as those for new builds.

| Climate Zone | BC | BC$_R$ | VH | VH$_R$ | M | H |
|---|---|---|---|---|---|---|
| NL | 35.4(1.76) | 37.2(1.84) | 15(1.09) | 20(1.30) | 35(1.75) | 20(1.27) |
| AK | 35.4(1.65) | 37.2(1.72) | 15(1.03) | 20(1.22) | 35(1.64) | 20(1.20) |
| HN | 60.1(1.75) | 63.1(1.82) | 15(0.77) | 20(0.92) | 60(1.75) | 40(1.35) |
| BP | 35.4(1.51) | 37.2(1.57) | 15(0.91) | 20(1.09) | 60(2.11) | 40(1.62) |
| RR | 87.0(2.00) | 91.3(2.08) | 15(0.75) | 20(0.88) | 60(1.58) | 40(1.24) |
| EC | 51.3(1.65) | 53.8(1.72) | 15(0.80) | 20(0.95) | 60(1.83) | 40(1.41) |
| WI | 87.5(1.96) | 91.8(2.04) | 15(0.67) | 20(0.80) | 60(1.52) | 40(1.18) |
| WN | 67.0(1.87) | 70.3(1.94) | 15(0.85) | 20(0.99) | 60(1.74) | 40(1.38) |
| MW | 61.7(1.83) | 64.7(1.91) | 15(0.86) | 20(1.00) | 60(1.80) | 40(1.42) |
| NP | 47.2(1.67) | 49.5(1.74) | 15(0.92) | 20(1.08) | 60(1.93) | 40(1.52) |
| TP | 106.3(2.13) | 111.6(2.22) | 15(0.69) | 25(0.91) | 70(1.61) | 50(1.31) |
| NM | 75.3(1.94) | 79.0(2.02) | 15(0.78) | 25(1.03) | 70(1.85) | 50(1.50) |
| WC | 104.9(2.15) | 110.1(2.24) | 15(0.75) | 25(0.96) | 70(1.66) | 50(1.36) |
| CC | 115.8(2.17) | 121.5(2.26) | 15(0.65) | 25(0.86) | 70(1.54) | 50(1.25) |
| OC | 171.4(2.41) | 179.8(2.51) | 15(0.54) | 25(0.71) | 80(1.39) | 60(1.16) |
| DN | 117.5(2.18) | 123.3(2.27) | 15(0.73) | 25(0.93) | 70(1.56) | 50(1.29) |
| QL | 169.6(2.44) | 177.9(2.55) | 15(0.58) | 25(0.75) | 80(1.44) | 60(1.20) |
| IN | 142.9(2.32) | 149.9(2.41) | 15(0.68) | 25(0.87) | 70(1.45) | 50(1.20) |

## Appendix C. Monthly specific space heating demand calculation

The monthly specific space heating demand calculation used in this paper is based on Ref. (CIBSE, 2006). Following Ref. (CIBSE, 2006), the gain to loss ratio is defined as

$$\gamma = \frac{Q_{\text{in}} + Q_{\text{solar}}}{Q_{\text{loss}}}, \tag{C.1}$$

where $Q_{\text{in}}$, $Q_{\text{solar}}$, and $Q_{\text{loss}}$ are the internal gains, solar gains, and heat loss rate respectively, all in W/m$^2$ (averages for each month). Note that we omit the $m$ and $n$ superscript for clarity. The heat loss rate is given by

$$Q_{\text{loss}} = U(T_i - T_e), \tag{C.2}$$

where $T_i$ is mean monthly indoor temperature (set to 20 C in this case) and $T_e$ is the mean exterior temperature for that month. $U$ is the overall heat-loss coefficient in units of W/(m$^2$K). The utilization factor is given by

$$\eta = \frac{1 - \gamma^{(1+\tau/15)}}{1 - \gamma^{(2+\tau/15)}}. \tag{C.3}$$

where we have assumed continuous heating and $\tau$ is the building's time constant in hours (CIBSE, 2006),

$$\tau = \frac{C}{U} \tag{C.4}$$

and $C$ is the specific thermal capacity in Wh/(m$^2$K). The average useful heat gain for a month is given by

$$Q_{\text{gain}} = (Q_{\text{in}} + Q_{\text{solar}})\eta \tag{C.5}$$

The base temperature for a month is

$$T^{\text{base}} = T^{\text{set}} - \frac{Q_{\text{gain}}}{U} \tag{C.6}$$

where $T^{\text{set}}$ is the indoor temperature (20 C in this case). $T^{\text{base}}$ is used in Eqs. (15) and (16). It depends on $U$ and thus Eq. (16) represents an implicit equation that can be solved for $U$. We solve this numerically via standard iterative techniques. Note that in Eq. (16) we have explicitly labelled $T^{\text{base}}_{m,n}$'s dependence on $m$ and $U^{\sigma}_{n,r}$'s dependence on scenario, territorial authority and new or retrofit. The resulting values for $U^{\sigma}_{n,r}$ are given in Table B.5.

To carry out the calculations of $U^{\sigma}_{n,r}$ we have made a number of assumptions to calculate solar gains. Simulations show that the overall results are not sensitive to the precise values of $C$, $Q_{\text{in}}$ and $Q_{\text{solar}}$. Thus all these quantities can be approximated without significant impact on the results. For completeness we report our assumptions. We used $C$ values of 53 Wh/(m$^2$K) for the Very High scenario and 44 Wh/(m$^2$K) for all others (Le Dréau and Heiselberg, 2016). We assume $Q_{\text{in}}$ to be fixed at 2.1 W/m$^2$ following the default/standard value used in the Passive House standard (Passive House Institute, 2016). $Q_{\text{solar}}$ is estimated by using climate files that contain the monthly average solar radiation (in W/$m^2_{\text{window}}$) from the cardinal directions for each territorial authority. These are multiplied by directionally-dependent window-to-floor ratios, $g$-values and reduction (shading) factors to get W/$m^2_{\text{floor}}$ using default values from Ref. (Passive House Institute, 2016). These are summed over all directions to get a total average solar gains for each month for each climate zone. For each climate zone, we want an average monthly $Q_{\text{solar}}$ in W/$m^2_{\text{floor}}$. We have average monthly $Q_{\text{solar}}$ for the cardinal directions in W/$m^2_{\text{window}}$, so it is useful to estimate window area to floor area ratios. We assume window to floor ratios of

$$[\omega_{\text{south}} \quad \omega_{\text{east}} \quad \omega_{\text{north}} \quad \omega_{\text{west}}] = [0.02 \quad 0.04 \quad 0.1 \quad 0.02]. \tag{C.7}$$

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