PASSIVE HOUSES IN NEW ZEALAND: a comparison between predicted and real performance through post-occupancy evaluation

Priscila Besen[1], Paola Leardini[2], Paola Boarin[3]

[1]*The University of Auckland, School of Architecture and Planning; pbes461@aucklanduni.ac.nz*
[2]*The University of Queensland, School of Architecture; p.leardini@uq.edu.au*
[3]*The University of Auckland, School of Architecture and Planning; p.boarin@auckland.ac.nz*

1. Introduction

A number of Passive Houses have been built in New Zealand since 2012, implementing the standard as a voluntary certification scheme. The Passive House standard offers well-established solutions to the main issues faced by New Zealand's housing stock: poor indoor air quality, thermal discomfort, fuel poverty and inadequate levels of insulation (Leardini, Manfredini, & Callau, 2015). However, this building standard still encounters resistance across New Zealand, as it challenges local assumptions about building construction and corresponding performance. Therefore, providing data from real case studies is essential to respond to the local scepticism, as well as enabling comparisons with the performance of code-complying dwellings. Post-Occupancy Evaluation (POE) is a key practice to verify actual performance of low-energy buildings against design expectations and simulation results. Previous research investigated the performance of the first two certified Passive Houses completed in New Zealand (Leardini & Cholmondeley-Smith, 2014). Now, after more houses have been completed and occupied for a few years, it is possible to investigate further case studies with different features and in different locations. Therefore, a long-term POE study was conducted on two dwellings located in Auckland and Whanganui. By collecting indoor environmental measurements, energy consumption data, and through interviews with occupants, a solid understanding of the strengths and weaknesses of each case study was achieved.

2. Methodology

POE is defined as "the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time. POEs focus on building occupants and their needs, and thus they provide insights into the consequences of past design decisions and the resulting building performance. This knowledge forms a sound basis for creating better buildings in the future" (Preiser, Rabinowitz, & White, 1988). A POE consisting of a quantitative and a qualitative assessment was carried out in two houses: House A, which is in the process of obtaining Passive House certification and is located in a coastal suburb in Auckland; House B is an already certified Passive House, is situated in a suburban/rural context in Whanganui. Both homes were completed in 2014; they have different designs, construction methods and features, which are summarised in Table 1.

Table 1 – Main features for each case study

	House A	House B
Location	Auckland NZBC Climate Zone 1	Whanganui NZBC Climate Zone 2
Heating Degree Days	1725 HDD (base 20^{o}C)	2402 HDD (base 20^{o}C)
Time integral of temperature differences (Gt)	24 kKh/a	33 kKh/a
Treated Floor Area (TFA)	216 m^2	138 m^2
Number of storeys	2	2
Number of occupants	4	5
Number of Bedrooms	4	4
Construction method	Timber frame with double layer of insulation	Insulated Concrete Forms (ICF)
Windows	Triple glazing with uPVC frames	Argon-filled double glazing with wood-aluminium frames
Total window area	85 m^2	32 m^2
Total window-to-floor area ratio	39%	23%
Heat Loss Form Factor (Total Envelope Surface Area / Treated Floor Area)	3.1	2.7
Active heating	Fireplace (lit occasionally)	400 W Panel heater (avrg use 6 hours/day in winter)
Photovoltaic Panels	8 kW	3 kW
Airtightness (at 50 Pascal)	0.48 ACH	0.47 ACH
Certification	Passive House certification in progress Homestar^{TM} certified – 8 star	Passive House certified

The number of bedrooms is the same in both houses but the floor area varies significantly between them. Another significant difference in their building envelopes is the window area; the window-to-floor area is much higher in the Auckland home. Although these dwellings were completed before the introduction of the new Passive House classes, both have photovoltaic panels installed, which are connected to the national grid.

2.1 Quantitative Assessment

The quantitative assessment of the two PHs consisted of the collection of indoor environmental data and energy consumption data as a long-term monitoring scheme.

The measurement campaign at House A was set up as a collaboration between the University of Auckland and the homeowners. The house was monitored using a wireless platform consisting of 10 low-power nodes and one data transmission bridge. The system gathered indoor environmental data at a 15 minute acquisition rate, including ambient temperature, relative humidity, wall heat flow, CO_2 concentration and luminance in select locations of the house, which was compared to values recorded by an exterior sensor (Besen, Leardini, & Melis, 2016). All sensors were installed according to ISO 7726 (1998) and positioned away from windows to avoid direct sunlight (Figure 1). Real-time results were made available online so that both homeowners and researchers were able to access them remotely. The monitoring campaign lasted 11 months (July 2015 – June 2016), to assess the hygrothermal behaviour of the house during different seasons. There were gaps during the monitoring period due to malfunctioning of the sensors; however, as such a long term monitoring was carried out, these gaps do not compromise the analysis of the overall performance of the house.

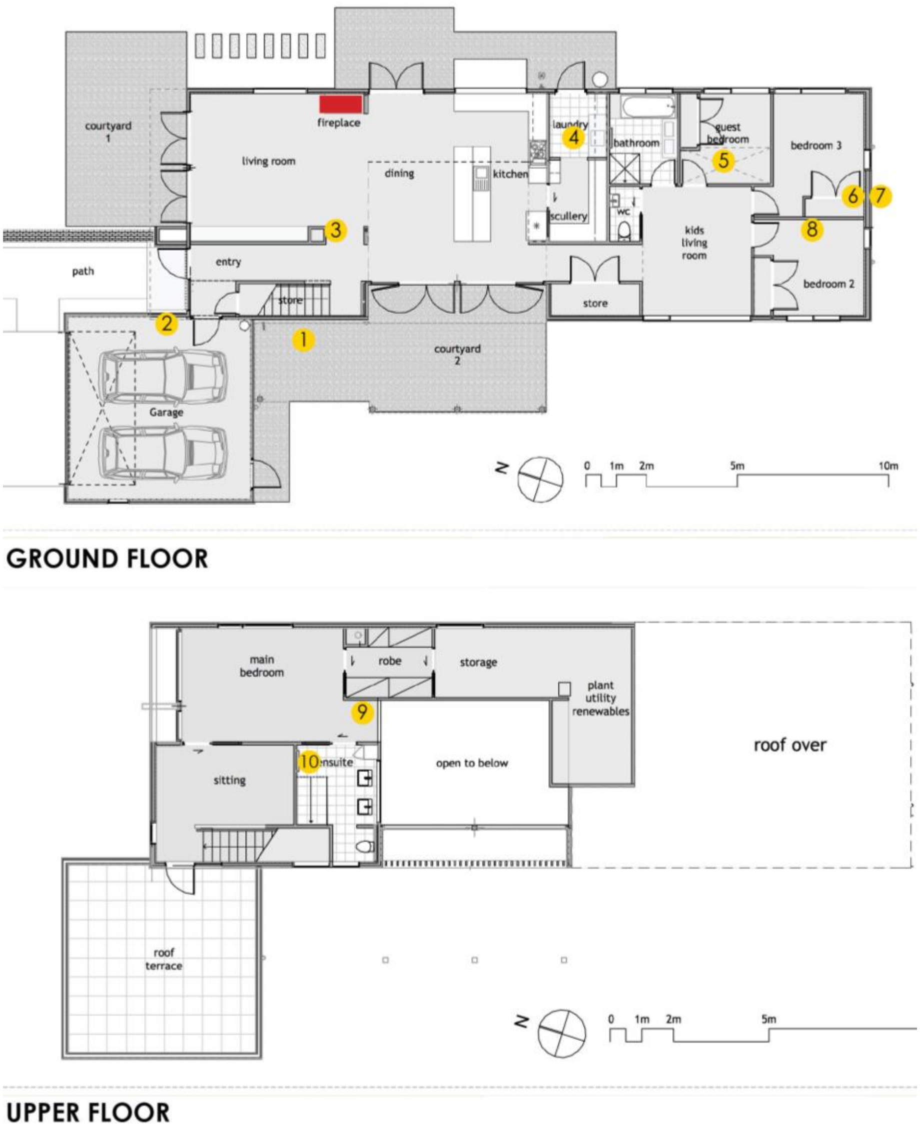

Figure 1 - Position of sensors (yellow) shown on Floor Plans of House A. Position of fireplace shown on Ground Floor Plan (red rectangle).

The measurement campaign for House B was implemented by the homeowners to check the performance of the house after completion. Data was shared with the researchers later in the process. The system was installed in January 2015 and data was collected until October 2015. Four sensors were installed in different rooms through the house to allow for verification of different internal ambient conditions, while one sensor was installed outside for measuring the external conditions (Figure 2). There were gaps during the monitoring period, but the available data allowed for a thorough verification of the performance in different seasons.

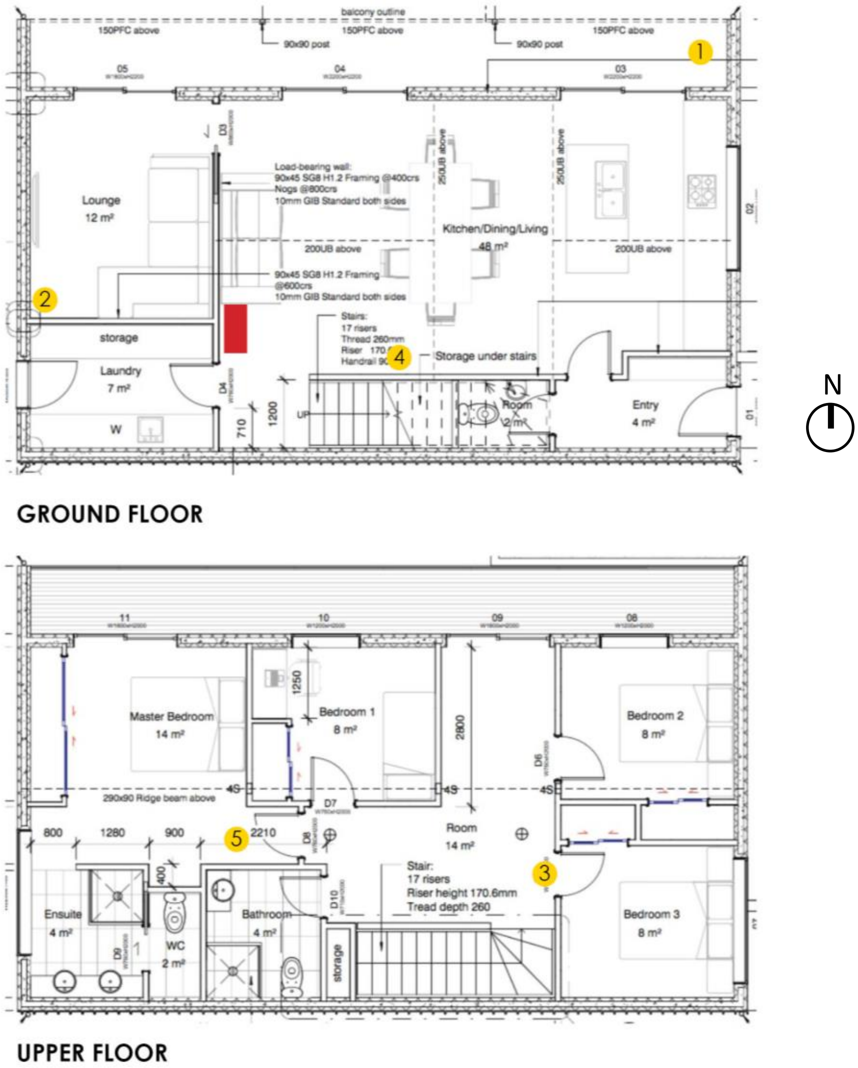

Figure 2 - Position of sensors (yellow) shown on Floor Plans of House B. Position of panel heater shown on Ground Floor (red rectangle).

2.2 Qualitative Assessment

To assess the thermal sensation of the occupants, interviews based on ISO 7730 (2005) were conducted in both houses, using a seven-point thermal comfort scale to evaluate the occupants' thermal sensation. The thermal sensation questions were retrospective – asking about comfort in different seasons of the year all at once. This method allows for good comparisons of thermal sensation in different seasons, but the occupants may not be entirely objective (Guerra-Santin & Tweed, 2015). Additional questions were related to their health while living in a Passive House, the level of clothing they wear at home, and comparisons between the indoor environmental quality in their homes and other buildings they spend time on. Given the limited number of occupants in each house, and the fact that their responses might have been influenced by their enthusiasm about Passive House, this information was validated by correlation against the quantitative data.

3. Results and Discussion

Overall, measurements of indoor temperature and relative humidity at both houses showed stable conditions when compared to the external environment. By using a mechanical heat recovery ventilation (HRV) system and, occasionally, active heating sources, both houses have accomplished constant and steady internal temperatures of around 20^{o}C even in the coldest winter days. As expected from a Passive House, temperatures were maintained between 20-25^{o}C most of the time, with indoor relative humidity between 30% and 70%, despite the high humidity rates in New Zealand. The occupants reported having no issues with moisture and condensation in their homes, even in wet areas such as bathrooms and kitchens. Constant ventilation provided by the HRV system is the main factor required to maintain these well-controlled humidity rates in both homes.

However, different conditions were found in various rooms. In House A, the occupants reported that the coldest rooms were the South-facing bedrooms; this was confirmed by the measurements of ambient temperatures. The warmest parts of the house were the bedroom facing North and the TV room facing West. In fact, to mitigate the high temperatures experienced during the first summer, Low-e window films were installed in the West-facing windows. Both case studies are double-storey buildings and both had higher temperatures on the upper floors. This is mainly due to the hot air from the ground floor rising to the upper floor, which reminds of the possibility of creating stack effect ventilation, which could be very beneficial in the summer months.

Winter performance was highly influenced by the use of active heating: in House A, a fireplace was lit only occasionally as indoor temperatures were judged as comfortable for most of the time by the occupants. In House B, a 400 W panel heater was used for approximately 6 hours a day in winter in cloudy days. These heating patterns are less than what was predicted on PHPP, therefore both houses achieved lower energy consumption than expected, while reaching temperatures around 18^{o}C in the coldest winter days (i.e. lower than the standard 20 ^{o}C used for PHPP calculation). In House B, the media room had 34% of the temperature readings below 20^{o}C. This may be explained by the separation of this room from the other spaces in the house. Although the heater is installed in a position quite close to the media room, most heat rises to the second floor rather than flowing to the media room, only connected through a small door. In addition, the position of the sensor in this room is quite close to the external wall, while all other sensors were positioned more centrally within the house. The windows in the media room face North, but are protected from the afternoon sun by an external wing wall facing West.

Summer performance appears to be critical for the Passive House in Auckland. Large glazed areas without adequate shading caused overheating especially in the upper floor. House A's master bedroom had 34% of readings above 25^{o}C, well above the limit of 10% expected for Passive Houses. This room receives a greater amount of solar gains from the North, East and West openings and also warm air coming from the lower level, as there is an opening between the living room and this space. The master bedroom's thermal behaviour is also affected by the PV inverter panel, placed in the upstairs service room within the thermal envelope. The unit produced significant heat gains and the PHPPv8 (originally used in the design stage) did not have a means of taking them into account. A bypass through the ventilation system was introduced to help flush the heat, however radiant heat will still flow through leading to significant gains particularly on sunny days. After the first summer, the occupants decided to install tinting films on the window facing West. Although this solution may ease the overheating problem, it might also significantly reduce solar gains in winter. Avoiding overheating by controlling excessive solar gains is essential in Passive Houses: with climate change, temperatures are expected to rise and dwellings should be prepared to face those conditions (Roaf, Crichton, & Nicol, 2009). Similar overheating issues have been found in other Passive Houses around the world due to similar causes (Ridley, et al., 2013). Another alternative to solve this issue is to provide additional natural ventilation: the occupants currently open the windows very little even in summer. Cross ventilation and night ventilation could be further explored to purge the excess heat, taking advantage from the nocturnal temperature drop.

The summer measurement results in House B were within Passive House limits with only up to 8% of the readings above 25^{o}C; this can be explained considering that this dwelling is situated in a slightly cooler climate and has windows mainly facing North, which are well shaded with horizontal overhangs. Another factor contributing to good summer performance in this house is that the occupants regularly open the windows at night to cool down the house.

Overall, occupants were very satisfied with the thermal environment in both Passive Houses. Occupants' behaviour is crucial for the actual performance of Passive Houses. The use of active space heating depends on their judgement of the indoor environment. The interviews also revealed the positive impact of the PH indoor environment on occupants' health. One of the children in House A who used to suffer from chest infection and pneumonia in previous houses they lived in, had no symptoms since they moved to the PH. In addition, occupants were asked to provide comparisons against previous houses they have lived, their workplaces and other houses they visit. The overall result was very clear: their homes achieve much superior indoor environmental quality than any other built environments they have experienced.

The comparison of both case studies against the average temperatures in New Zealand housing stock shows significant differences. Data on houses built after 1978 (when insulation became mandatory) from the Household Energy End-use Project (HEEP) was considered for this comparison (BRANZ, 2016): on average, bedrooms in the two Passive Houses have temperatures that are 6^{o}C higher than the housing stock in winter (Figure 3).

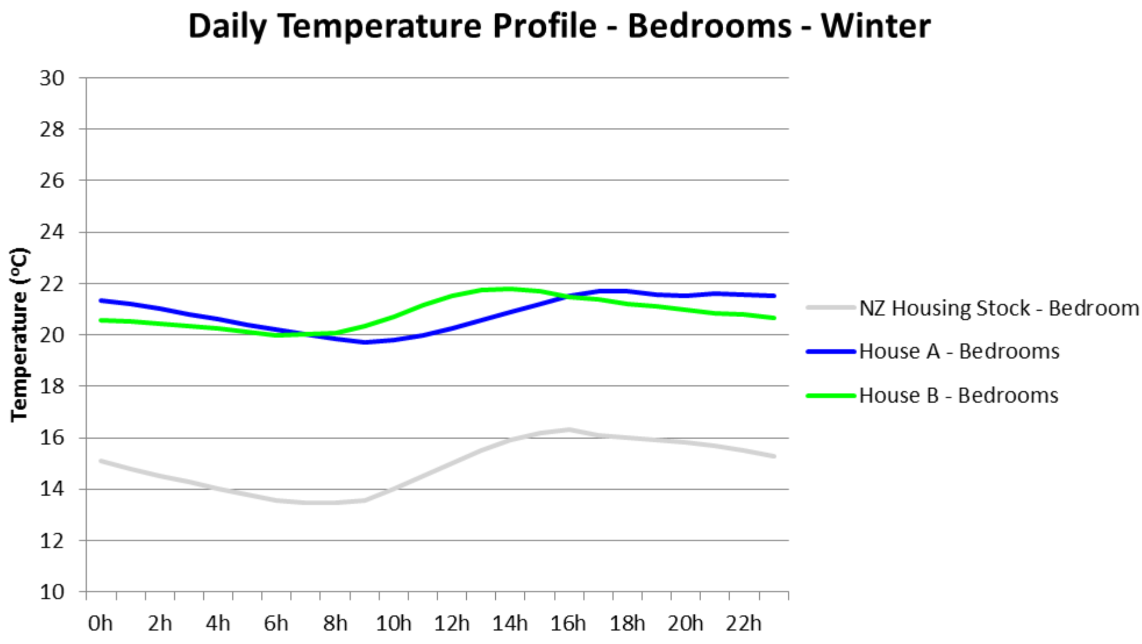

Figure 3 – Daily temperature profile for bedrooms in winter: comparison between House A, House B and average from NZ housing stock built after 1978 (BRANZ, 2016).

In order to provide a correlation with more recent code-complying dwellings, data collected for this study was also compared with results of a survey of fifteen free-running code-compliant houses built in New Zealand after the year 2000 (Rosemeier, 2014). A comparison of time-weighted temperature ranges is given in Figure 4, for bedrooms. It is clear that Passive Houses achieve significantly better indoor conditions. The percentage of temperatures below 21°C is predominant in code-compliant houses, while in the Passive Houses they occur for less than 35% of the time. Temperature readings below 16°C are very common in New Zealand homes, especially in bedrooms, as it is common to heat only the living room (Isaacs, et al., 2010). According to the World Health Organisation (WHO, 1987), 18°C is the minimum temperature recommended, and values below 16°C may trigger additional health symptoms. In the Passive Houses, no temperatures below 16°C were recorded, and only up to 1% of readings were below 18°C.

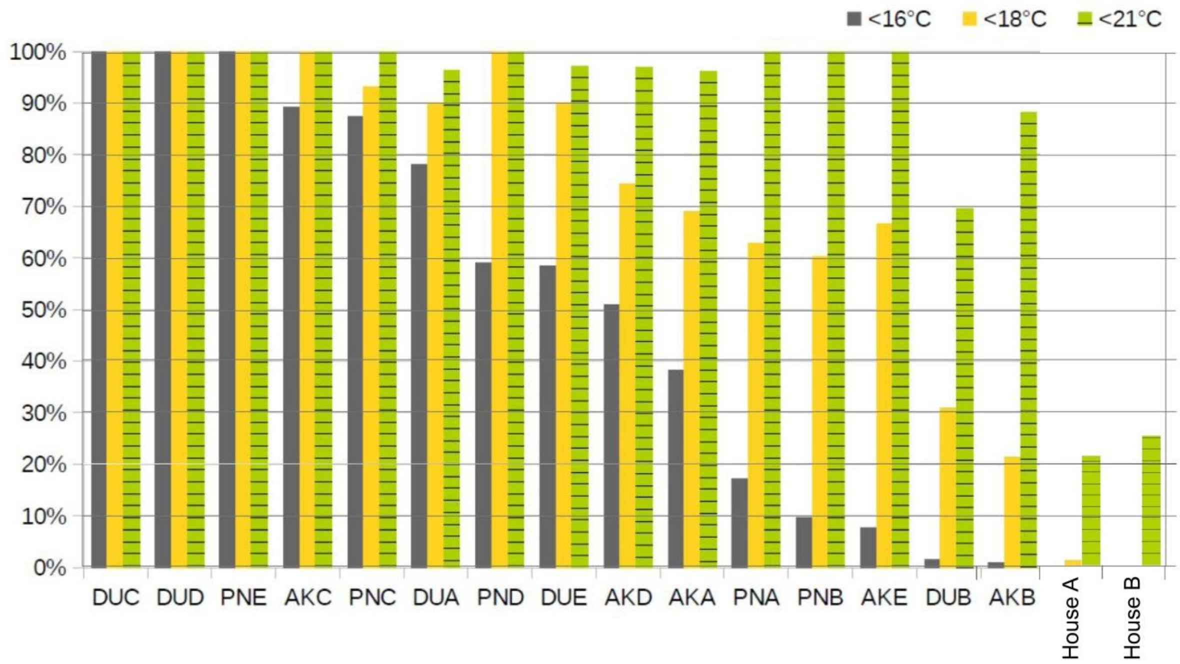

Figure 4 - Time-weighted temperature ranges for bedrooms: Comparison between 15 code-compliant houses (left) and two Passive Houses (right) (Graphic elaboration of the author based on Rosemeier, 2014)

The energy consumption measurements in both houses showed a significantly different total primary energy demand: 14,994 kWh for House A and 9,635 kWh for House B, mainly due to the difference in their floor areas. Indeed, when taking into consideration the treated floor area (TFA) of each house, a very similar rate per square metre was achieved: 69.4 kWh/m^{2}a in House A and 69.8 kWh/m^{2}a in House B. Table 2 provides the average annual electricity consumption per person for Auckland and Wellington according to the HEEP study (Isaacs, et al., 2010), compared to the measured values in the two Passive Houses divided by the number of occupants - four in House A and five in House B. Although New Zealand homes already have some of the lowest consumption in OECD countries (Schipper, L. et.al., 2000), the Passive Houses achieve even lower consumption than code-complying homes, while keeping optimum indoor conditions.

Table 2 – Annual electricity consumption per person: comparison between case studies and average values for each region based on HEEP (2010)*

	Auckland Region average (HEEP)	**House A**	**Wellington Region average (HEEP)**	**House B**
Annual electricity consumption per person (kWh/occupant/year)	2,390	1,575	2,610	1,007

*For the PH case studies, the total annual electricity consumption was divided by the number of occupants: four people in House A and five in House B. The values from HEEP are also divided by the number of people in each dwelling being monitored.

4. Conclusions

Interviews with occupants showed very satisfactory thermal comfort ratings for both case studies. Quantitative data was compared to the requirements of the Passive House Standard and to results of previous research about code-compliant houses in New Zealand. In both houses, temperature went beyond the Passive House limits for limited periods, yet their indoor comfort levels remain much higher than those recorded in New Zealand housing stock. House A had issues with overheating in summer, while House B was underheated in winter. Lack of adequate shading was the main cause of overheating in House A, while restricted use of active heating by the occupants caused the low temperatures in House B. Nonetheless, the occupants felt comfortable in these conditions in both case studies as confirmed by the interviews. Both dwellings have managed to maintain well-controlled indoor relative humidity, being the heat recovery ventilation system key for this result. In terms of energy, the consumption was significantly lower than the limit for Passive House certification, due to the limited use of active heating by the occupants. In addition, both houses generated energy on site by using solar-powered photovoltaic panels, which corresponded to 125% of the energy used in House A (positive energy) and 70% in House B.

Overall, post-occupancy data showed that Passive Houses achieve superior results in terms of energy and comfort when compared to New Zealand's housing stock. These results confirm that the standard delivers what it promises: low energy consumption and high levels of indoor comfort. However, the number of Passive Houses built in New Zealand remains very limited and the standard still faces scepticism in the country. The future challenge is no longer to confirm the performance of Passive Houses in New Zealand's context, but to investigate ways to make them more affordable and increase people's and developers' awareness of their benefits.

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