Australia's National Science Agency

Air Infiltration of New Dwellings in Australia

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Acknowledgement

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Finally, we would like to thank all the households in Australia that registered their interest in being involved in the project and a very special thank you to those households that were selected for testing and welcomed us into their homes and made the whole project possible! We hope that you found the experience enjoyable, interesting and informative.

Executive Summary

New dwellings in Australia are required to demonstrate compliance with the energy efficiency provisions of the National Construction Code (NCC) (Australian Building Codes Board, 2023) at the design stage. There are several compliance pathways that are available, but undertaking a NatHERS assessment is the most common. It is estimated that around 85% of new dwellings utilise this method (CSIRO, 2023). NatHERS modelling uses an assumed air tightness level, but concern has been raised with the increasing stringency of the NCC, there is a possibility that homes are being delivered with performance that falls short of modelled predictions. This project aimed to explore the actual air tightness being achieved of newly constructed dwellings, both houses and apartments, and then compare that to the assumed air tightness values that are utilised within the NatHERS modelling process.

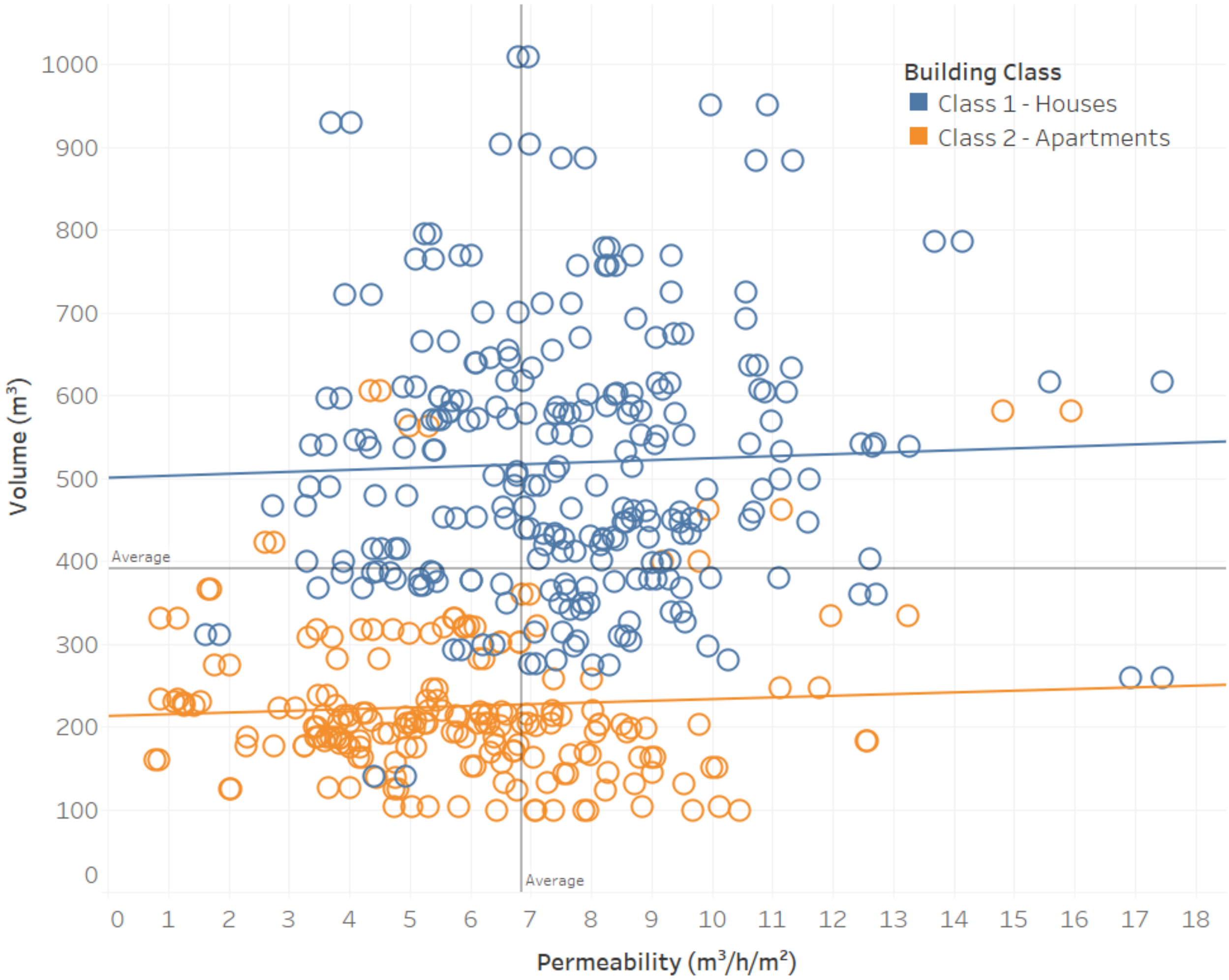
233 newly built dwellings were tested in Melbourne, Sydney, Brisbane, Canberra and Adelaide, comprising of 105 apartments and 128 detached houses. All dwellings had to have been constructed within the last four years, be “typical” builds and not have had air tightness as a specific design objective. Dwellings with high NatHERS star ratings were not excluded.

The Air Tightness Testing and Measurement Association (ATTMA) Australia was engaged to manage and undertake the required air tightness tests and all tests were undertaken in compliance with ATTMA Technical Standard L1 (TSL1) (ATTMA, 2021). Testers also completed a survey about the location of air leaks and details on the type of appliances and systems that were installed in each dwelling. For this study Air Permeability (qE_{50}) is the measurement that has been utilised. Air permeability is the amount of air leakage in a building in a given hour at 50 Pascals pressure divided by the internal envelope area of the building. Units are $m^3/h/m^2$ @ 50 Pa.

The table below lists the overall air permeability results for the various dwellings in various regions as well as the overall average results. Apartments recorded the lowest overall average qE_{50} of 5.8 $m^3/h/m^2$ with Queensland apartments recording the lowest of the regions with an average *qE50* of 4.3 $m^3/h/m^2$. Single storey houses had an average qE_{50} of 6.8 $m^3/h/m^2$ while two storey homes recorded the highest average qE_{50} of 8.5 $m^3/h/m^2$.

Dwelling Type	ACT	NSW	QLD	SA	VIC	All Regions
	Average Permeability ($m^3/h/m^2$ @ 50 Pa)					
Apartment	6.71	6.38	4.28	5.93	5.62	5.80
Single Storey House	5.42	6.35	6.61	7.65	6.30	6.77
Two Storey House	9.57	9.07	8.16	7.61	8.44	8.55
All Dwelling Types	7.20	7.31	5.85	7.40	6.57	6.86
	Minimum Permeability ($m^3/h/m^2$ @ 50 Pa)					
Apartment	3.49	1.77	0.86	4.34	0.79	0.79
Single Storey House	5.38	1.63	4.39	3.70	3.29	1.63
Two Storey House	8.18	2.74	5.50	4.38	4.34	2.74
	Maximum Permeability ($m^3/h/m^2$ @ 50 Pa)					
Apartment	11.16	13.25	10.45	7.98	15.94	15.94
Single Storey House	5.45	12.61	10.68	10.98	11.31	12.61
Two Storey House	11.11	14.15	12.73	11.33	17.46	17.46

It was expected that as dwellings got larger their permeability would most likely increase and so apartments would be tighter than detached houses and that two storey houses would be leakier than single storey houses. However, as the chart below shows, a correlation between permeability and building size was not actually evident in our data.



The overall results achieved show a marked improvement in the air tightness of newly constructed dwellings in Australia. A previous CSIRO study undertaken in 2015 tested 129 newly constructed dwellings and returned an average air change rate of 15.4 Air Changes per Hour (ACH) @ 50Pa (Ambrose and Syme, 2015). For this project a target qE_{50} of 10 $m^3/h/m^2$ was selected. This is the threshold cited in NCC 2022 V2H6V3 as the performance requirement for dwellings seeking compliance through the performance provisions of the building code. Using the average permeability of each dwelling, this target was exceeded by only 9.7% of dwellings (11.7% of Class 1 and 7.1% of Class 2).

Analysis was undertaken between the assumed air tightness level that NatHERS calculates and the actual air tightness that was measured. Overall, this analysis showed that the assumed air tightness values correlate well with the actual measured permeability of the built dwelling, particularly with Class 1 dwellings, with an average difference of only 0.01 $m^3/h/m^2$ between them. For apartments the measured (as-built) air permeability was lower than the assumed (as designed) air change rate for all apartments. On average the difference was 2.17 $m^3/h/m^2$. In most cases the assumed value was slightly more conservative than the measured value which gives assurance that NataHERS is not underestimating air tightness.

The post-test survey identified multiple leakage points in most dwellings. Bathroom fans were identified as one of the major leakage points in both apartments and houses. These were identified 56 times in apartments and 81 times in houses and 63% of apartments and houses had bath fans identified as a leakage point. The most reported leakage point for apartments (59 reports) was sliding glass doors and 63% of apartments had these as an issue. Sliding doors were also a major issue in houses, recorded 63 times in 48% of houses. For houses their most reported issue was poor or missing door seals. This was reported 84 times in 65% of houses.

Often simple solutions could be found to rectify these leaks. Various penetrations through walls were a common issue that could easily be resolved through gap sealants being used while more structural related causes need to be addressed at the time of construction.

1 Background

New dwellings in Australia are required to demonstrate compliance with the energy efficiency provisions of the National Construction Code (NCC) (Australian Building Codes Board, 2023) at the design stage. There are several compliance pathways that are available, but undertaking a NatHERS assessment is the most common. It is estimated that around 85% of new dwellings utilise this method (CSIRO, 2023). A NatHERS assessment involves modelling the proposed building through an approved tool that models the thermal performance of the design. A range of inputs are required to meet the NCC regulatory requirements for a NatHERS assessment, including building materials, location, building areas, shading and exposure. In addition to these inputs a range of assumptions are also utilised as part of the modelling process, that are not part of the NCC regulatory requirements for a NatHERS assessment. One such assumption is the expected air tightness of the dwelling.

There will frequently be a difference between modelled and as-built results for building air tightness. This may be due to a range of factors including design issues, build quality and material selection. The difference between the actual and modelled air tightness may be a negative or positive value. That is, the actual air tightness may be tighter than modelled or it may be leakier than modelled. In the case where air tightness is leakier than modelled, energy performance may be worse than expected. In the case where as-built air tightness is tighter than modelled, then additional energy savings may not be reflected in the modelling results. Improving the agreement between modelled performance and as-built conditions will help to both address a problem and seize an opportunity.

According to CSIRO (Dong Chen communication 2020), typical inputs in NatHERS assessments represent performance that would be expected from a home built to 6 or 7 ACH50. (Note for this conversation, ACH50 ($m^3/h/m^3$) and permeability in $m^3/h/m^2$ are used interchangeably). The threshold cited in NCC 2022 V2H6V3 is a permeability of 10.0 $m^3/h/m^2$ @ 50Pa (Australian Building Codes Board, 2023). A previous CSIRO study has demonstrated that it is common to see as-built tests of air leakage much higher than this – even as high at 30 or more ACH50. In fact, more than 60 percent of results in that study were greater than 10 ACH50 (Ambrose and Syme, 2015).

Concern has been raised then when increasing mandatory stringency of the NCC, there is a possibility that homes are being delivered with performance that falls short of modelled predictions. In some cases, performance can be as much as one or two stars worse than predicted due to excess air infiltration alone. The opportunity to realise real-world savings in energy use and occupant comfort by including air tightness in compliance can be significant. A US study on the energy impacts of envelope tightening estimated that an typical house in California that undertook average tightening measures would reduce their energy use by 500kWh/year (Logue et al., 2013). In Australia, this would translate to a 7% reduction in annual energy use. Another study by Lawrence Berkeley Labs found for new Californian homes to meet California's zero net energy requirements, air leakage rates will need to be halved, from roughly 4 ACH50 to 2 ACH50 or less. This represents a 15% energy saving compared to conventional new homes (Lawrence Berkeley National Laboratory, 2024).

Nevertheless, studies also find that builders in Australia regularly demonstrate the ability to deliver homes with world-class air tightness. Results from ATTMA Australia's Lodgement database demonstrate this as well as results from the 2015 CSIRO study that found more than 30 percent of the homes tested at 10 ACH50 or less, and more than 6 percent were less than 5 ACH50.

There is a limit to how well this better air tightness can be represented in a NatHERS assessment using current software. This means that as a savings strategy along with insulation, glazing, orientation and others, air infiltration may be underrepresented. As a result, other less cost-effective savings strategies may be used to meet a required star rating. There is an opportunity to remove this constraint on the market, and foster innovation and competition among market leaders. This study aims to determine the typical air tightness that is being achieved with newly built dwellings, both houses and apartments and identify areas that could be improved to achieve even better air tightness performance.

2 Project Objectives

The primary aim of the project was to explore the actual air tightness being achieved of newly constructed dwellings, both houses and apartments, and then compare that to the assumed air tightness values that are utilised within the NatHERS modelling process. The project also aimed to identify where the leakage points were within each dwelling based on what the blower door tester discovered during the test. In addition, a series of additional tests were conducted to determine leakage rates of specific building elements. This included entry doors of apartments, ceiling exhaust fans in bathrooms and laundries and heating/cooling ductwork.

3 Methodology

A selection of newly built Class 1 (house) and Class 2 (apartment) dwellings were tested in 5 state and territory capital cities and their surrounding regional areas of Melbourne, Sydney, Brisbane, Canberra and Adelaide. 205 dwellings were tested in total.

3.1 Recruitment

The initial aim for the recruitment of dwellings was to have around 90 apartments and 115 detached houses spread equally across the four regions (NSW and ACT being regarded as one region). A variety of recruitment strategies were undertaken including approaching developers of new estates to invite residents within their estates to participate. This approach was very effective for recruiting residents in detached houses but was ineffective for apartment residents. Consequently, an alternative strategy was developed for recruitment of apartment residents with a targeted Facebook advertising campaign designed and deployed. This approach was highly successful and resulted in an over subscription of interested households from both apartment residents and detached house residents. Expressions of interest were lodged through a dedicated webpage that provided additional information and collected the necessary privacy and consent information. In total 570 expressions of interest were received for participating in the project.

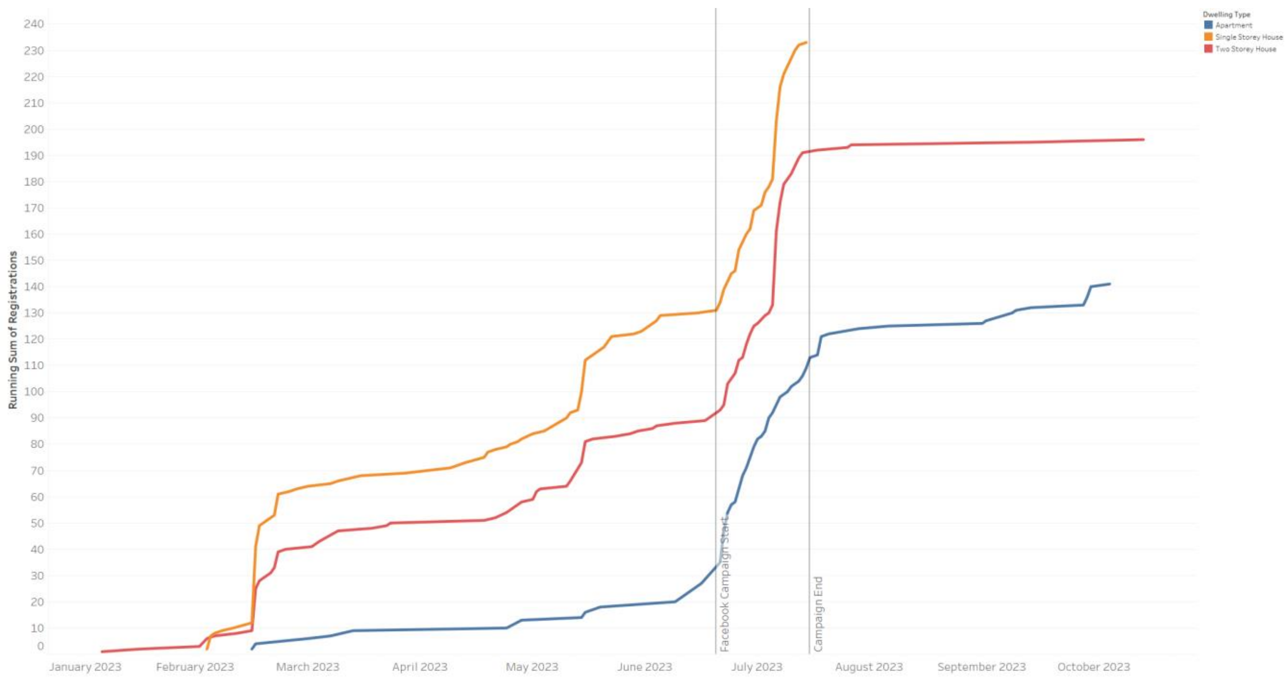


Figure 1 Recruitment timeline.

3.2 Selection criteria

The primary aim of the project was to determine actual air tightness levels in a typical, newly built dwelling. Consequently, there were some mandatory requirements that dwellings had to meet including that each dwelling had to be:

- within the project catchment area.
- less than 4 years old (built in the year 2020 and onwards).
- a totally new build – no extensions and/or renovations to existing dwellings.
- a “typical” build. Homes using alternative building techniques, such as straw bale for example, were excluded, and

- air tightness was not a specific design objective.

Homes with high NatHERS ratings (considered higher than 7.5 stars) were included. This was to meet one of the analysis objectives, to determine whether a correlation existed between higher star rated homes and air tightness levels.

Homes that met all the mandatory requirements were then contacted and invited to participate in the project and provide additional information, such as building plans (if available). Building plans were utilised to confirm the mandatory requirements and to calculate input parameters for the testing process.

3.3 Testing protocol

The Air Tightness Testing and Measurement Association (ATTMA) Australia was engaged to manage and undertake the required air tightness tests utilising its tester members. ATTMA assessors are independently audited and certified, with a scope covering air tightness testing to the ATTMA Technical Standards. All tests were undertaken in compliance with ATTMA Technical Standard L1 (TSL1) (ATTMA, 2021) which is fundamentally based on ISO Standard 9972:2015 (Thermal Performance of Buildings - Determination of air permeability of buildings - Fan pressurization method) (ISO, 2015). This Technical Standard provides detailed guidance and clarification of ISO 9972:2015 to ensure consistency by testing companies.

Tests were conducted in both positive and negative direction according to ISO 9972:2015 Method 1 Building in use. Building preparation included turning off HVAC systems, closing exterior doors and windows, opening interior doors and windows, closing any closable vents, and generally leaving other openings closed but not sealed. An example was bath fans which were turned off before the test but not sealed.

There was a consideration of whether systems like bath fans or evaporative coolers would be fairly represented by testing in either positive or negative direction if left unsealed before testing. These appliances may have a damper the closes in one direction and opens in another, meaning that measured leakage may be more in one direction than the other. Many appliances simply did not have any dampers, removing this concern.

For those devices that did have dampers, some test lab measurements were made with a small rig on a bath fan with no ductwork attached downstream. Measured leakage in positive direction was similar to leakage in negative direction, even though the fan had an integrated damper. A reason for this is the relatively low test pressure of 50 Pascals which is lower than the design pressure drop across the fan, as well as resistance caused by the fan itself. In a real installation, fans should also have ductwork to carry the airflow out of the building envelope. This adds further resistance that reduces flow in either test direction. The testing showed a small difference in airflow between test directions.

Consultation was sought from experts at Lawrence Berkeley National Labs in the U.S. who have conducted similar large-scale studies of housing air tightness. Though the potential for some difference in performance according to test direction was likely, it was found to be negligible and therefore acknowledged and ignored. We took a similar approach. Test results were lodged through the ATTMA lodgement portal where quality checks were undertaken by ATTMA to ensure compliance with the technical standard.

3.4 Assessment survey

On completion of each test the assessor was required to complete an online assessment survey that captured data about the location of air leaks and details on the type of appliances and systems that were installed in each home.

3.5 Comparison study

Where the original NatHERS project file was available for the dwellings tested, a comparison and analysis was undertaken between ISO 9972:2015, which is the standard the ABCB refers to in H6V3 when measuring air permeability, and the current calculation method used in Chenath V3.21. 21 dwellings that were tested had their NatHERS project file available to run this comparison.

3.6 Additional tests

A series of additional tests were undertaken to determine the leakage rates of specific building elements. This included:

- Apartment doors – Entry doors to apartment in three apartment buildings with shared interior corridors were tested for leakage rates to and from the common corridor.
- Exhaust fan ventilation – Exhaust fans in 50 dwellings were tested to determine the ventilation rates they were achieving in different operating modes.
- Duct leakage – A range of heating/cooling ducted systems were tested in 10 dwellings to determine leakage rates from these ducted systems.
- Leakage point measurements – 8 dwellings had a range of specific leakage points measured to determine their contribution to the overall permeability rate of the dwelling.

4 Dwelling testing

4.1 Selected dwellings

The initial aim for the makeup of the dwellings to be tested was an even split between the various regions. The initial regions were Victoria, NSW and Southeast Queensland. However strong interest from households in the ACT allowed us to include ACT dwellings as part of the NSW cohort. South Australia was also not initially to be included, but an expansion of the project scope and timeline allowed South Australian dwellings to also be added to the pool. The inclusion of apartments in all the regions was also a critical aspect. Apartments had not been part of the 2015 CSIRO air tightness study. The aim was to have apartments make up around 40% of the total dwellings tested. The project funding allowed for 205 dwellings in total, but air tightness results from an additional 28 dwellings (mainly apartments) were made available to the project at no cost. These dwellings met the selection criteria and had been tested to the same protocol as the funded dwellings, so have been included in the air tightness analysis. These additional dwellings did not have surveys undertaken, so are excluded from the survey analysis. Table 1 lists the final makeup of dwellings tested. The overall split between apartments and detached housing was 45:55 which was close to the 40% apartment target. However, the split was not consistent across the regions. The ACT dwellings were dominated by apartments, while South Australia was dominated by detached housing.

Table 1 Dwellings tested

State	Apartment	Single Storey House	Two Storey House	Grand Total
ACT	15	1	4	20
NSW	27	14	22	63
QLD	24	10	8	42
SA	5	20	11	36
VIC	34	18	20	72
Grand Total	105	63	65	233

The differences in the split between apartments and detached housing in each region is to be expected given the actual split between class types in each region. Figure 2 shows the split in building classes in each region for all NatHERS certificates issued for the last four years. Only in NSW do apartments constitute most new dwellings (55%), while in South Australia apartments represent only 8% of new dwellings (CSIRO, 2024a). This means that apartments are overrepresented in our testing cohort in all regions, except NSW.

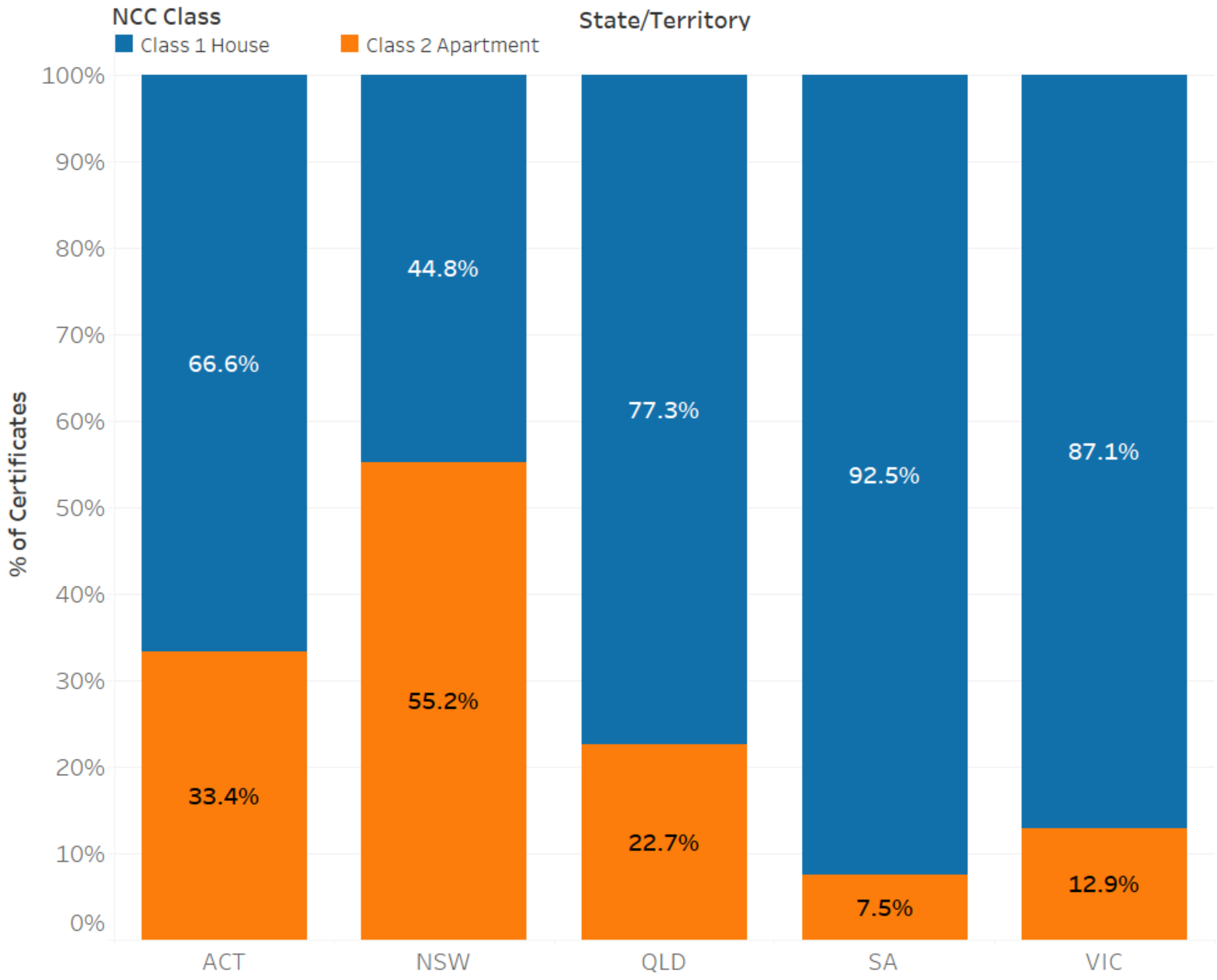
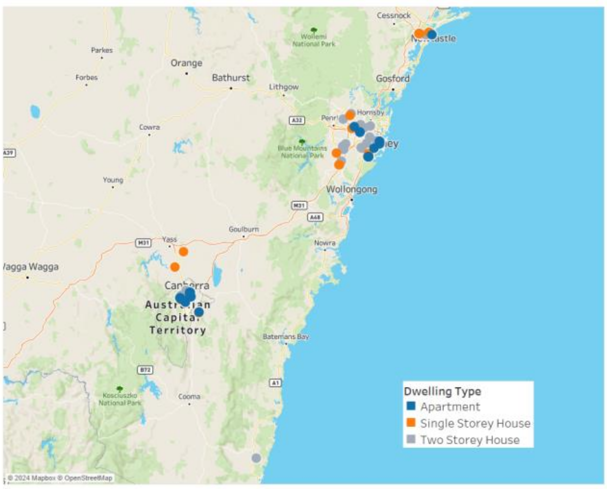
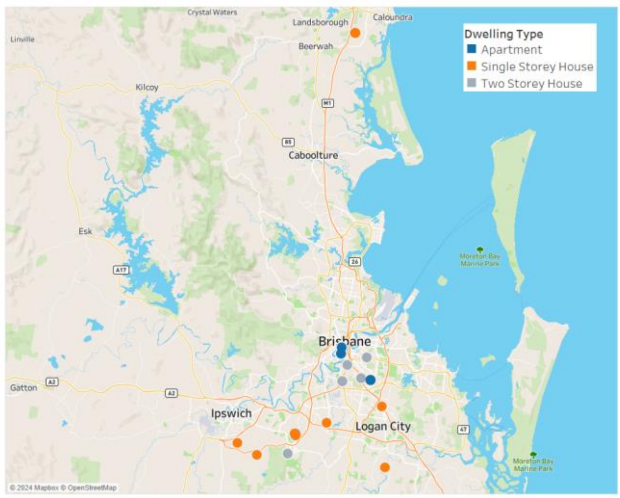


Figure 2 New dwelling certificates by class and region

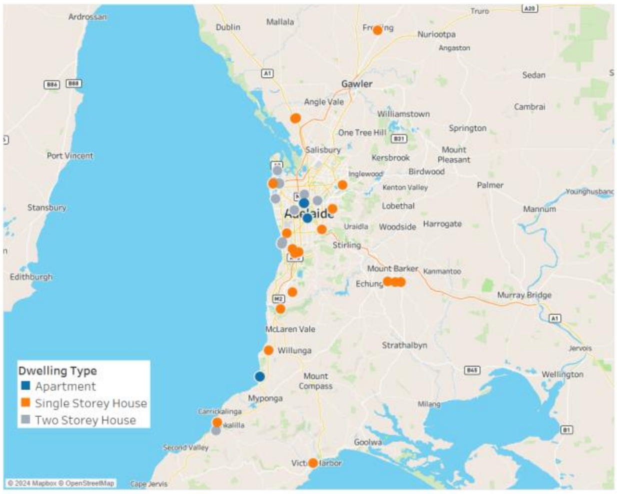
Figure 3 shows that most dwellings were in the major urban areas within each region, with apartments tending to be in the central and inner suburb areas of the capital cities. However, there was regional representation of class 1 dwellings in each region.



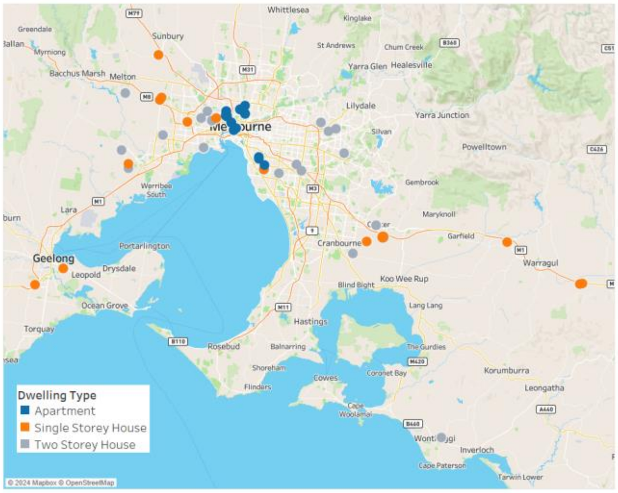
ACT and NSW



Queensland



South Australia



Victoria

Figure 3 Maps of dwelling locations by region

Where known, the NatHERS star rating of the dwelling was recorded. Specific air tightness is not a factor that is considered in the regulatory star rating assessment, however an assumed air tightness value has been calculated in the back end of modelling software since 2006 and more recently displayed in the user interface in some software in non-regulatory mode. Star ratings were verified for 40% of the dwellings tested. Figure 4 shows the distribution of the star ratings within each dwelling type. Around 60% of detached houses rated within the 6.0 to 6.5 star range. This correlates well with the general Class 1 star rating profile where 55% fall within this range for dwellings built since the introduction of NCC 2019, based on analysis from the Australian Housing Data portal (CSIRO, 2024b).

Apartments generally have a broader distribution of star ratings due to use of the averaging of star ratings for apartment developments. According to NCC 2019 requirements an apartment development must achieve an average rating of 6 stars, with individual apartments rating at least 5 stars. Correspondingly the star rating distribution of the apartments in this study achieved a similar star rating distribution. Generally, Class 2 apartments tend to achieve higher star ratings than detached Class 1 dwellings. 57% of the apartments in this study rated at or above 7 stars, compared to only 11% of class 1 dwellings. Again, this correlates well with the general star ratings achieved for new dwellings in the NCC 2019 regulatory period where 12% and 39% rate at or above 7 stars and for Class 1 and Class 2 dwellings respectively (CSIRO, 2024a).

Overall, the dwellings recruited and tested for this study are considered a good representation of typical new dwellings being constructed across Australia.

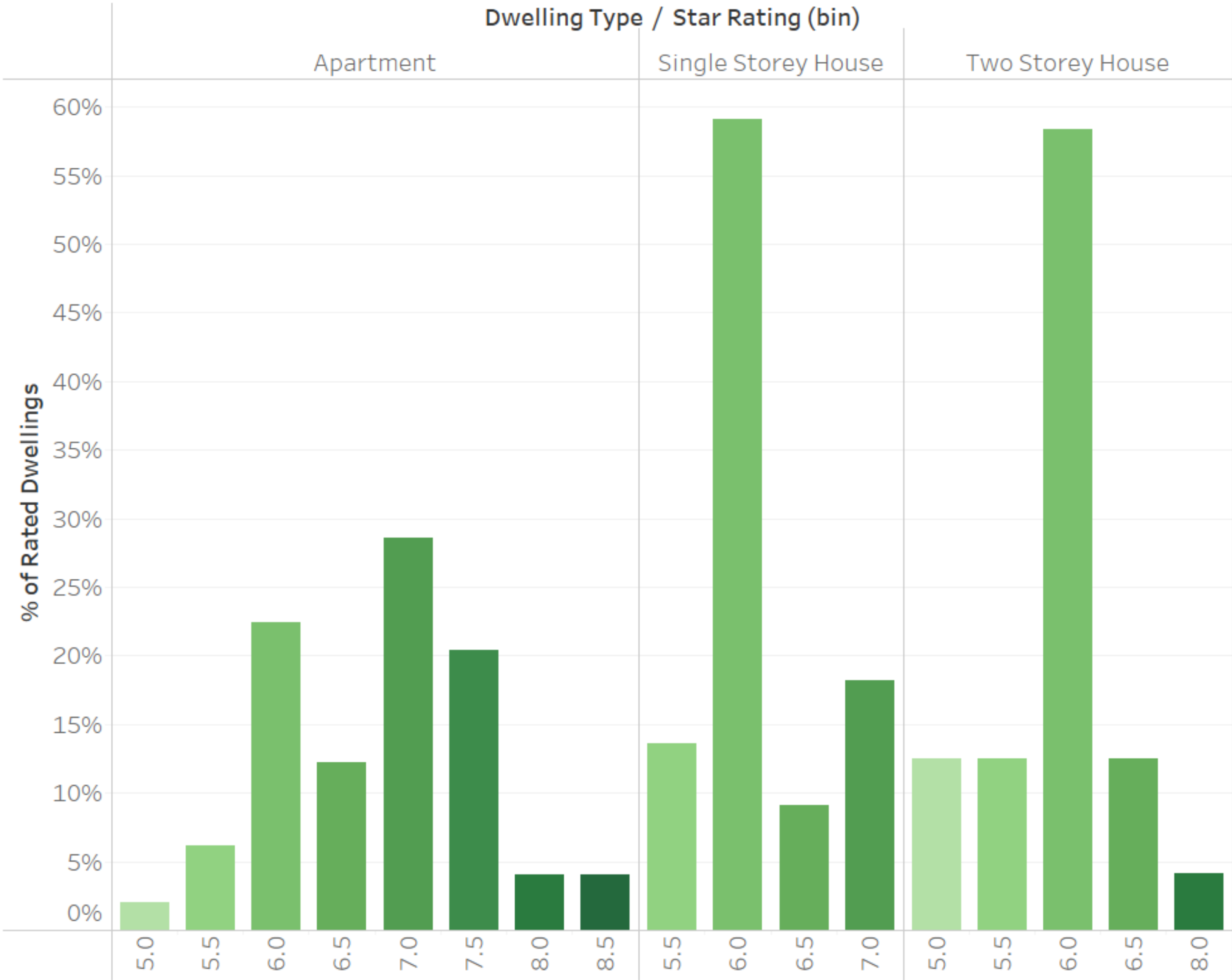


Figure 4 Star rating distribution by dwelling type

4.2 Air tightness testing process

The primary reason for undertaking an air tightness test is to measure the amount of air that is entering and/or exiting a building through uncontrolled air movement, such as through gaps or cracks in floors or walls or at window or door junctions. This is especially important where the internal air is conditioned (heated or cooled) as increasing levels of uncontrolled air infiltration will increase the energy required to maintain the internal conditions. Increased air leakage can also lead to an increase in external dust, pollen and pollutant levels within the internal environment which can have detrimental health impacts on occupants. Conversely, inadequate ventilation rates can cause poor internal air quality which can also have detrimental health impacts. Consequently, a combination of envelope air tightness and controlled ventilation is critical in maintaining healthy internal environments and lowering energy consumption for space conditioning.

Air tightness is measured using a calibrated fan that is temporarily installed into the external envelope of the dwelling, usually via an external doorway as shown in Figure 5. The fan then supplies air into or extracts air out of the dwelling creating a series of controlled building pressure differentials. Using calibrated equipment, the tester measures then calculates the air flow into or out of the dwelling thus determining the air leakage rate for the dwelling. Results can be presented in several ways, most commonly at a reference pressure of 50 Pascals:

1. **Air Leakage**, known as 'Q_{pr}', is the amount of air entering or existing the building at a given pressure per hour. Q_{50} is used to denote the air leakage at a building pressure of 50 Pa. Units are m^3/h @ 50 Pa.
2. **Air Permeability**, known as 'qE_{50}', is the amount of air leakage divided by the internal envelope area of the building. qE_{50} is used to denote the air permeability at a building pressure differential of 50 Pa. Units are $m^3/h/m^2$ @ 50 Pa.
3. **Air Changes per Hour**, known as 'N_{pr}', is the amount of air leakage divided by the internal volume of the building. N_{50} is used to denote the air changes per hour at a building pressure differential of 50 Pa. Units are $m^3/h/m^3$ @ 50 Pa (ATTMA, 2021).

The standard metric cited by the 2022 NCC is surface permeability in $m^3/h.m^2$ @ 50 Pascals according to AS/NZS ISO 9972:2015 (ISO, 2015). This metric was chosen because it is more evenly applied to buildings of different size and shape, while other metrics such as the volume-derived air changes per hour (*n50*) lose applicability to very large or very small buildings. It is the metric most broadly used in building codes and standards abroad.

Consequently, for more direct applicability to Australian regulation and the NCC, Air Permeability (qE_{50}) is the measurement that has been utilised for this study. All tests were undertaken by ATTMA registered and qualified testers following the ATTMA Technical Standard TSL1, which is based on ISO 9972. All dwellings had both a pressurisation (positive pressure/air in) test and a depressurisation (negative pressure/air out) test.

Figure 5 Typical air tightness setup

5 Air permeability results

Table 2 lists the air permeability results for the various dwelling types within each region. Averages have been calculated for each dwelling type by each region as well as for the overall data set. Apartments recorded the lowest overall average qE_{50} of 5.8 $m^3/h/m^2$ with Queensland apartments recording the lowest of the regions with an average qE_{50} of 4.3 $m^3/h/m^2$. Single storey houses had an average qE_{50} of 6.8 $m^3/h/m^2$ while two storey homes recorded the highest average qE_{50} of 8.5 $m^3/h/m^2$. It is interesting to note that houses in the ACT recorded both the lowest average for a single storey house (qE_{50} of 5.4 $m^3/h/m^2$) and the highest average qE_{50} of 9.6 $m^3/h/m^2$ for two storey houses, although it should also be noted that the total number of houses in the ACT was small, see Table 1.

Table 3 lists the average volume for each dwelling type in each region and as expected apartments have the smallest volume, followed by single storey houses. Double storey houses have the highest volume**.** The only exception is the ACT where the single storey house has an average greater than that for the double storey, but again the very small number of dwellings in these categories in the ACT means caution is required in drawing conclusions from those results.

Table 2 Average, minimum and maximum permeability by dwelling type and region

Dwelling Type	ACT	NSW	QLD	SA	VIC	All Regions
	Average Permeability ($m^3/h/m^2$ @ 50 Pa)					
Apartment	6.71	6.38	4.28	5.93	5.62	5.80
Single Storey House	5.42	6.35	6.61	7.65	6.30	6.77
Two Storey House	9.57	9.07	8.16	7.61	8.44	8.55
All Dwelling Types	7.20	7.31	5.85	7.40	6.57	6.86
	Minimum Permeability ($m^3/h/m^2$ @ 50 Pa)					
Apartment	3.49	1.77	0.86	4.34	0.79	0.79
Single Storey House	5.38	1.63	4.39	3.70	3.29	1.63
Two Storey House	8.18	2.74	5.50	4.38	4.34	2.74
	Maximum Permeability ($m^3/h/m^2$ @ 50 Pa)					
Apartment	11.16	13.25	10.45	7.98	15.94	15.94
Single Storey House	5.45	12.61	10.68	10.98	11.31	12.61
Two Storey House	11.11	14.15	12.73	11.33	17.46	17.46

Table 3 Average volume by dwelling type (m^3)

Region	Apartment	Single Storey House	Two Storey House
Australian Capital Territory	219.0	570.9	491.5
New South Wales	237.5	460.6	567.7
Queensland	195.6	323.9	585.3
South Australia	333.9	473.3	569.4
Victoria	208.6	511.0	563.8
All	222.8	459.1	564.3

It was expected that as dwelling volumes got larger that air permeability results would increase as the greater volumetric area allows for greater opportunities for air leakage points. It was therefore expected that apartments would have lower air permeability results (be tighter) than detached houses and two storey houses would have higher air permeability results (be leakier) than single storey houses. The tightest dwelling tested was an apartment in Victoria that returned an qE_{50} of 0.79 $m^3/h/m^2$, while the leakiest was a two-storey dwelling also in Victoria that returned an qE_{50} of 17.46 $m^3/h/m^2$. In the ACT, Queensland and Victoria the tightest dwelling tested was an apartment while in all regions, except the ACT, the leakiest was a two-storey dwelling. The linkage between building size and permeability also appears to be reflected in the minimum and maximum air permeability values that were recorded.

However, closer examination of the results obtained show that a correlation between air permeability and building size was not actually present. Figure 6 shows the plot of dwelling volume to their two air permeability tests. A linear trend has also been plotted for both dwelling classes. Although the overall trend was positive the R-squared value is below 0.1 for both, meaning that no correlation exists. This result was surprising and unexpected. The results suggest that the variability we see in air permeability rates is due to factors unrelated to the size of the dwelling. This might suggest build quality issues or the way penetrations in the building envelope are dealt with that can affect the air tightness of a dwelling rather than volume. Penetrations can include light fittings, power outlets, exhaust fans and ductwork for air conditioning systems.

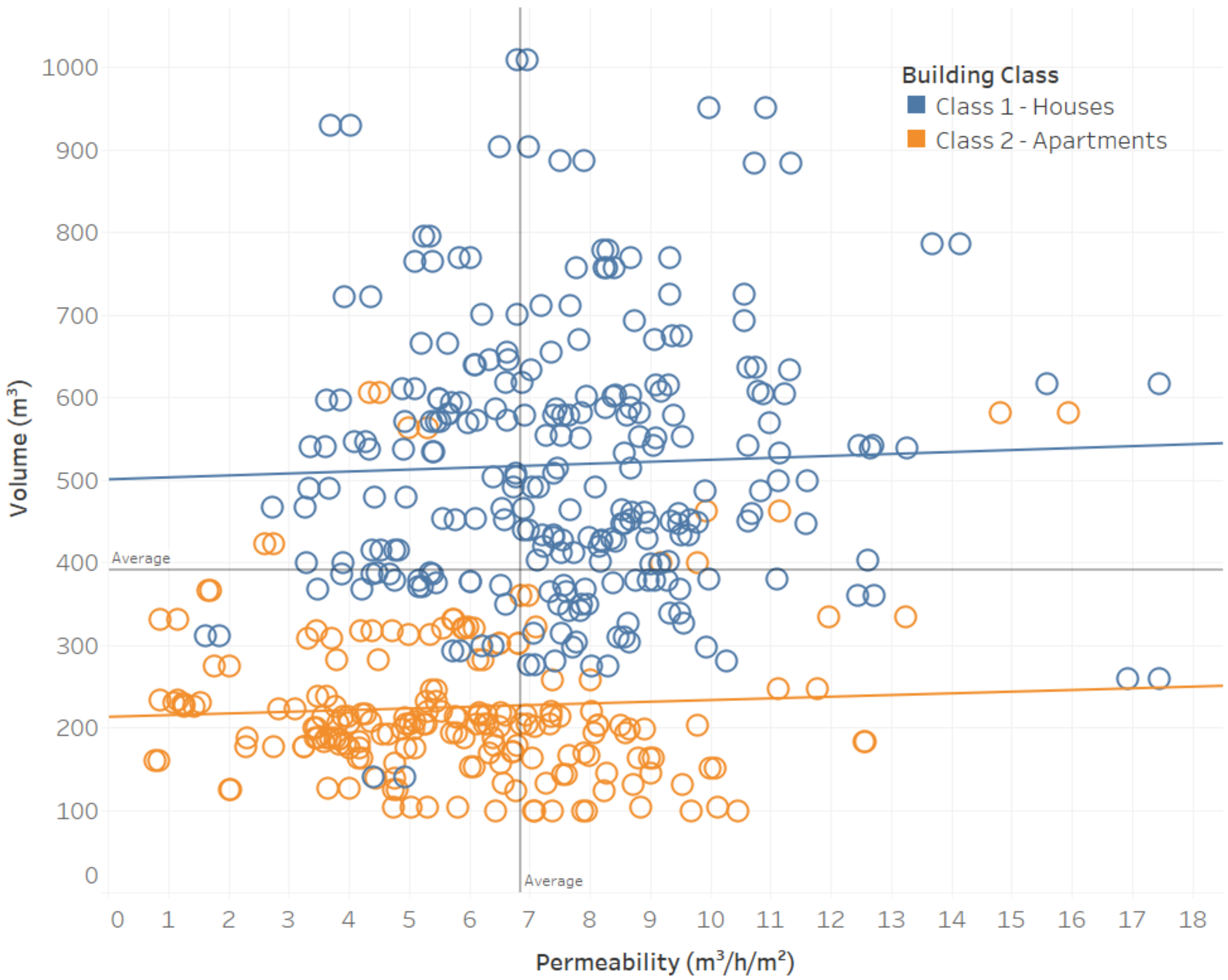


Figure 6 Permeability to dwelling volume

Overall, the results achieved show a marked improvement in the air tightness of newly constructed residential dwellings in Australia. A previous CSIRO study undertaken in 2015 tested 129 Class 1 dwellings up to 10 years old and assumed to be between a 4 and 6 star rating, to the same ATTMA standard used in this study. The 2015 study returned an average air change rate of 15.4 ACH @ 50Pa (Ambrose and Syme, 2015) whereas Table 2 shows that this study has returned an overall average air permeability of 6.86 $m^3/h/m^2$. Noting the 2015 study had results in air changes per hour (N_{pr}) and this study used permeability (qE_{50}), the two measurements are generally considered comparable. Figure 7 plots all results and shows that only 5 results (1.1%) exceed the average that was recorded in the 2015 study.

For this project a target qE_{50} of 10 $m^3/h/m^2$ was selected. This is the threshold cited in NCC 2022 V2H6V3 as the performance requirement for dwellings seeking compliance through the performance provisions of the building code. Using the average permeability of each dwelling, this target was exceeded by only 9.7% of dwellings (11.7% of Class 1 and 7.1% of Class 2). Considering that most dwellings in Australia use the NatHERS provisions in the NCC, rather than the performance provisions, as the compliance pathway, it is encouraging that 90.3% of dwellings achieved the performance requirement. This demonstrates that the current performance requirement is achievable for NatHERS assessments and allows scope for future tightening of this requirement.

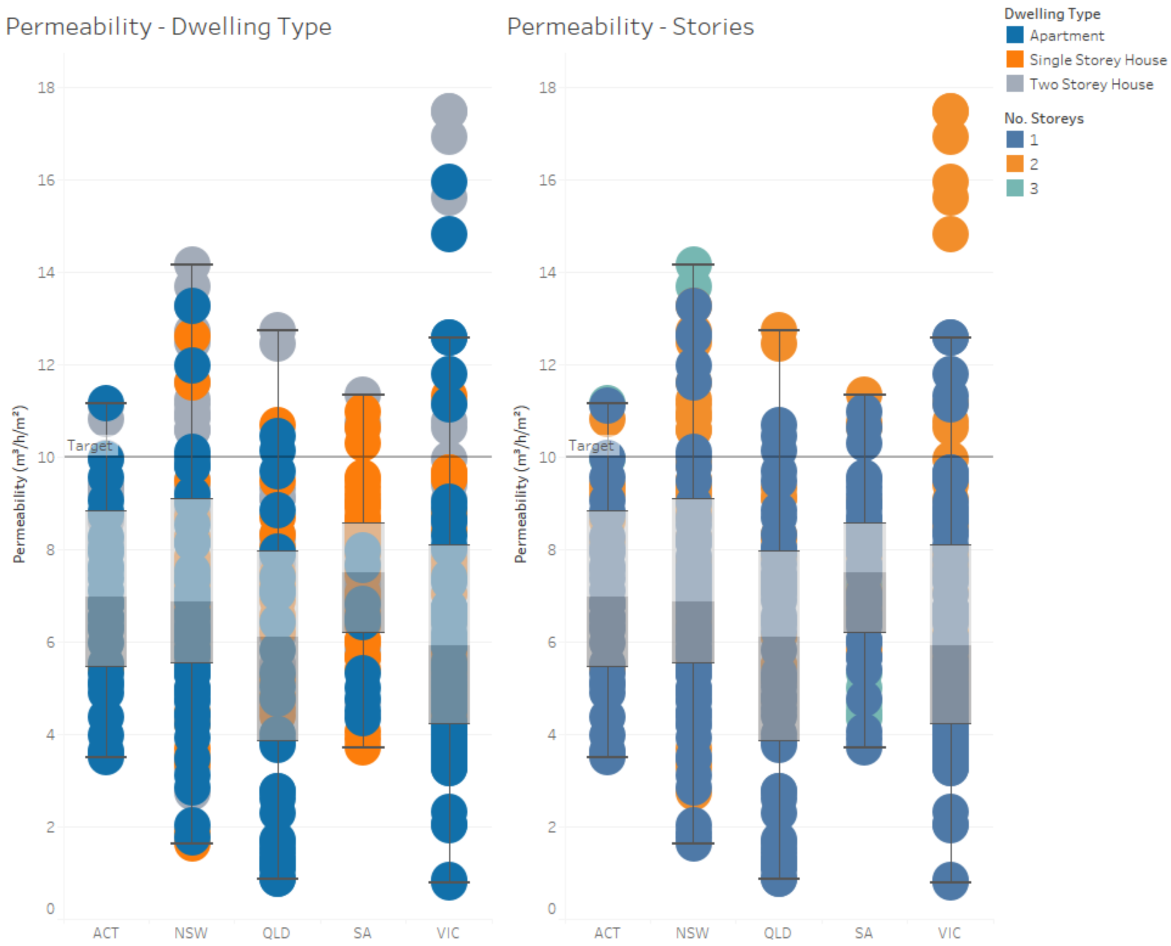


Figure 7 Permeability results for all dwellings by region

These results also compare well to air tightness standards required in other countries. For example, the UK has recently increased its air tightness requirements for new dwellings from a maximum permeability of 10 $m^3/h/m^2$ to 8 $m^3/h/m^2$ (HM Government, 2021). 66.5% of dwellings in this study achieved this target (53.9% of Class 1 and 82.7% of Class 2).

Of concern though was approximately 26% of dwellings in the study were tested below a permeability of 5 $m^3/h/m^2$ @ 50 Pascals (15.6% of Class 1 and 39.1% of Class 2). The NCC currently requires application of continuous mechanical ventilation when below this threshold. However, because these homes were not aware of, or aiming for a specific permeability rate, no testing was done and consequently, no continuous ventilation was installed. Such low permeability rates can lead to problems with condensation and moisture build up when no controlled ventilation system is installed. This in turn can lead to mould and other health issues. The presence of mould can also have structural consequences for the building through the rotting of structural timbers.

The NatHERS star ratings reflect the thermal performance of the building envelope. To achieve a high star rating (out of a possible 10 stars) a dwelling will usually need to have high levels of thermal insulation, good solar orientation and high performing glazing. Although air tightness is currently not specifically included in the star rating assessment, the inclusion of additional insulation materials and high-quality glazing units suggested that a correlation between star rating and air permeability might exist. In addition, the building of very high star rated homes (8 stars or more) would usually indicate that energy efficiency was a design objective, and that air tightness would form part of the overall design solution, even though its inclusion would not impact the star rating.

Figure 8 shows the plot of air permeability to NatHERS rating as well as the trend lines for the two building classes. It demonstrates that no correlation exists between the star rating and the air permeability being achieved. Although the class 1 trend line does trend in the expected direction, that is, as star ratings increase the air permeability decreases, the R-squared is below 0.1. For class 2 dwellings the trend line is virtually flat. Indeed, the highest star rated dwelling was an apartment that rated at 8.9 stars and it returned an average qE_{50} of 9.1 $m^3/h/m^2$ which is above the overall apartment average of 5.8 $m^3/h/m^2$ and also above the average qE_{50} of 6.9 $m^3/h/m^2$ that was achieved for all the dwellings that the study found star ratings for. The dwelling with the lowest qE_{50} of 0.8 $m^3/h/m^2$ was an apartment that achieved a star rating of 7.3 stars.

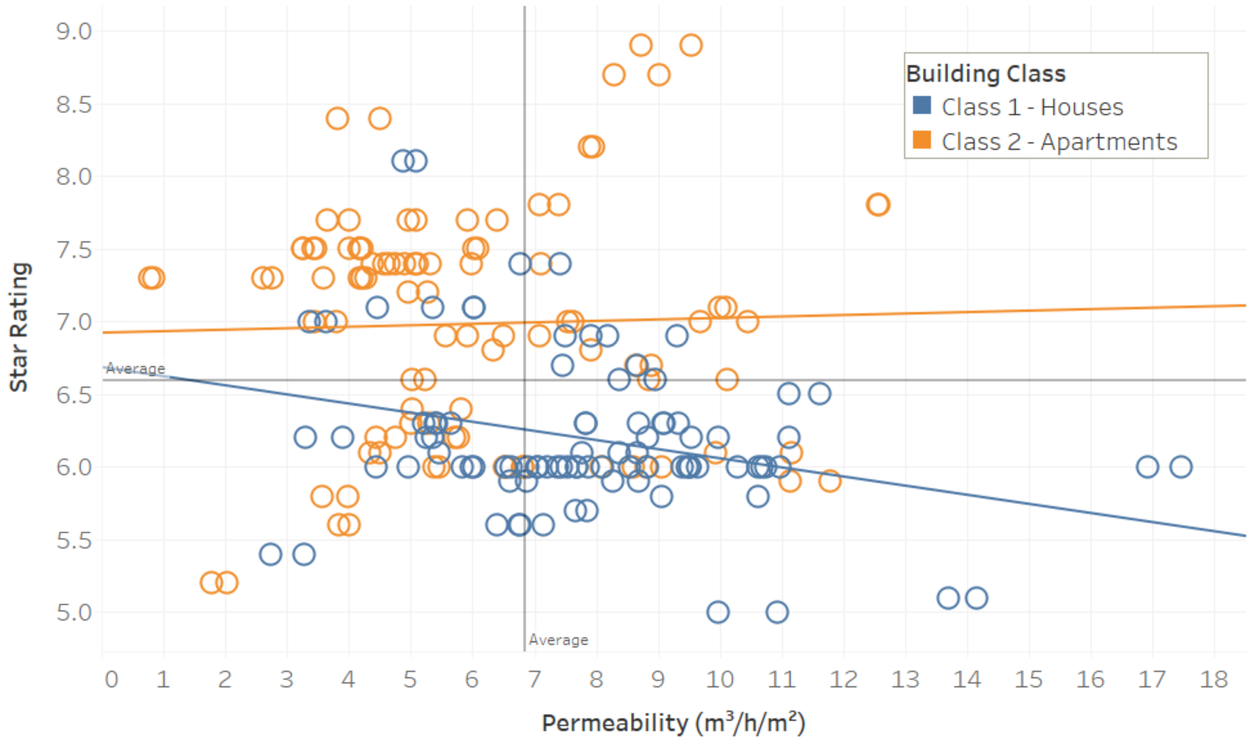


Figure 8 Permeability to star rating

5.1 Actual air tightness to modelled air tightness

NatHERS modelling files were available for 13 of the houses and 8 of the apartments tested. Through examination of the NatHERS modelling data the assumed air tightness value was able to be determined for each. This assumed value is what the NatHERS model utilises to determine the overall star rating of the dwelling. Figure 9 shows the comparison between the measured air permeability of the tested dwelling (qE_{50}) and the NatHERS modelled air change rate (N_{pr}). Although the measured results are an air permeability value and the modelled is an air change per hour value, for the purposes of this comparison they are considered equivalents. It shows that, on average, the measured and modelled values for houses was remarkably close with only a difference of 0.01 $m^3/h/m^2$ between them. For apartments the measured (as-built) air permeability was lower than the assumed (as designed) air change rate for all apartments. On average the difference was 2.17 $m^3/h/m^2$. For these apartments it may mean that their as-built NatHERS star rating is slightly higher than their as designed star rating if air permeability was taken into account in a NatHERS rating. The star rating for each dwelling is listed at the bottom of each column in Figure 9 and it is interesting to note that the apartment with the lowest star rating (5.2 stars) is also the apartment with the lowest permeability value and the most airtight (1.9 $m^3/h/m^2$). This apartment is very likely to have achieved a higher star rating had the as-built permeability value been included in the as designed NatHERS rating.

Overall, this analysis shows that the assumed air tightness values used in the NatHERS design modelling correlate well with the actual measured permeability of the built dwelling, particularly with Class 1 dwellings.

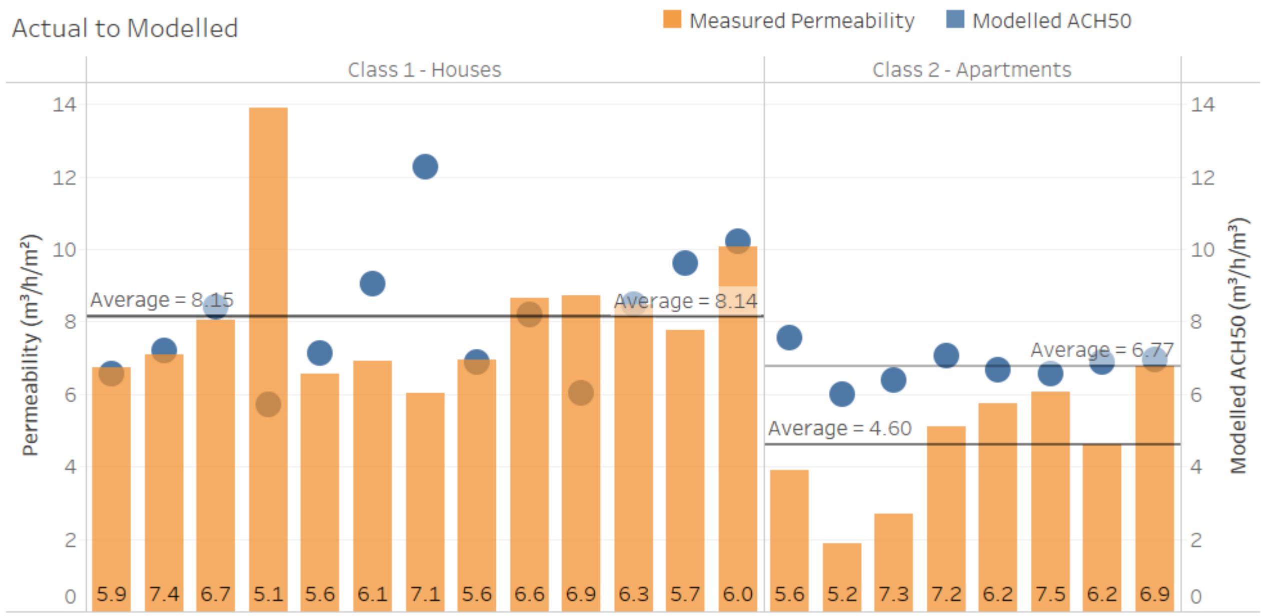


Figure 9 Measured permeability to modelled air change rate

6 Comparing ISO 9972:2015 to NatHERS

The Chenath engine that underpins all NatHERS software and regulatory star ratings currently calculates air changes per hour (volume). A further calculation method is being developed to output the air infiltration rate using surface areas and output a value at $m^3/hr.m^2$ @50Pa. The Chenath engine follows a slightly different calculation method than ISO 9972:2015 suggests, which creates a slightly different and generally more conservative result. It is useful to understand the magnitude and direction of this difference.

In Chenath, the calculations for the volumes are done from inside face to inside face of individual rooms (Figure 10). Consequently, the volume of walls separating internal zones are excluded for the air permeability calculations (Figure 10, 27). Likewise, the surface areas of the intersections of those interior walls with exterior floors, walls, and ceiling are also excluded. Lastly, the volume and surface area of inter-floor spaces on multi-story dwellings is also ignored (Figure 12).

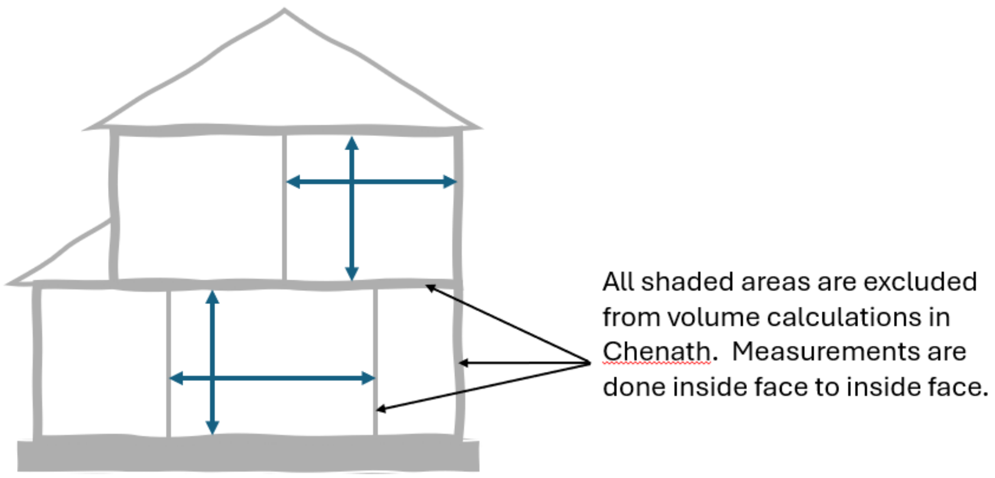


Figure 10 Cross section of house showing Chenath measurement approach

This differs from a straightforward application of the calculation method suggested by ISO 9972:2015 section 6.1 (Figure 11). This method is simpler in comparison to the Chenath engine's calculations and includes any internal volumes and their intersections with the exterior surface.

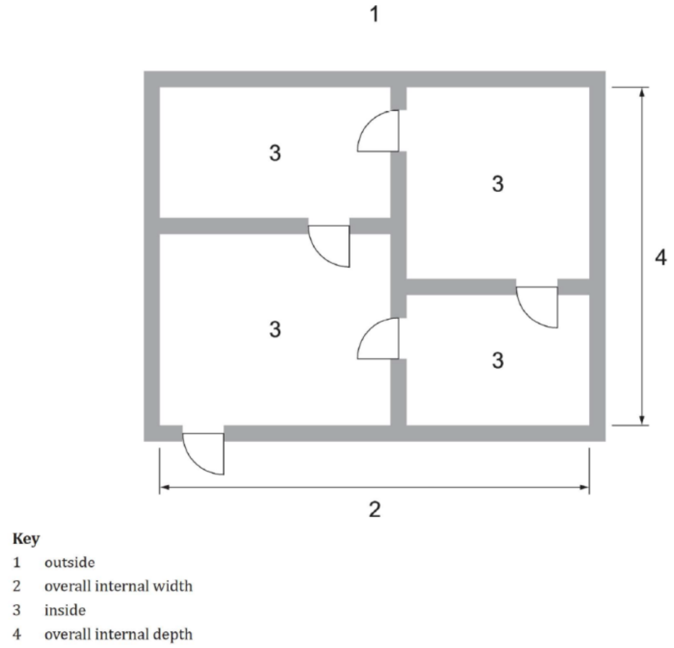
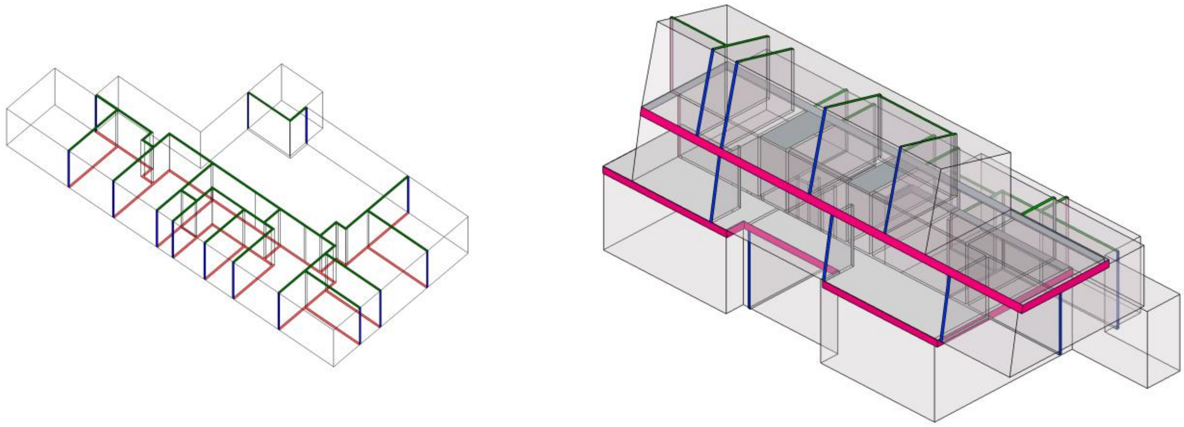


Figure 11 Overall internal dimension of plan

It should be noted that ISO 9972:2015 section 6.1 also states, "Depending on the purpose of the test, possibly for compliance to a building code or standard, additional reference values could be used...If such values are used, they shall be defined in the report." Thus, for use in Australian jurisdictions, another reference value such as one defined by NatHERS methods, could be used and still explicitly comply with ISO 9972

For this study, 21 calculations of surface area and volume were made according to both the NatHERS and ISO 9972:2015 methods as commonly practiced by ATTMA testers. Calculations were made using SketchUp 2017. Drawings were scaled with a precision of 1 cm. For whole buildings, the error introduced by scaling, particularly when the analysis is comparative, is found not to be significant.

Figure 12 shows the areas of difference schematically. Clear wireframe shows the general outline of a building envelope, while coloured areas highlight differences between ISO 9972:2015 and NatHERS. Blue lines show the difference resulting from inclusion of interior walls with exterior walls. Green lines show the difference resulting from the inclusion of interior walls with exterior ceilings. Bright pink areas show the difference resulting from the inclusion of inter-floor spaces with exterior walls. The amount of difference depends on the geometry of a particular dwelling.



Single storey house		Three storey house

Figure 12 Areas of difference in single and triple storey houses

Overall, there is an average difference of 3.7% between the method suggested by ISO 9972:2015 and the NatHERS calculation method, with the NatHERS figures always being smaller. The difference was smaller for apartments and single-story houses, and greater for multi-story houses, from a minimum of 1.5% up to a maximum of 6.3%, see Figure 13. The sample size is small, and only one three-story house was calculated, but there is a clear, overall trend, which is mathematically rational. The main difference with multi-story dwellings is due to the presence of an inter-floor space.

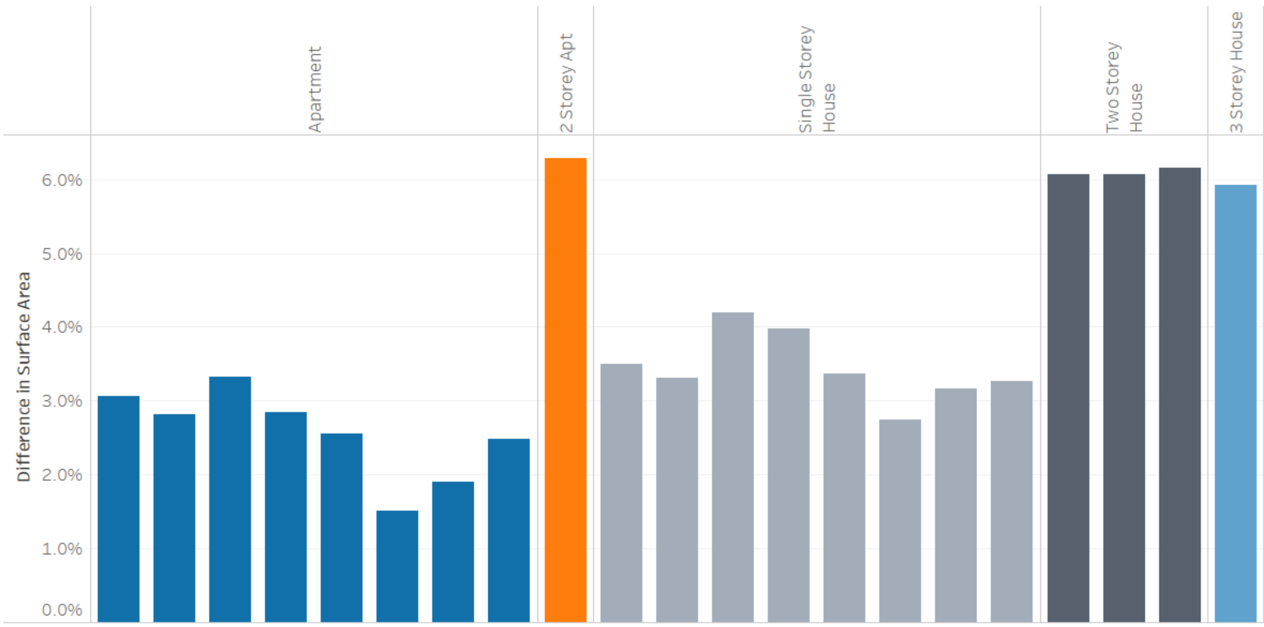


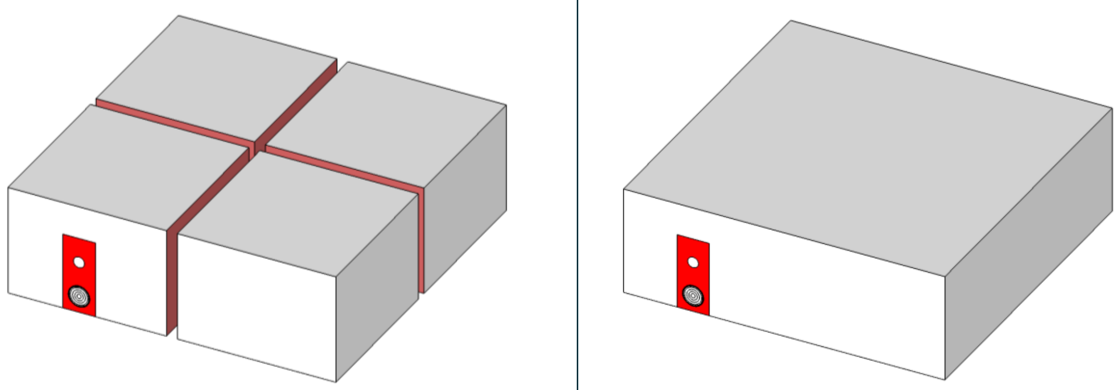
Figure 13 Difference in surface area calculations by ISO 9972:2015 and NatHERS

The overall trends are listed in Table 4.

Table 4 Overall trends in comparing ISO 9972:2015 to NatHERS

	Average Difference in Surface Area	Average Difference in Volume	Maximum Difference in Surface Area	Maximum Difference in Volume
Apartment	2.6%	3.2%	3.3%	4.1%
Single Storey House	3.4%	4.3%	4.2%	5.1%
Two Storey House	6.1%	9.9%	6.3%	9.9%
Three Storey House	5.9%	9.5%	5.9%	9.5%

To express air permeability, an air tightness test result is divided by the dwelling's surface area. As demonstrated above, the surface area in square meters resulting from the NatHERS method will usually be smaller, as it underestimates the total surface area of a dwelling than one resulting from the ISO 9972:2015 method. Therefore, the air permeability figure according to the NatHERS surface area calculation will be worse or leakier, than one divided by a surface area according to the ISO 9972:2015 method, see Figure 14.



Surface area by NatHERS practice: 485/ m^3	Surface area by ISO 9972:2015: 500 m^3
Blower door result: 2000 m^3/hr @ 50 Pa	Blower door result: 2000 m^3/hr @ 50 Pa
Calculated permeability: 4.12 $m^3/h.m^2$ @ 50 Pa	Calculated permeability: 4.0 $m^3/h.m^2$ @ 50 Pa

Figure 14 Comparing NatHERS method to ISO 9972:2015 method

Applied in a regulatory context, demonstrating compliance with a maximum leakage target in the design stage will therefore usually be more conservative when using the NatHERS method than when using the ISO 9972 suggested method. For this reason, if a dwellings design can meet a target in NatHERS it will by default show that it meets that target according to ISO 9972:2015.

For example, a house may have 475 square meters of surface area according to ISO 9972 but 450 square meters according to the NatHERS calculation method, a reduction of 5.6%.

A permeability of 10 $m^3/h.m^2$ using ISO 9972:2015 calculation would require a leakage rate of 4750 m^3/h @ 50 Pa or less.

A permeability of 10 $m^3/h.m^2$ using the NatHERS figures would calculate a tighter leakage rate for the design of the dwelling of 4500 m^3/h @ 50 Pa or less.

Therefore, if the test result meets the permeability target using the NatHERS method, it also meets the target using ISO 9972. Again, it should be noted that ISO 9972:2015 states that if a regulator chooses another method of calculating a reference value, that value may be used.

7 Survey results

The air tightness tests reveal the air permeability of a dwelling, but do not explain the cause of the air permeability result. In dwellings with high air permeability values it is important to discover the reason for the high value and possibly identify corrective measures that could be undertaken to improve the building's thermal performance. In dwellings with very low air permeability values it is important to ensure that appropriate controlled ventilation is occurring to avoid issues associated with low air flow such as mould, condensation and poor indoor air quality that could have health implications for residents.

To better understand the reasons behind the air permeability results being obtained we required each tester to undertake a post-test survey of the dwelling to try and identify the causes. This helped to explain the results, but also helped to identify common and reoccurring causes. Identification of these common causes could be utilised to develop educational material for the building industry, improved technical specifications and enhanced future building regulations.

7.1 Air tightness a goal

As part of the dwelling selection criteria, dwellings where air tightness had been a design objective were generally excluded, to avoid selection bias in the sample set. Nevertheless, a small number of homes tested (9.8%) did have air tightness as an objective, mostly located in Victoria (Figure 15). Although only a small percentage of dwellings claimed air tightness as an objective, it provided an opportunity to see whether these dwellings achieved better air tightness results than those where air tightness was not an objective. Analysis shows that those dwellings that claimed air tightness as a design objective achieved an average qE_{50} of 7.8 $m^3/h/m^2$ while those dwellings where air tightness was not an objective or unknown achieved an average qE_{50} of 6.9 $m^3/h/m^2$. This is a surprising result as dwellings with air tightness as an objective achieved, on average, a worse result than dwellings where it was not an objective. Some of the homes that had air tightness as an objective also had known targets. Only one of these homes had a target that would be considered ambitious (qE_{50} of 5.0 $m^3/h/m^2$) while the other homes set targets around a qE_{50} of 10.0 $m^3/h/m^2$.

Informal dialog with homeowners during the test visit revealed that affordability was the primary design objective. Still, after moving in many were interested in how their homes performed compared to their peers. Some related concerns about comfort such as "draughty-ness" or sound during high winds. Such comments were common from single detached homes to high-rise apartment buildings. It should be noted that the majority of homes in SA were unoccupied new construction, so interviews were with builders, not homeowners. Builders related cost efficiency as the primary motivation, while for homebuyers it was affordability. The combination puts downward pressure on prices but may also increase a gap between expectations and delivered outcomes. This gap is the reason for regulation of air tightness in other countries such as the U.S. and the U.K. It may also be the reason that many homeowners volunteered for the study.

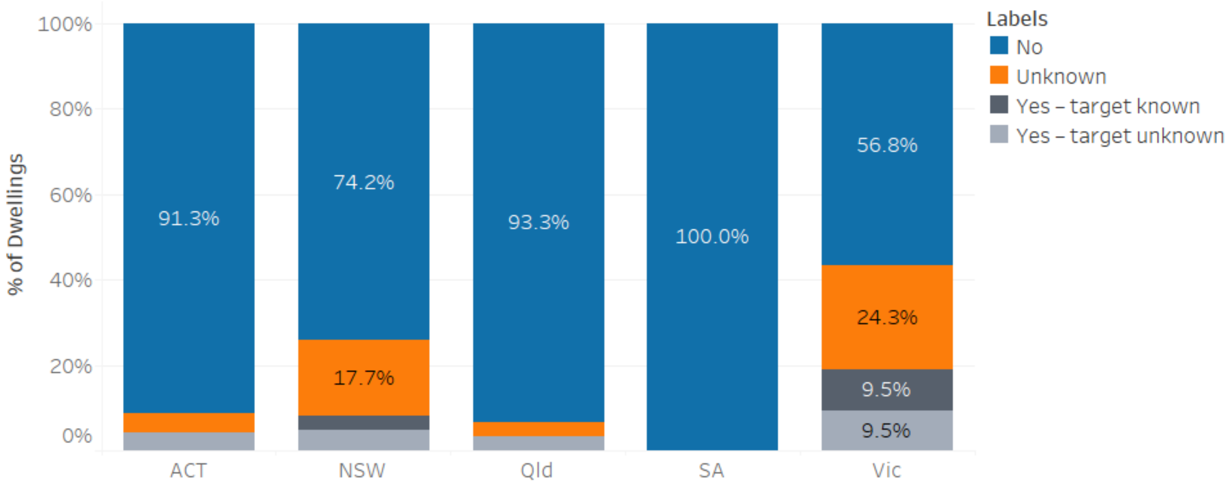


Figure 15 Air tightness as a design objective.

7.2 Bath ventilation

Regulations for tested dwellings built in the last 4 years required that all bathrooms have a mechanical ventilation system installed. Generally, this will be achieved through the use of a simple ceiling mounted exhaust fan controlled by occupants via an on/off switch. Each dwelling tested had at least one bathroom, but the survey allowed up to three bathrooms to be examined. Both the ventilation type and the ventilation control system were recorded in each bathroom. The simple intermittent extraction fan is by far the most common type of ventilation system installed (Figure 16). The second most common is the combination heat lamp and extractor fan (Figure 16) which is also an intermittent extraction fan. Continuous extraction fans were rarely encountered.

			
Simple intermittent fan with no damper	Combo heat lamp and extractor fan	Remote fan with no damper	Exhaust fan with damper

Figure 16 Range of bathroom exhaust fans

Regulations also required that extraction fans have a damper installed to reduce air loss. These dampers are usually simple flaps that will open when a fan is running due to fan pressure. Many of these dampers can become ineffectual when air conditioning systems are operating as the positive pressure within the dwelling is sufficient to push open the damper and allow conditioned air to escape. Figure 17 shows that these dampers are the most common control system used, but also shows that a significant number of exhaust fans had no dampers installed. This is surprising considering all the dwellings in this study were less than 4 years old and regulations for the requirement to have dampers on exhaust fans has been in place since 2016. This highlights a potential aspect for building inspectors to check as part of the building compliance requirements.

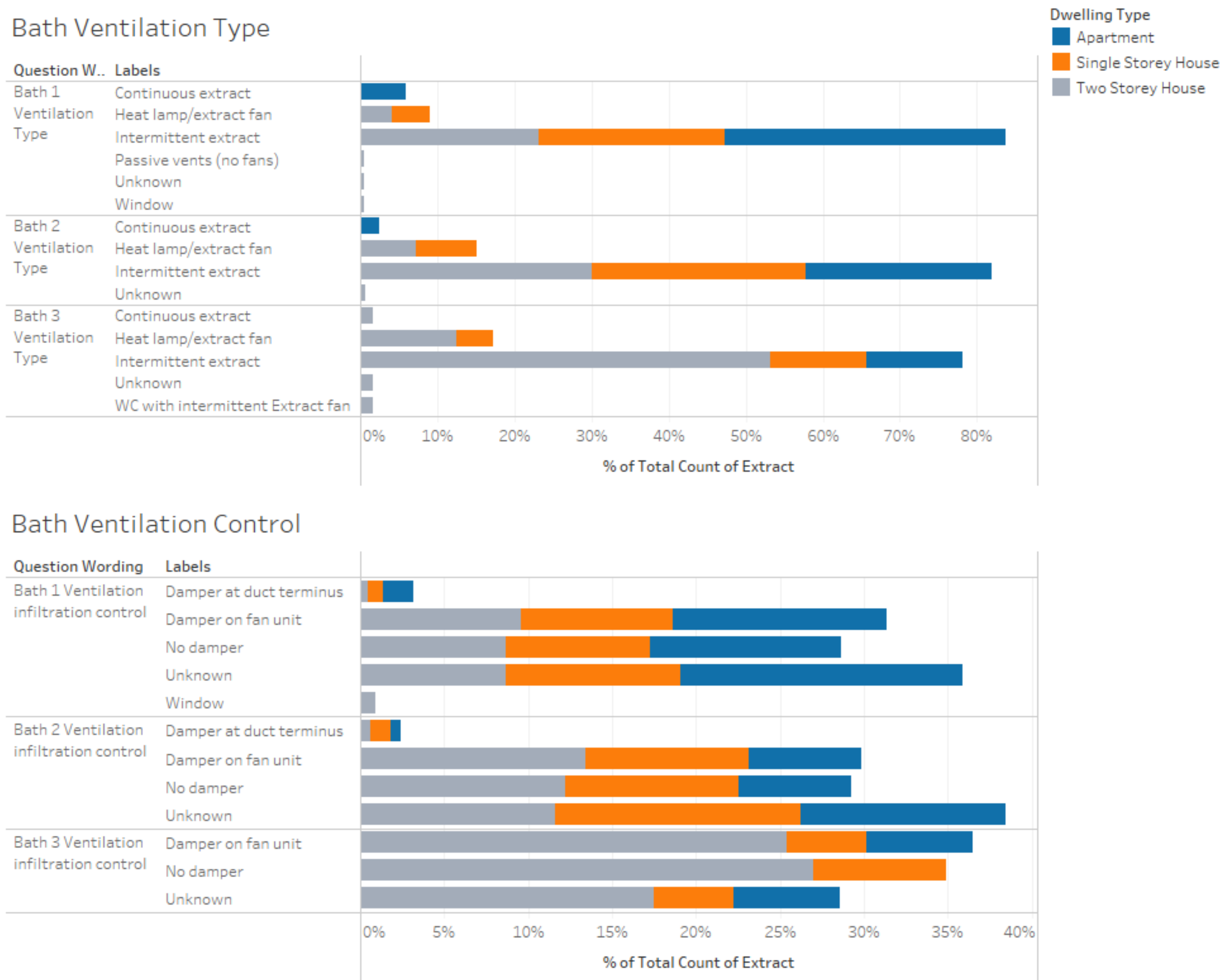


Figure 17 Bath ventilation type and control

7.3 Kitchen ventilation

Like bathrooms, kitchens are also required to have a mechanical ventilation system located over any stove cooktop. Figure 18 shows that the standard rangehood with a user-controlled extraction fan is the most common solution. 97% of houses and 88% of apartments use this approach. It is more difficult to determine the control systems on these units than it is with ceiling exhaust fans, so the high percentage of "Unknown" for ventilation control is to be expected. Where the control system could be determined, the majority of rangehoods in houses had dampers installed, but the reverse was true in apartments where the majority had no damper. Unlike ceiling exhaust fans, rangehoods are not required to have a damper if they have a filter installed. The vast majority of rangehoods do use filters, so the requirement for a damper is usually negated.

There are several reasons for having ventilation systems above kitchen stoves and ovens. The most obvious is to remove smells, steam, smoke, etc when cooking, but it also removes unwanted gases from the combustion process from gas stovetops. Figure 20 shows the energy types within each region and by dwelling type. Dwellings in the ACT mainly have all electric ranges, while apartments in NSW are mainly gas stovetops. Victorian homes have traditionally had a high uptake of gas based appliances, but the Victorian dwellings in this study have a relatively even split between gas and electric.

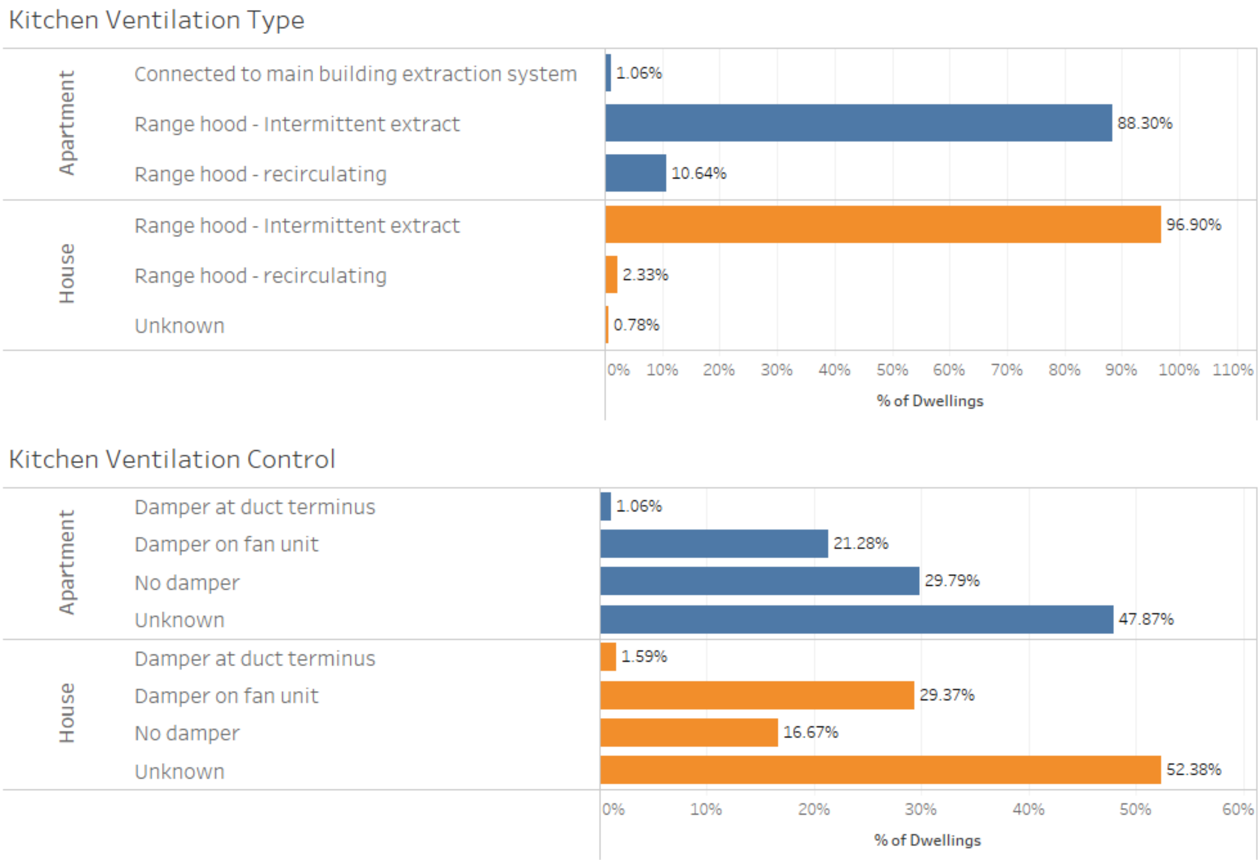


Figure 18 Kitchen ventilation type and control

Typical kitchen rangehood

Ducted through wall

Duct through ceiling – note removed insulation

Figure 19 Kitchen rangehoods and duct setups

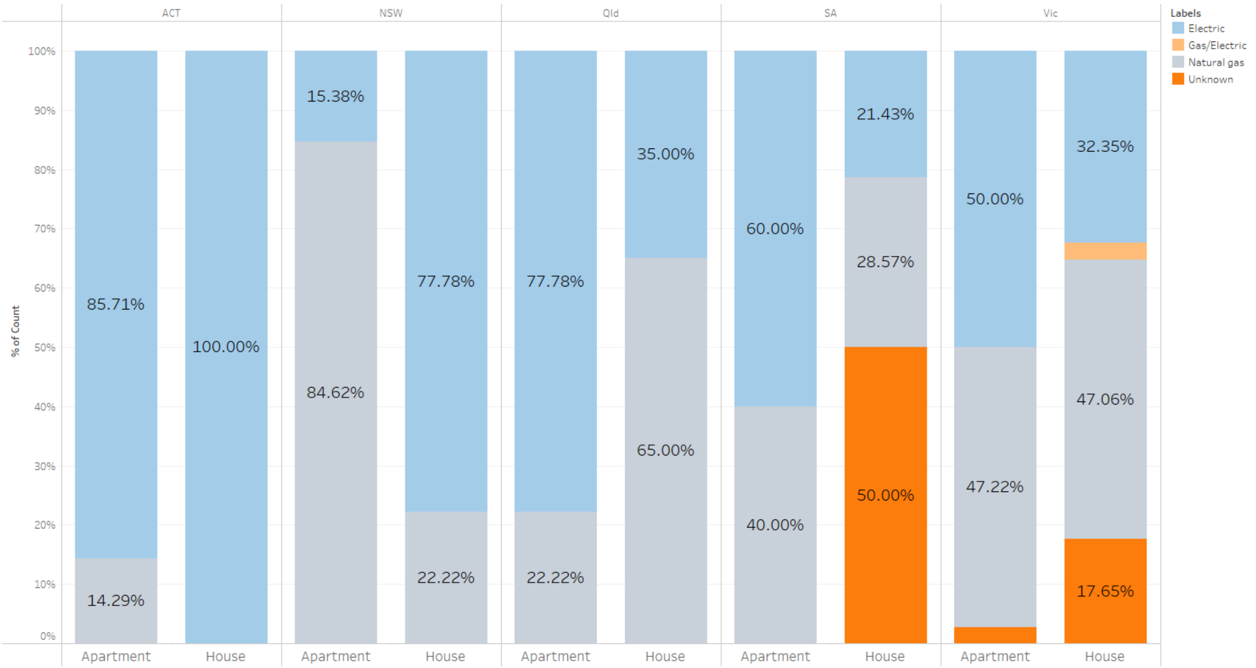


Figure 20 Kitchen range energy type

7.4 Clothes dryers

Clothes dryers are a common appliance found in many homes. Where access to external space is limited, such as apartments, clothes dryers are often the only practical method of drying washing and even in dwellings where external clothes lines are available, people still utilise clothes dryers as a quick and convenient method for drying. Traditional clothes dryers simply use heated air to evaporate moisture from wet clothes. This is energy intensive and produces a lot of humid warm air that is often exhausted directly into the dwelling. This will often lead to condensation on nearby cool surfaces that could potentially encourage mould and mildew. Recent regulation changes now require ventilation of exhaust air to the outside via an exhaust duct for venting clothes dryers (ABCB, 2024).

Within our study, most dwellings did have a clothes dryer, although in Queensland 60% of apartments and 40% of houses had no dryer. Amongst those dwellings that did have a dryer the majority were traditional venting dryers with no or unknown external venting and relied on intermittent extraction of humid air via a ceiling exhaust fan or an open window. Figure 21 shows the types of clothes dryers that were present. The most efficient dryers are heat pump dryers which recover most of the energy in the humid exhaust air and reuse it to dry the clothes (Milne and Reardon, 2022). It is interesting to note that in Victorian houses that had dryers, 55% were heat pump dryers.

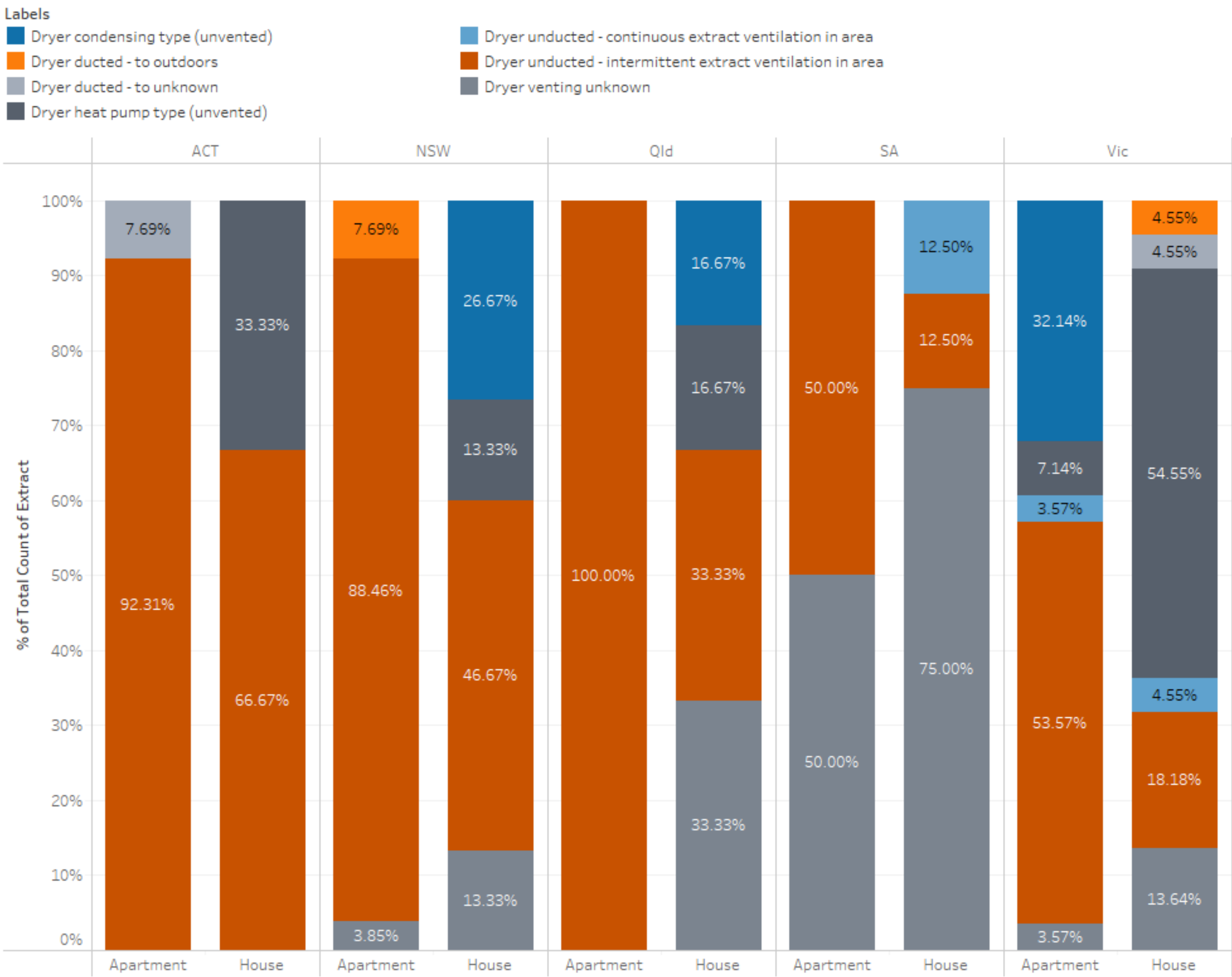


Figure 21 Clothes dryer type

7.5 Downlights

Downlights are a very common form of lighting and within our study dwellings, 80% had downlights installed. Downlights create penetrations in the ceiling that can lead to increased air permeability as well as breaks in the insulation layer on the ceiling. Modern downlights will usually be LED lighting. These are not only significantly more energy efficient than old halogen lighting, but many LED downlights (IC rated) also allow insulation to be installed over them. This means that a continuous insulation layer is possible across the ceiling leading to much greater thermal performance. In addition, modern LED downlights are often sealed units that do not require ventilation, so air infiltration through them is minimised. Nevertheless, downlights can still be a source of air leakage in modern dwellings if they have been poorly installed.

		
CFL downlight - leaky	Directional downlight - leaky	Sealed LED downlight - good

Figure 22 Downlight types

On average, there were 17 downlights installed in each apartment in this study and 37 downlights installed in each house.   Figure 23 shows the downlight number distribution by dwelling type. Over 90% of apartments have less than 30 downlights while over 13% of houses had 50 or more downlights installed. Every installed downlight is a potential source of air leakage, so careful planning to optimise downlight use and placement will reduce overuse of downlights and sources of air leakage.

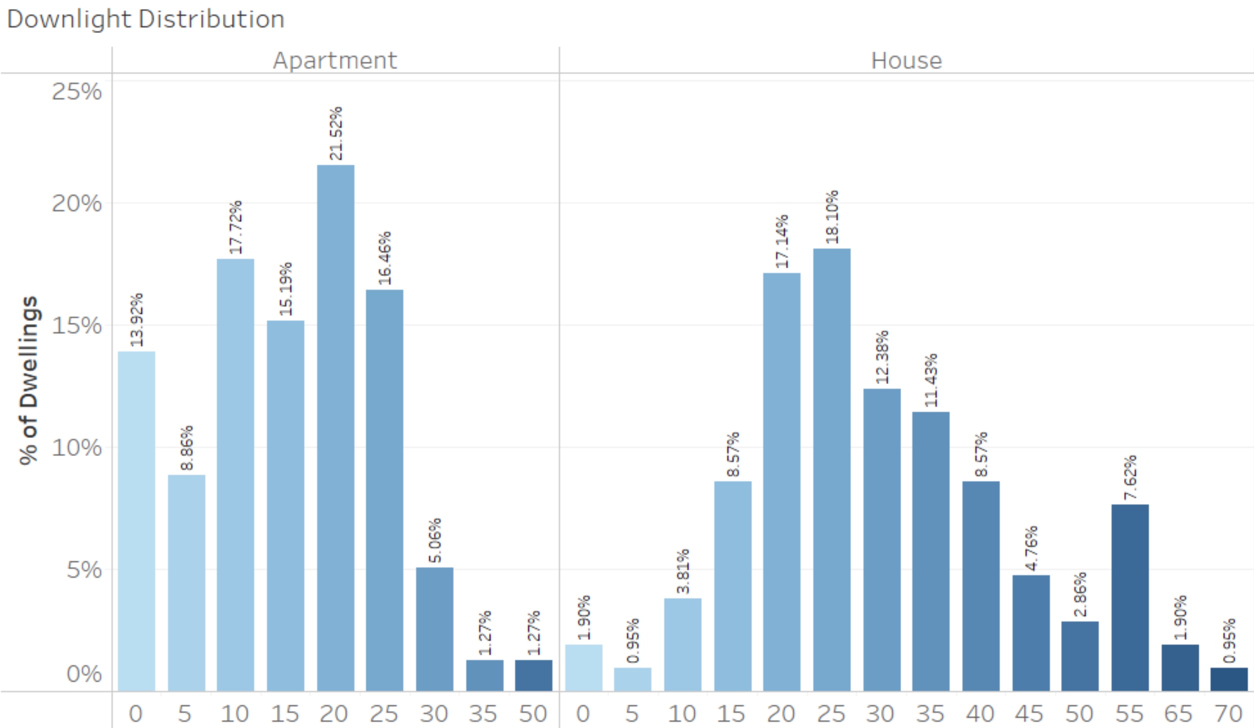


Figure 23 Downlight number distribution by dwelling type

7.6 Heating/cooling systems

Most dwellings will have some form of heating/cooling system installed. Figure 24 shows the range of systems installed in the dwellings in this study. A surprising 18% of apartments had no system installed while only 1.4% of houses had no system installed. It is assumed that those dwellings with no system installed relied on plug in systems to provide conditioning. Most installed systems will require penetrations of some type. Ducted systems will have registers and ductwork while split systems will have pipework to outside compressors. Wall mounted heaters will have flues or chimneys. Of the installed systems listed, only in-slab hydronic heating has no penetrations.

70% of houses and 38% of apartments had ducted heating/AC systems installed. Split AC systems were more common in apartments (44%) than houses (24%). Only a very small percentage (3%) of houses had ducted evaporative cooling installed. All these systems have penetrations in walls and/or ceilings that are potential air leakage points. Ducted systems can be significant causes of air leakage as the registers in the ceiling are usually unable to be closed off when not in use. This allows direct access to the ductwork in the ceiling space which has multiple opportunities for air leakage through joins and junctions that have been poorly sealed or through damage to the ductwork itself.

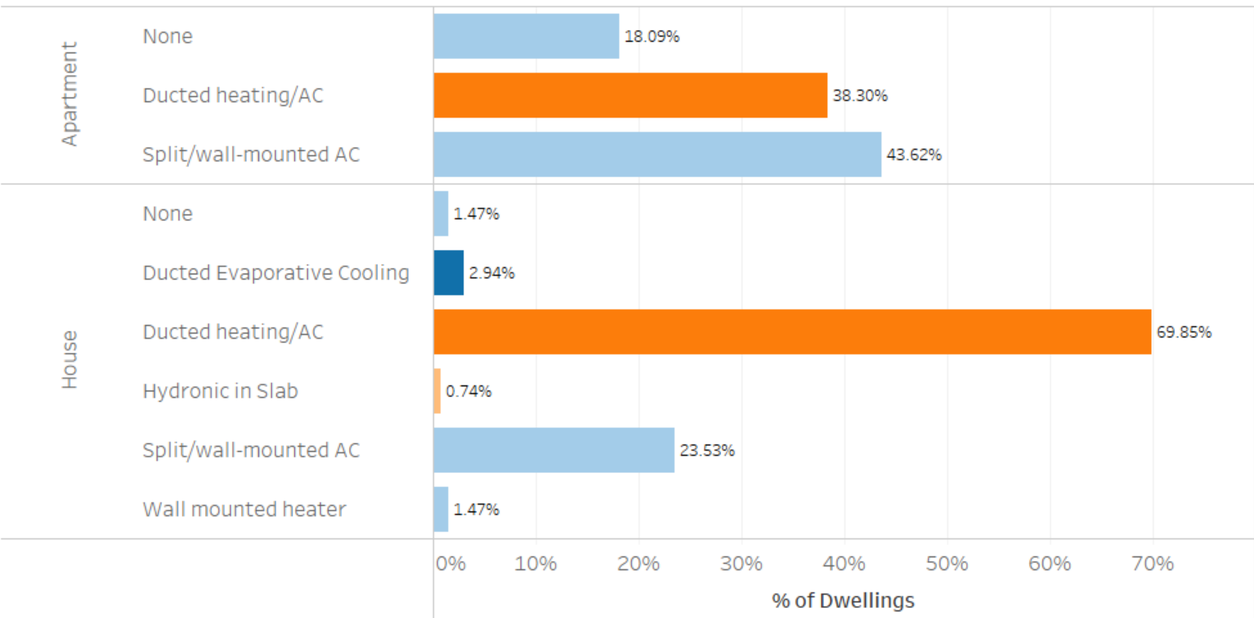


Figure 24 Heating/cooling systems installed

7.7 Air infiltration barriers

Building wraps are utilised for a variety of reasons including providing a barrier to air infiltration. Wraps also serve as general weatherproofing to prevent moisture and dust egress and vapour control to prevent mould. Figure 25 lists the types of barriers that have been installed in roof/ceiling and external wall systems in tested dwellings. Apartments tend to rely on their structural elements (concrete floors and walls) while houses are generally wrapped with sarking materials. Often it was difficult to determine what type of barrier had been utilised as it is hidden behind the interior cladding system. A surprisingly large percentage of houses had no wrap in the roof/ceiling system (29%) with only the plasterboard acting as a barrier.

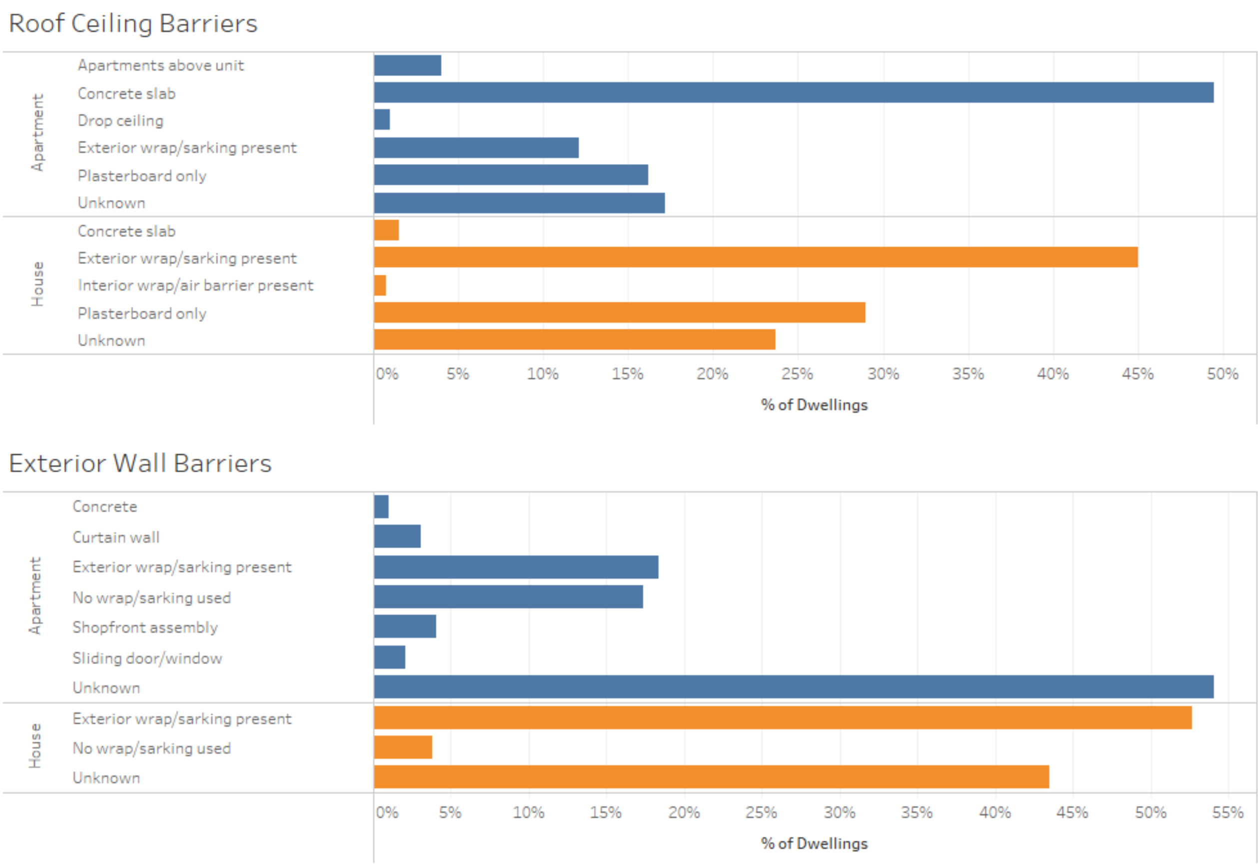


Figure 25 Types of barriers used in roof, ceiling, and wall structures

7.8 Leakage points

Figure 26 lists the various air leakage points that were identified by testers in the dwellings being tested. Often there were multiple air leakage points identified within a dwelling. The chart shows the count of each air leakage point and the percentage of dwellings within each dwelling type that recorded that air leakage point. For example, downlights were identified 7 times in apartments and 17 times in houses and was one of the air leakage points in 7% of apartments and 13% of houses.

Bathroom fans were identified as one of the major air leakage points in both apartments and houses. These were identified 56 times in apartments and 81 times in houses and 63% of apartments and houses had bath fans identified as an air leakage point. As discussed earlier in

Section 6.2, the lack of dampers or poorly performing dampers on ceiling fans is a major reason why bath fans are such significant leakage points.

The most reported air leakage point for apartments (59 reports) was sliding glass doors with 63% of apartments having this issue. For most apartments the sliding door will usually lead to a balcony and is often the primary means of obtaining outside air and natural ventilation. These doors get high levels of use and consequently this can lead to damage of weather and door seals. Install quality and the quality of the door system itself can also lead to poor performance of the door over time. Sliding doors were also a major issue in houses (63 reports) with 48% of houses having this issue.

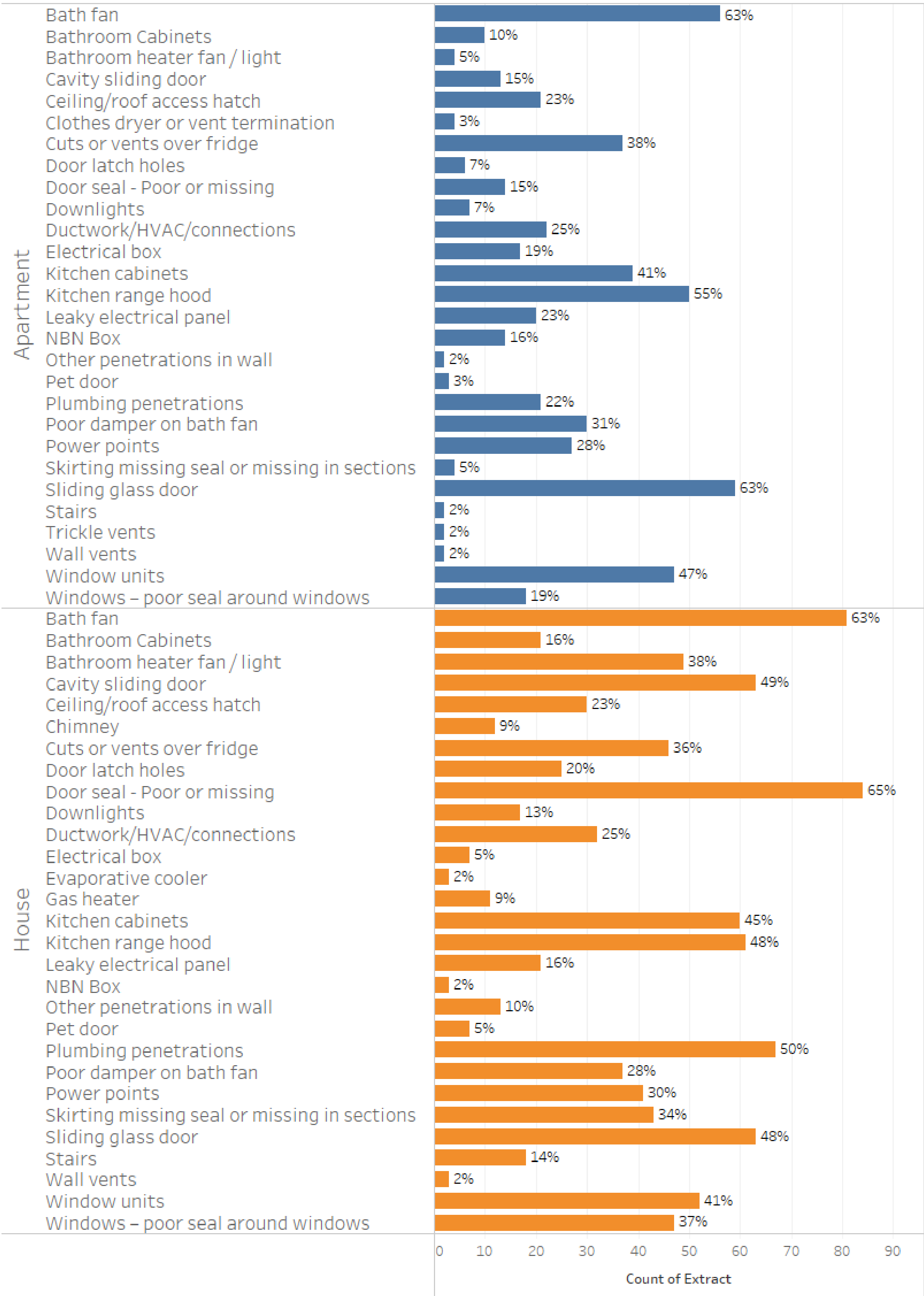


Figure 26 Identified leakage points

For houses the most reported issue was poor or missing door seals. This was reported 84 times and occurred in 65% of houses. This is a similar issue to sliding doors, although this focused on external doors that are not sliding doors, so primarily front entrance doors. This is why this issue was not as significant in apartments.15% reported this as an issue as many apartment entry doors are accessed from internal corridors. As with sliding doors, frequent use can lead to the quick degradation of the seals, so regular maintenance is required to maintain their effectiveness.

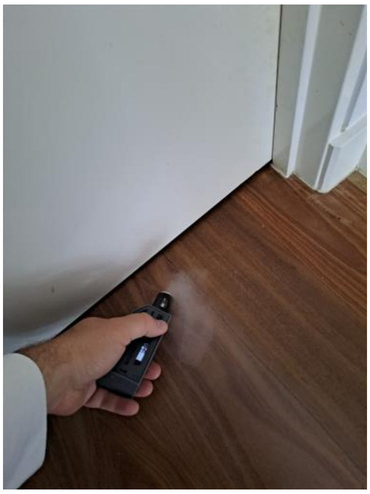
Kitchen cabinetry was identified in both apartments and houses as a leakage point, 41% and 45% of the time respectively. This was not the cabinets themselves, but rather the connection of the cabinetry to the walls and inadvertent penetrations and holes through the walls to the cavity behind that were not properly sealed and rectified after the cabinetry install. Such penetrations allow for conditioned air to escape into the wall cavity which will generally lead directly to the roof space.

Related to kitchen cabinets is often the inclusion of a vent above the refrigerator cavity. This was reported as a leakage point in 38% of apartments and 36% of houses. These vents are designed to allow waste heat from refrigerators to escape and often will simply lead straight into the wall cavity. However, as far as the authors could establish, there is no current regulatory requirement for such vents. Also, fridge manufacturers do not require such ventilation for their products. Refrigerators do require ventilation around them, but this can be achieved by simply allowing additional space around the refrigerator. Most modern refrigerators require at least 50mm gap for the sides and 100mm gap from the top to allow air to circulate and heat to dissipate (Samsung, 2024).

The inclusion of these vents seems to be an historic one from when older fridges had greater ventilation requirements. Reference to them was found on some current government websites (NSW Government, 2024) and some builders complained about the "need" to install them, but no specific and current regulation could be found that requires them to be installed. Consequently, educating the building industry to not include these vents would appear to be a simple solution to this leakage point.

Many other leakage points were identified, and often simple solutions could be found to rectify these leaks. Various penetrations through walls were a common issue that could easily be resolved through gap sealants being used while more structural related causes need to be addressed at the time of construction. For example, cavity sliding doors were identified as a leakage point in 49% of houses and 15% of apartments. Cavity sliding units are typically unsealed framed units that fit within the wall cavity. Simply enclosing these units before install into the wall cavity would greatly reduce air leakage through sliding doors. Trying to seal cavity sliding units after they are installed is a complicated and expensive task.

Internal cavity sliding door



Garage entry door from house

Sliding glass door

Vent over fridge

Figure 27 Typical leakage points identified

8 Additional measurements

A series of additional measurements were undertaken to test specific aspects of dwellings that are known leakage points.

8.1 Apartment door leakage

In multi-unit residential buildings, the interaction between dwelling unit air tightness and ventilation is direct and important for energy use and indoor air quality reasons. In some cases, discrete air leaks may form direct pathways for air movement. Leakage in doors from dwelling units to shared enclosed corridors may be one of the larger pathways. This has implications for fire safety as well as indoor air quality.

Dwelling unit ventilation designs that rely on a one-way airflow path, such as exhaust-only, depend on makeup air to function properly. Leakage around corridor doors is an ubiquitous pathway, but more current standards do not allow airflow from this source to be counted as part of required “outdoor air”. Leakage around doorways should be quantified so that it can be seen how much it factors into ventilation function, intentionally or not.

For this study doors in three multi-residential buildings in Melbourne were tested, ten doors in each. As part of the process, the leakage of the testing apparatus itself was tested by taping a door, testing the leakage of the enclosure, then removing the tape from the door and testing again. The leakage of this test rig was then removed from the results of each test, yielding a leakage rate for the doors themselves.

One door was also tested in both positive and negative directions to illustrate the difference in leakage rates. By “negative” direction, we refer to the pressure acting on the test chamber. An illustration of the test setup is shown in Figure 28. A test chamber was created by placing thin pressure tubes in the chamber and under the door, taking care not to inadvertently raise the drop seal on any door with insertion of the probe. Then, a thin, rigid plastic board product was sealed with tape to the door frame under test.

Pressure was then applied to the test chamber with a Retrotec 300 series test fan system with a TEC DG-1000 or Retrotec DM-32 micromanometer to record pressure. Data was entered into Retrotec Fantestic software for calculation of the projected leakage rate at 50 Pascals. Pressures were applied generally in increments of 2 to 3 Pascals, from 2 Pascals in the test chamber up to approximately 15 Pascals.

Above 15 Pascals, it can be seen that the door under test may be pushed away from its seals to the point that it possibly leaks more than in typical operation at lower pressures. For this reason, test pressures were generally capped at about 15 Pascals.

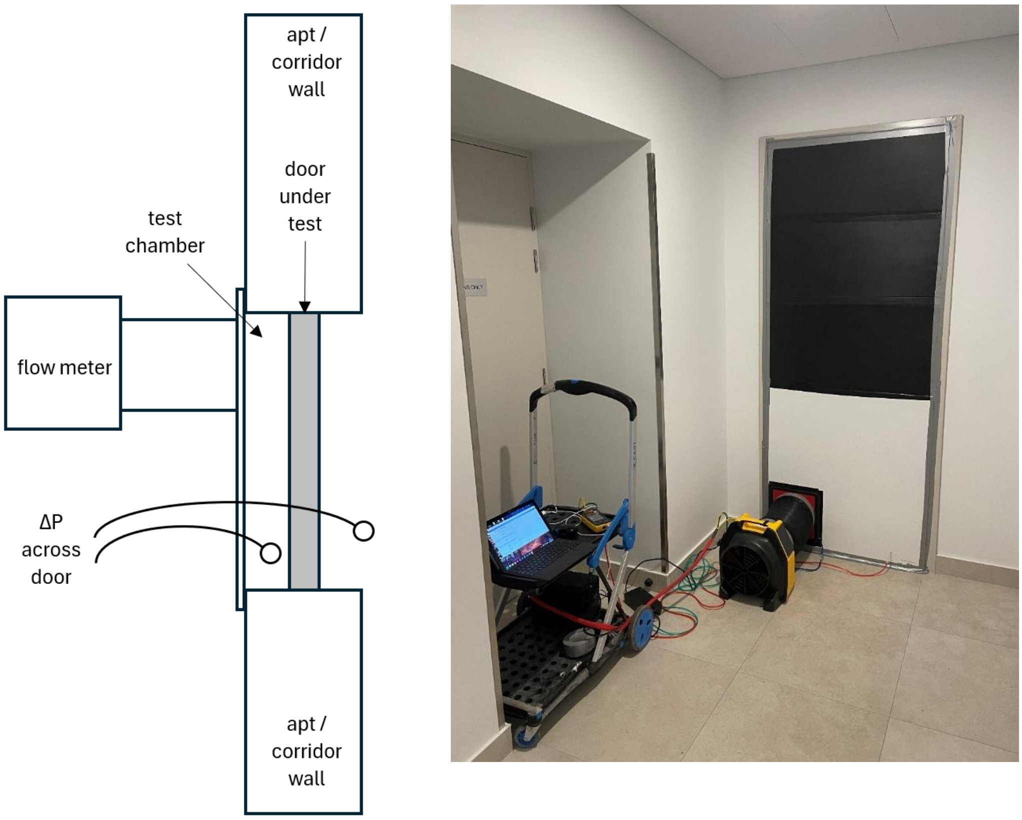


Figure 28 Door leakage test rig setup

Pressure was applied to the test chamber with a Retrotec 300 series test fan system with a TEC DG-1000 or Retrotec DM-32 micromanometer to record pressure. Pressures were applied generally in increments of 2 to 3 Pascals, from 2 Pascals in the test chamber up to approximately 15 Pascals.

Figure 29 shows that doors have more leakage under positive test pressure. This is because, as they open towards the apartment interior, they push away from any seals on the door jambs and head and contact becomes less firm. Above approximately 15 Pascals of positive pressure, it can also be seen that leakage increases. At higher pressures, the door under test may be pushed away from its seals to the point that it possibly leaks more than in typical operation at lower pressures.

For these reasons, the tests were conducted under negative pressures and were generally capped at about 15 Pascals. Data was entered into Retrotec Fantestic software for calculation of a projected leakage rate at 50 Pascals for comparison.

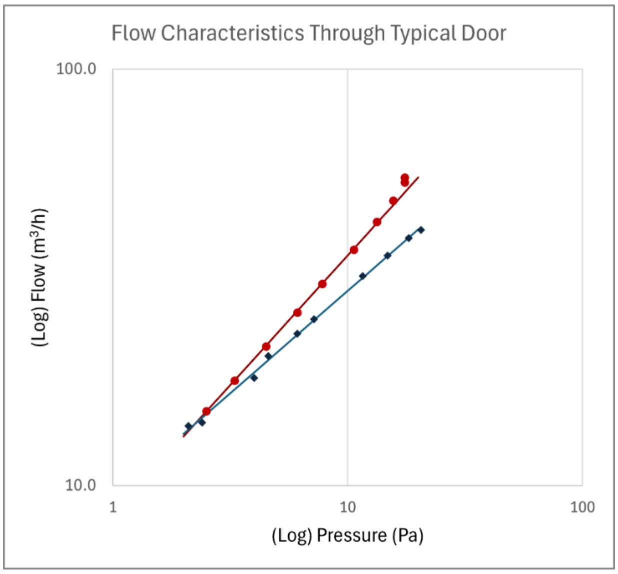


Figure 29 Flow characteristics through typical door

The doors in the three buildings had fairly similar results, with average leakage from the doors generally being relatively low. The characteristics from ten doors on the same floor in three different buildings is shown in Table 5. While the averages were fairly similar and fairly low, the minimum was quite low and the maximum was appreciable.

Table 5 Door leakage results

Building	Door size	Average door leakage (m^3/h @ 50 Pa)	Maximum (m^3/h @ 50 Pa)	Minimum (m^3/h @ 50 Pa)
1	2.09m x 0.89m	26.9	74.6	4.3
2	2.35m x 0.89m	47.1	85.2	10.5
3	2.60m x 0.89m	26.8	43.7	10.2

Each building had doors with “drop seals”, or trigger-activated door seal mechanisms. When the doors shut, they push an adjustable pin in that drops a seal to close the gap under the door, see Figure 30. When the door opens, the pin releases and the mechanism pulls the drop seal out of the swing path of the door. This has the benefit of maintaining the long-term condition of the door seal. In general, the door seals did a good job of cutting down air movement through the door. Some of the doors had poorly-adjusted door seals, and this was likely the cause of higher leakage rates through some of the them.

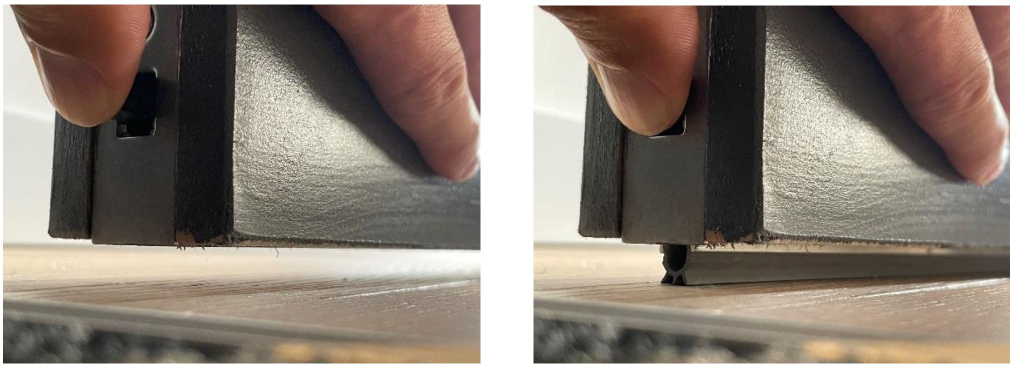


Figure 30 Drop seals

To check how much a drop seal contributed to door leakage, we tested a door with the drop seal both raised and lowered. The effect was significant, increasing the leakage from one door from 9.6 to 78.4 m^3/h @ 50 Pascals, or more than 800%.

A 2014 study in the Northeast U.S. tested door leakage as a functional part of apartment ventilation, whether by design or accident. Eight doors were tested in one building and seven were tested in another. They showed an average of 208 and 365 m^3/h @ 50 Pascals per door, respectively. Notably, the doors of either building did not have drop seals. They also sometimes had significant door undercuts or gaps (Maxwell et al., 2014). These traits probably lead to the main difference between those higher results and the results from this study.

Air passage through corridor doors is a significant risk to fire safety. The doors in this study had leakage of anywhere from 1-30% of the averages of doors in the U.S. study. Whether attention has been brought to the issue in other countries over the 10 years since that study's publication, and whether practice has improved in that jurisdiction from a fire safety perspective, is unknown by this study.

One limitation of typical air tightness test practice with a blower door is that the placement of the test door in the apartment/corridor door means that leakage through that door itself is not measured at all. When this leakage is significant, that can be a serious omission. For instance, an apartment may show an air permeability of 1.0 m^3/h.m2 @ 50 Pa or less with a blower door, but its door may leak at 85 m^3/h @ 50 Pa. The leakage through the door may be therefore represent 20-30% of the total leakage of an apartment, meaning that much of the makeup air for an exhaust-only ventilation design may come from corridors.

The reason that leakage through corridor doors is relevant is that, in some jurisdictions, constant ventilation is required by building codes, and provision of fresh air is required. Whether intentionally or not, airflow through corridor doors can be significant. One could not call airflow under a corridor door fresh "outdoor air" as required by standards like ASHRAE 62.2-2022, which is why that standard explicitly prohibits exhaust-only systems in residential buildings with shared enclosed corridors.

However, because the leakage of doors in this Australian study was so low, it cannot not be counted as a significant air pathway. If Australia were to adopt requirements for continuous ventilation in multi-residential systems, it should be taken into consideration where makeup air or pressure relief will be obtained. The use of balanced (supply with complimentary exhaust) ventilation is a recommended alternative.

8.2 Ventilation measurements

Effective ventilation is essential to indoor air quality and should be paired with building air tightness. As part of this study, ventilation rates were measured in more than fifty homes and apartments. One goal was to understand what ventilation rates were typically being delivered by common construction methods and materials. Another was to see whether common systems could be used to deliver continuous ventilation should it be required by regulation in the future.

Ventilation was measured in homes and apartments in Victoria and New South Wales. Measurements were made in bathrooms and laundry rooms, but not from kitchens range hoods. Kitchen range hoods are challenging to measure consistently.   Figure 31 shows a typical test setup.

Measurements were made with fans in different operating modes. One was with the door to the zone open, and one with the door closed. This was to observe the effect that closing doors had on the performance of the system. For example, if bathrooms do not have sufficient door undercut or other gaps, they may be starved for pressure relief and may not function effectively. Flow rates were measured with doors open and closed, and pressure drop across the door was measured when closed. Finally, visual observation of the door undercut was made to estimate the size.

Figure 31 Measuring exhaust fan ventilation

In total, airflow measurements were made from 121 different fan installations at 51 separate dwellings. Some were very large and drew large flow rates; others were small and drew much lower rates. The lowest measured flow was 16 m^3/hr, but there were others that were likely lower. These lower rates could not be measured with the equipment on hand. Figure 32 shows a box and whisker plot of the flow results for exhaust fans in various locations all with the door to the zone being open. A range of measuring devices were used for the testing, these are noted on Figure 32.[1]

Figure 32 Flow rates for exhaust fans with door open

Table 6 lists the various statistical results for each of the exhaust fans tested with the door open in each zone.

Table 6 Ventilation rate statistics for exhaust fans with door open

	Bath Fan 1 (m^3/h)	Bath Fan 2 (m^3/h)	Bath Fan 3 (m^3/h)	Laundry Fan 3 (m^3/h)
Average	139	153	122	131
Median	140	141	114	123
Max	324	324	259	274

[1] Devices for ventilation measurements:

ACIN https://acin.nl/en/air-measurement-instruments/balo-en/flowfinder-mk-2/

TSI https://tsi.com/getmedia/9dbdc75d-2eeb-4455-a63c-12980b2f6ab4/8371-AccuBalance-1980335D?ext=.pdf

TEC https://store.energyconservatory.com/exhaustfanmeter.html

Min*	16	28	32	47

**Lower rates below measurable range*

The systems observed included individual ceiling units, bathroom units with integrated heating lights, and remote in-line fans with ductwork to single or multiple ceiling registers. Figure 33 shows some of the typical ceiling exhaust fan units that were tested.

Single bath or laundry fan — Unit with integrated heating light — Ceiling vent with remote in-line fan

Figure 33 Typical types of ceiling exhaust fans

All fans observed were connected to power and operating, but on some houses flows were too low to measure by the device in use. Reasons for differing levels of performance likely include product selection. In general, axial fans are intended to generate higher flow rates at a lower static pressure. Centrifugal fans generate greater flow against higher static pressure but may create less total flow. Exhaust from some units was ducted to the exterior, while from others it was to the roof cavity or unknown.

One area of interest is the effect of poor installation of systems with ductwork attached. Ductwork is required by the current National Construction Code to carry exhaust directly to the exterior from the fan. That is, exhaust may not be discharged directly into building cavities or roof spaces due to the risks of introducing moisture. Though it was not part of the study, observations were made of some systems to help identify the reasons for poor performance.

Some fan installations were subject to poor ductwork installation. In a few houses, some fans were performing normally, while a single fan was specifically low. Upon investigation in the roof space, it could be seen that the ductwork connected to the fan was longer than necessary, winding, and crimped in some areas, all contributing to lower airflow (Figure 34).

Figure 34 Crimped excess exhaust fan ductwork

Another area of interest is the effect on flow rates when doors to the bathrooms or laundry are closed. A concern is that if insufficient door undercut is provided, pressure may build up in the bathroom or laundry and airflow through the ventilation would be hindered. Fortunately, this did not appear to be the case in most systems measured.

Table 7 shows that on average, a reduction in airflow of only 5% was observed. 89% of units showed that the door position was not closely related to flow rate, with flow not changing more than 10% whether the door was open or closed.

Table 7 Exhaust fan ventilation results

	Reduction in flow from closing door	Pressure created by closing door (Pascals)	Door undercut (mm)
Average	5%	4.0	8
Median	5%	4.0	8
Max	38%	33.3	26
Min*	0%	0	2

*No measurable difference

Door undercut also did not seem to be directly related to the pressure created. This is likely because door undercut is only one of four sides of the door opening, and gaps at the sides or top also provide pressure relief. This finding may be of interest to regulators who would like to know whether ventilation requirements should include greater attention to door undercuts or other pressure relief.

It is possible that higher flow rates may be more strongly affected by closed doors. Figure 35 shows the measured flow rates and the flow reduction that occurred when the door was closed. It shows that the highest measured flow rate of approximately 324 m^3/h was affected by 38% when the door was closed. In these cases, insufficient makeup of air will result in reduced performance. For lower flow rates that may conceivably be required by regulations such as NCC 2022 H6V3 (2) (iii), usually less than 100 m^3/h or 30 L/s for a given house, the effect is quite minor.

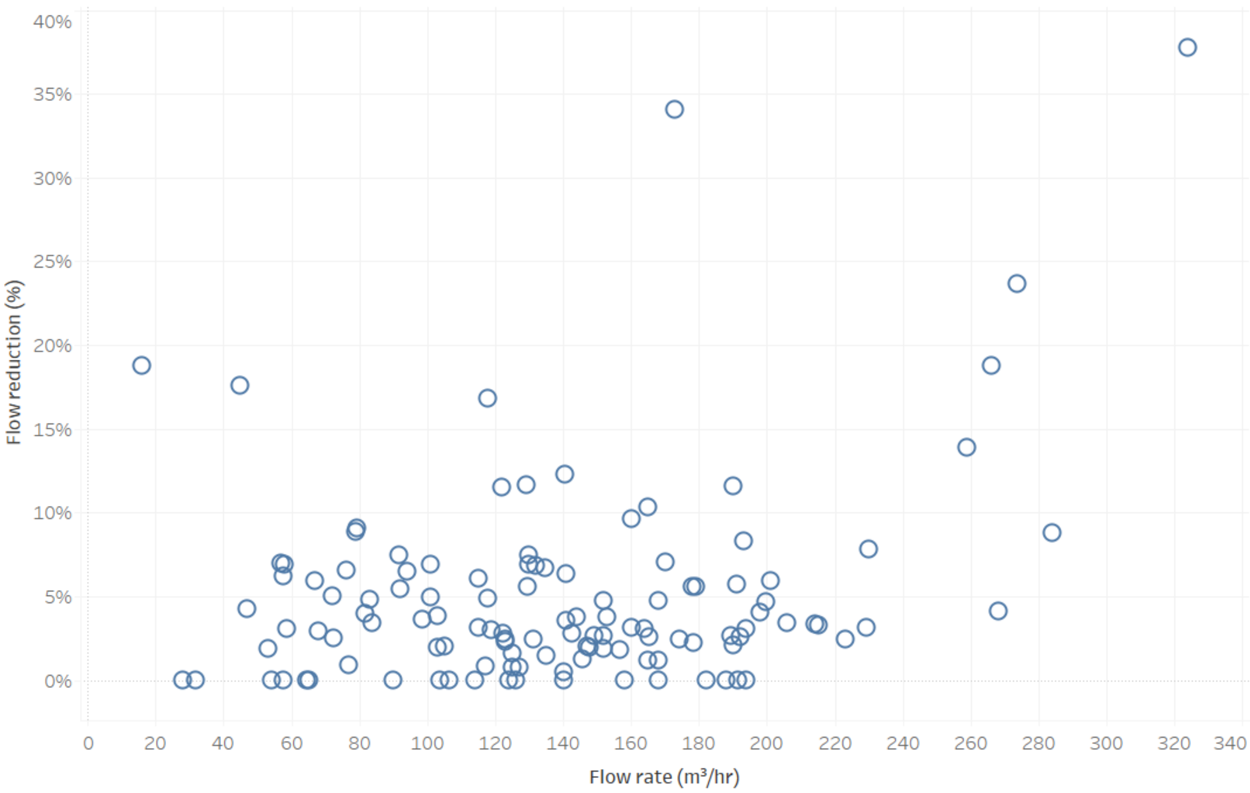


Figure 35 Measured flow rates and flow reductions from closed door

The results show that typical Australian construction can deliver systems that provide effective minimum ventilation. If air tightness is a regulatory focus, it should be paired with a requirement for continuous ventilation. The same installation details apply for any ventilation system already – product selection for the intended application and proper installation of the system.

8.3 Duct air leakage

Duct leakage can have significant energy, performance, and occupant health consequences. NatHERS focuses on the thermal efficiency of the building envelope and the new Whole of Home component also includes the type of heating/cooling system installed and its efficiency and includes calculations for duct energy losses while heating/cooling systems are in use. However, air leakage through ducts when not in use, is not currently considered. To investigate this issue further, duct system air leakage was tested in 11 houses in this study.

Duct systems were tested in one of two different ways, depending on the system type. Evaporative cooling systems, which are essentially open-ended systems that do not recirculate indoor air, could only be tested with a subtraction method with a blower door test. That is, the whole house was tested with a blower door in normal operating position, then again with the registers sealed with plastic. The difference between the two was taken as the air leakage attributed to the evaporative cooling system. The process was conducted in both positive and negative pressure and the average used. The results were calculated and expressed as air leakage in m^3/h at 25 Pascals.

All other systems were reverse-cycle cooling systems and they all had return air pathways to recirculate indoor air through the unit to be treated again. The system used for this method was a Minneapolis Duct Blaster by The Energy Conservatory. The test method followed was ANSI/RESNET 380.

The duct tester was connected to the return register with the filter removed, see Figure 36. The pressure in the ductwork was measured at the nearest supply register. After recording a baseline pressure, the ducts were then pressurised to 25 Pascals and the leakage rate recorded. The results were expressed as leakage in m^3/h at 25 Pascals.

Figure 36 Duct testing setup

There were four main system types evaluated: ducted reverse cycle system with a ducted return register in the ceiling; a ducted reverse cycle system with a return duct mounted on a wall building cavity that served as ductwork; a bulkhead-mounted system that largely used wall/ceiling cavities as ductwork; and evaporative coolers that only had supply ductwork and no return air path. Other system configurations are possible but were not found in the population of volunteered homes. All homes were Class 1 detached homes, not apartments.

Table 8 lists the results and shows there is room for improvement on all of the systems that were tested. One method of comparison is duct air leakage per unit of living space, such as m^3/hr @ 25 Pascals per m^2 of floor area. For reference, the 2021 International Energy Conservation Code sets a maximum leakage allowance of 4 CFM per 100 square feet of floor area (about 0.73 m^3/h per square meter of floor area) when tested at 25 Pascals. None of the systems tested would pass this target, and the averages were well above.

While all systems would fail the current IECC 2021 leakage requirements, some would have passed the IECC 2009, the first year in which duct testing was required in that building code. A few more systems would have passed either the total leakage test or the leakage to outside test.

Table 8 Duct testing results compared to IECC 2021 and IECC 2009

System type	Return air path		IECC 2021	IECC 2009	
		Air leakage m^3/hr @ 25 Pa per m^2 floor area	Total air leakage <0.73 m^3/hr @ 25 Pa per m^2 floor area	Total air leakage <2.19 m^3/hr @ 25 Pa per m^2 floor area	Air leakage to outside <1.46 m^3/hr @ 25 Pa per m^2 floor area
Ducted reverse cycle	Ceiling register	1.69	Fail	Pass	Fail
Ducted reverse cycle	Ceiling register	0.80	Fail	Pass	Pass
Ducted reverse cycle	Ceiling register	2.20	Fail	Fail	Fail
Ducted reverse cycle	Ceiling register	0.90	Fail	Pass	Pass
Bulkhead-mounted reverse cycle	Wall cavity	3.30	Fail	Fail	Fail
Evaporative cooler	n/a	0.98	Fail	Pass	
Evaporative cooler	n/a	5.27	Fail	Fail	
Evaporative cooler	n/a	9.13	Fail	Fail	
Ducted reverse cycle	Wall cavity	0.85	Fail	Pass	
Ducted reverse cycle	Wall cavity	1.87	Fail	Pass	
Ducted reverse cycle	Wall cavity	11.61	Fail	Fail	

Table 9 lists the average performance of systems of different types, expressed as leakage per m^2 of floor area.

Table 9 Average performance of ducted systems

System type	Return air path	Air leakage m^3/hr @ 25 Pa per m^2 floor area
Ducted reverse cycle	Ceiling register	1.40
Ducted reverse cycle	Wall cavity	4.78
Bulkhead-mounted reverse cycle	Wall cavity	3.30*
Evaporative cooler	n/a	5.13

** Only one of four systems installed in this house was tested, so the total is likely much higher*

In particular, the house with the bulkhead-mounted system had exceptionally bad performance (Figure 38). Only one of the four systems installed in the house was tested. Presumably, if the other three systems had similar performance, the combined result could conceivably be four times worse. This constitutes an extraordinary energy loss.

Any duct air leakage to an unconditioned space such as a roof space is a direct energy penalty. There is no possibility of recovering the energy spent on heating or cooling that air. However, when ductwork is located within the conditioned envelope the losses are lessened. An example is a wall surface-mounted split system. All air that passes through the system is directly recovered from the living space, and distribution losses are nil, see Figure 37.

Distribution entirely outside the conditioned envelope

Distribution entirely within the conditioned envelope

Figure 37 Ducting distribution systems

Many ducted systems have elements both within and outside the conditioned envelope. For example, some multi-story homes have ducts in the roof space but also others that pass through inter-floor spaces that are within the conditioned envelope. Any duct air leakage outside the conditioned envelope results in direct energy losses, but air leakage within the conditioned envelope may still indirectly condition the space to some extent.

One test method seeks to distinguish between “total air leakage” and “air leakage to outside”. Some building codes tried to differentiate between them as well. The IECC 2009 indeed had two options for compliance: either pass a limit for total leakage, or a limit for leakage lost to outside. ANSI-RESNET-ICC- 380-2016 describes the test method.

To conduct an air leakage-to-outside test, the ductwork is pressurised or depressurised to 25 Pascals. Then, the house itself is co-pressurised to the same pressure. Because the house and the ducts in which they are installed are then at the same pressure, any leaks between the two – that is, air leakage between the ducts and conditioned space – should produce no flow and should not be measured. As a result, only air leakage lost to spaces outside the conditioned envelope should be measured.

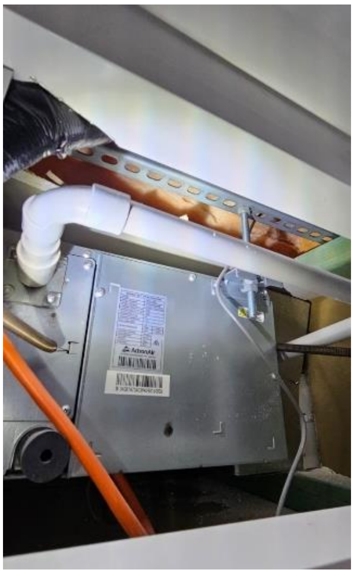
In this study, the air leakage-to-outside test was done on five systems. Table 10 lists the result and shows that almost all the duct air leakage measured (79-93%) would be directly lost to unconditioned space.

Table 10 Leakage to outside test results

System type	Return air path	Number of systems tested	% duct air leakage lost to outside
Ducted reverse cycle	Ceiling register	1 of 1	93%
Ducted reverse cycle	Ceiling register	1 of 1	84%
Ducted reverse cycle	Ceiling register	1 of 1	84%
Ducted reverse cycle	Ceiling register	1 of 1	79%
Bulkhead-mounted reverse cycle	Wall cavity	1 of 4	82%

While duct air leakage to outdoors is a direct energy loss, leakage not lost to the outdoors still has a performance penalty mainly due to systems not being able to deliver designed levels of airflow where needed. Systems run longer and harder as a result, and occupant thermal comfort may be impacted. In addition, any disproportionate duct air leakage on the supply or return side of a system may pressurise or depressurise a building due to more air being pumped into the building by the supply side or drawn out by the return side, respectively. This can have major problems in some climatic conditions when moisture may be drawn across the building envelope to negative effect.

It is worth discussing the result for the bulkhead-mounted system further. Figure 38 shows the design intent. The bulkhead is meant to be located within the conditioned envelope so that any air circulated to and from the unit should remain within the thermal envelope. Unfortunately, when the registers were removed, fiberglass insulation can be seen above the unit but only partially enclosed by plasterboard. The separation between "inside" and "outside" is not well executed.



Insulation visible above unit, showing poor isolation

Bulkhead over bed, where dust collected during testing

Figure 38 Poor isolation examples

Apart from the direct energy loss, there are major penalties for system performance, particularly on days of peak cooling demand. For systems like these, much of the air drawn into the unit comes from the hot roof space, causing major spikes in power usage during peak hours.

There are also health issues related to use of building cavities as ductwork. For example, when the blower door test on the house with the bulkhead-mounted systems was conducted, dust and fiberglass particles were sucked from the roof cavity and landed on a bed below. Because a blower door test only exerts a maximum pressure on a building perhaps equivalent to one produced by 40 km/h wind, periodic events of dust collection will probably be common in this house.

In another house, even a relatively well-sealed building cavity return contained copious rodent droppings and insect carcasses (Figure 39). In a two-storey house with especially bad leakage rate, the cavity return was being used as a general passage for many electrical and plumbing services. As a result, during the duct test, air could be felt from doorways, wall skirting, and even plumbing penetrations several rooms away, see Figure 39.

Building cavity leading to second floor

During testing, air could be felt from areas not considered "ductwork"

Systems with a ducted return generally performed better

Dead insects and mouse droppings in the return cavity on another building

Figure 39 Ducting issues

For occupant health, appliance performance, and energy use reasons, bulkheads and other building cavities should not be considered effective components for air distribution. Codes around the world have gradually disallowed this practice. For example, the IECC 2006 stated that building framing cavities shall not be used as supply ducts, but by the next edition IECC 2012, it expanded the exclusion to any ducts for plenums, supplies or returns included (IECC 2009, IECC 2012 403.2.3).

Figure 40 compares the duct leakage results to the overall permeability results for the dwellings where duct leakage was measured. Interestingly, it shows that no obvious relationship exists between the duct leakage rates and the permeability of the dwelling. The ducted systems with the lowest average leakage rate (ducted RC with ceiling registers) also recorded the highest average permeability rate. Dwellings with ducted RC with wall cavity returns or ducted evaporative coolers had similar average duct leakage rates and identical permeability rates. The number of systems tested was only small and so caution is needed in drawing any conclusions from these results. However, it does show that well installed ducted systems of any type tested here can perform well and have low leakage rates.

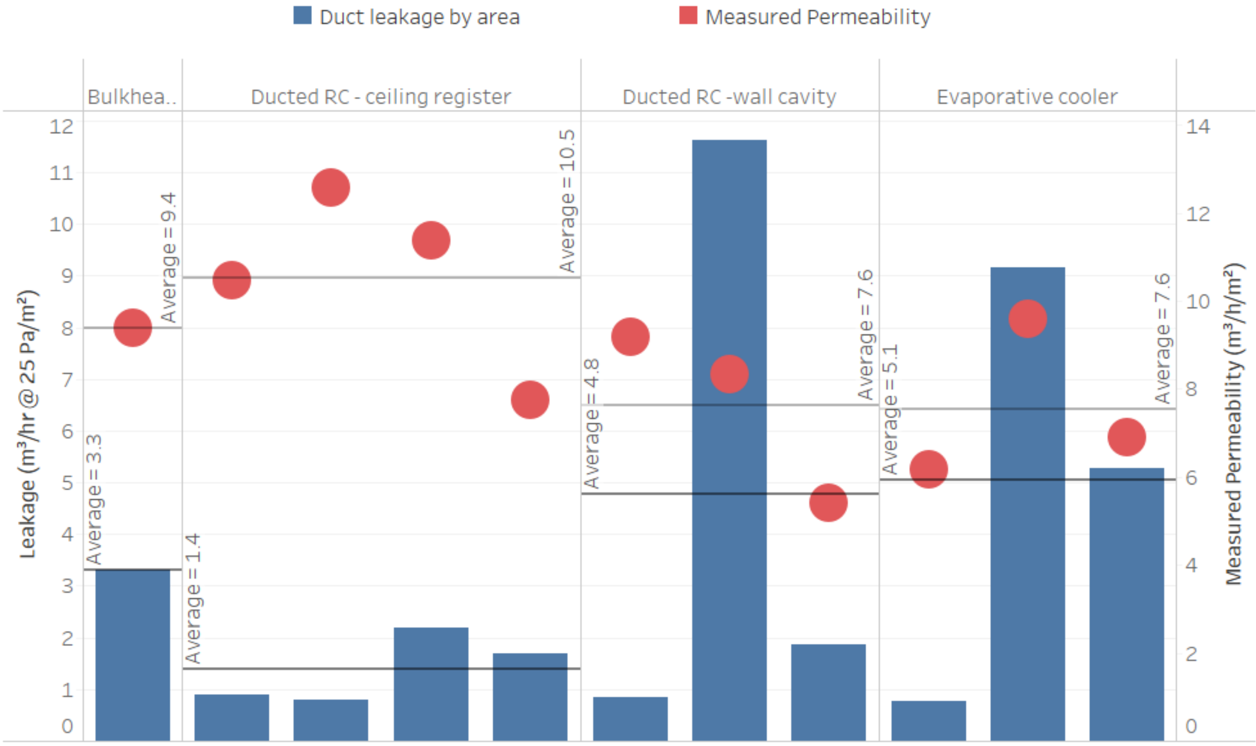


Figure 40 Duct leakage compared to dwelling permeability by HVAC system

8.4 Leakage point testing

An air tightness test aggregates all leaks of any size and shape and simplifies their performance as a single number. However, the process also enables diagnostics to be performed in a wide variety of ways, both qualitative and quantitative. For this study, leakage diagnostics were performed on homes in three cities in Victoria with the intention of quantifying some of the more common and easily measurable leaks.

The procedure involved depressurising a house to 50 Pascals, then using a powered flow hood to collect and measure the airflow from individual leakage points. Some leaks were straightforward to measure, such as light fixtures or access hatches. Others were presented in an odd shape, requiring adaptations to capture and measure the airflow, see Figure 41. Still others were too diffuse, long, or awkward to be measured with the devices in use. The measurements expand our knowledge of what leakage points in a building are responsible for the greatest losses in air tightness. Therefore, they represent some of the most attractive opportunities for improvement.

Direct measurement with flow meter	Measurement with flow meter and additional capture hood
	

Figure 41 Examples of methods for undertaking individual component leakage testing

There is variability in all the leakage data, which is useful to note. In the data, an average is shown, as well as the maximum and minimum values, and an expression of variability, derived simply as the standard deviation of the dataset divided by the average value. The high variability of some leak types shows that there is great inconsistency in construction. For example, while there were a few examples where building cavities were used as ductwork without major penalty, on average they do not perform well. In addition, some examples are extremely bad. This inconsistency and potential for major failure is a useful consideration for addressing these problems with regulation.

8.4.1 Measurement methods

Flow measurements were made with an ACIN FlowFinder Mk II, a powered capture hood that compensates for back pressure when the hood is placed over the leak. This is the most accurate method of measuring an air leak and is the method used for almost all of the leaks in the study. While none of the leaks were too large to be measured by the instrument, many were below the stated lower limit of the measurement range of 10 m^3/h. While such measurements should be regarded with greater uncertainty, it still means that they are relatively very minor leaks.

When a leak was too large or inaccessible to be measured directly with the flow meter, an accessory capture hood was constructed to corral all the leakage to a point where it can be captured by the flow meter. The error introduced by this addition is minimal, because pressure compensation of the flow hood also acts on the capture hood. Therefore, even if the capture hood were imperfectly sealed over the leak, pressure compensation meant that the pressure acting on an imperfect seal was close to zero pascals, minimising the error.

For this small study, leakage from duct systems was directly measured with the flow hood with the house depressurised to 50 Pascals with the blower door, where they connected to the conditioned space at the register. Duct leakage testing is commonly performed for building code compliance in some countries by using a calibrated fan to pressurise systems that have been temporarily sealed with tape. The test is easily standardised and repeatable which makes it useful for regulation, but it does not readily indicate the location or severity of leaks. One benefit of performing local measurements of leakage is that the leakage rate of individual duct segments can be measured. While this method may underestimate total duct leakage and is more indicative of leakage to outside, its diagnostic character leads to useful insights.

In one case, a return for an air source heat pump system was made from a building cavity and the flow was too great to be measured directly with the flow hood. A subtractive method with a blower door was used. First, a blower door test was done with the ducts as they were found. Next, the duct was sealed with foam board and the test was repeated, see Figure 42. The difference between the first and second measurements can be attributed to the duct leak. There are drawbacks to this approach, including the imprecision of the blower door measurement which increases uncertainty. Also, slight changes to duct pressures elsewhere in the system during masking may reduce the scale of the measured difference, so the figure may be a slight underestimate. Still, the technique lends an approximation to an otherwise unknown value.

8.4.2 Leakage point measurement results

Table 11 is a summary of measurements from the eight houses in this portion of the study. All the systems showed major performance penalties from duct leakage. The figures include leaks from ducts themselves, from the heating and cooling units serving them, from building cavities used as ductwork, and from connections of duct register boots to the interior finish. The two houses with evaporative coolers had a duct system for the evaporative cooler as well as a ducted heating system. All ductwork has leakage losses as well as thermal conductivity losses throughout the year.

The data shows that the houses with evaporative coolers had a higher average leakage rate than those with a single system providing both heating and cooling.

Table 11 Leakage point measurement results

Leak Category	Average m^3/hr @ 50 Pa	Minimum m^3/hr @ 50 Pa	Maximum m^3/hr @ 50 Pa	Number of separate measurements	Variability*
Houses with evaporative cooling					
AC ducts – Evap.	1667.9	947.5	2388.2	2	61%
Heating ducts	448.9	250.6	647.3	2	62%
(total ducts – evap. + heating)	2116.8	1198.1	3035.5	2	61%
Houses with air source heat pump					
AC ducts - ASHP	1006.9	302.8	2439.7	6	88%
Return ducts					
Ducted AC return	230.8	109.4	478.1	5	69%
Cavity AC return	802.2	142.2	1411.2	3	79%
*std deviation as % of average value					

8.4.3 AC ducts – evaporative cooling system and separate ducted heating system

Two houses were fitted with evaporative cooling systems that were paired with separate ducted heating systems. Leakage from the systems were measured at each individual distribution register (Figure 42). For the cooling systems, it could not be confirmed whether the systems possessed dampers meant to close when the systems are not in operation. It is possible that they possessed weighted dampers and that these pulled open during testing with the house under negative pressure. Therefore, it is possible that in normal building operation, these systems do not leak as much. If not, these were by far the single largest leak in the study. Remediation would require the use of better dampers, ideally motorised so that they are not subject to opening by breezes.

One side note is that the airflows measured from individual registers for the evaporative cooling systems were consistent within the same house. Inconsistent readings may indicate that local factors such as individual duct-to-space connections that allow building air infiltration were not likely a large factor in the measured values. The measured values are therefore likely to be attributable to the leakage of the cooling system itself. In addition, the use of a separate duct system for cooling and heating means that the total duct leakage figure for these houses should include both systems. The leakage rate of the systems combined was particularly bad in one house, amounting to close to an equivalent effect on the building's air permeability of 6.8 $m^3/h.m^2$ @ 50 Pascals. The ductwork of the two systems in the other house contributed close to 2.2 $m^3/h.m^2$ @ 50 Pascals. These represent a significant performance and comfort penalty.

Measuring flow rate of duct system leakage from an individual register	Measuring flow rate of return duct building cavity using subtractive method with a blower door	
		

Figure 42 Measurement techniques for ducted systems

8.4.4 AC ducts – heating and cooling sharing same system

In the other buildings with air source heat pumps, the heating and cooling systems shared a single system of ductwork. Leakage from these was measured with the powered flow hood at each register with the house depressurised to 50 Pascals. Obvious, was the major performance penalty from the common practice of the use of wall and floor cavities as ductwork. This practice has been explicitly banned in building codes abroad for many years because it is so problematic. Every building cavity used as a return was inspected, and each contained many dead insects inside, a testament to how open these cavities are to the unconditioned environment.

Figure 43 shows how this construction suffers major performance penalties. When the return register was removed, many dead insects were observed in the bottom of the cavity. Looking up, a large gap in the interior finish of the cavity allows air from the bulkhead over kitchen cabinets to pour into the return cavity. The duct from the range hood over the cooktop can be seen. This connectivity means that during summer months, air from the super-heated roof space is being pulled down into the return, greatly exaggerating cooling loads. This single assembly is estimated to contribute more than 1400 m^3/h of leakage at 50 Pascals.

Building cavity as AC return, register removed. Pathway for air leakage from roof space is shown with arrow.	Looking up towards roof inside return cavity. Ceiling insulation can be seen.	Ceiling insulation above range hood duct in bulkhead over cabinets. Duct from range hood visible.

Figure 43 The use of building cavities as ductwork

In another building, the use of building cavities as ductwork carried a similar penalty. The wall cavities used as a return duct are estimated to contribute more than 850 m^3/h @ 50 Pa. However, another common practice showed negative results. In this two-story home, ducts on the ground floor were placed in floor cavities but the final connection of the register boot to the interior finished surface was incomplete (Figure 44). Presumably the assumption is that the floor cavity would act as ductwork. Unfortunately, significant air leakage from the floor cavity entered at each of these points.

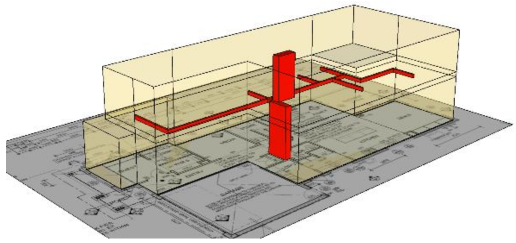
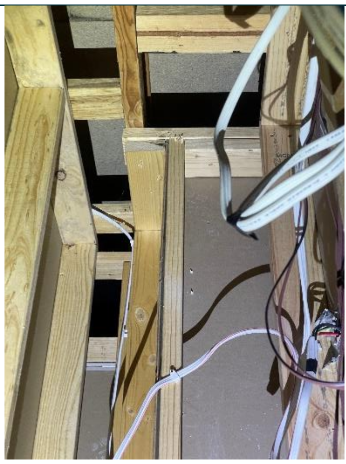
Register not connected to interior finish	Register well sealed to interior finish	Building cavities functioning as ductwork in a two-story home
		
Building cavity as return	View into building cavity return	Cavity is connected to floor assemblies and level above
		

Figure 44 Examples of building cavities being used as ductwork

Leakage rates of different supply and return registers in the two-story house are shown in Table 12. The average leakage measured at the registers on the ground floor, which used floor cavities as ductwork, was more than twenty times as much as that from registers upstairs which were sealed to the interior finish.

Table 12 Leakage rates of different supply and return registers in a two-story house

Floor location	Type	Register boot mounting	Leakage m³/hr @ 50 Pa
Downstairs	Supply	Building cavity	63
Downstairs	Supply	Building cavity	251
Downstairs	Supply	Building cavity	107
Downstairs	Supply	Building cavity	337
Downstairs	Supply	Building cavity	292
Downstairs	Supply	Building cavity	207
Downstairs	Supply	Building cavity	235
Both	Return	Building cavity	853
Upstairs	Supply	Sealed to surface	8
Upstairs	Supply	Sealed to surface	6
Upstairs	Supply	Sealed to surface	7
Upstairs	Supply	Sealed to surface	9
Upstairs	Supply	Sealed to surface	9
Upstairs	Supply	Sealed to surface	9
Upstairs	Supply	Sealed to surface	26
Upstairs	Supply	Sealed to surface	10
Upstairs	Supply	Sealed to surface	9
		Total	2440
		Average	
Upstairs	Supply	Sealed to surface	10
Downstairs	Supply	Building cavity	213
Both	Return	Building cavity	853

From the larger study there were many examples of leaks that would be valuable to quantify if given the opportunity, such as leaks from ceiling plenums that are common in premium apartments and houses (Figure 45). There are many systems that are based on a design of using a building cavity as ductwork, with bulkhead units among them. These demonstrated major flow rates of air leakage.

Leakage from ceiling plenum	Ceiling plenum in house	Ceiling plenum in apartment
		

Figure 45 Ceiling plenums

A wide variety of individual leaks were measured to investigate their penalty and these are listed in Appendix B.

9 Conclusion

233 newly built dwellings were tested in Melbourne, Sydney, Brisbane, Canberra and Adelaide, comprising of 105 apartments and 128 detached houses. Apartments recorded the lowest overall average qE_{50} of 5.8 $m^3/h/m^2$ with Queensland apartments recording the lowest of the regions with an average *qE50* of 4.3 $m^3/h/m^2$. Single storey houses had an average qE_{50} of 6.8 $m^3/h/m^2$ while two storey homes recorded the highest average qE_{50} of 8.5 $m^3/h/m^2$. This is a significant improvement in air tightness performance since a previous study in 2015 determined an average air change rate of 15.4 ACH @ 50Pa for newly constructed houses, effectively double the rate determined in this study. This compares well to requirements in other countries, such as the UK, which has a new maximum permeability requirement for new dwellings of 8 $m^3/h/m^2$.

For this project a target qE_{50} of 10 $m^3/h/m^2$ was selected. This is the threshold cited in NCC 2022 V2H6V3 as the performance requirement for dwellings seeking compliance through the performance provisions of the building code. Using the average permeability of each dwelling, this target was exceeded by only 9.7% of dwellings (11.7% of Class 1 and 7.1% of Class 2). In addition, analysis between the NatHERS assumed air tightness level and the actual measured air tightness showed a close alignment, particularly with Class 1 dwellings, with an average difference of only 0.01 $m^3/h/m^2$ between them. For apartments the average difference was 2.17 $m^3/h/m^2$. In most cases the assumed value was more conservative than the measured value which gives good confidence in the ability of NatHERS to accurately model air tightness with a specified air tightness target.

Nevertheless, the post-test survey did identify leakage points in most dwellings. Ceiling exhaust fans were identified as a leakage point in 63% of apartments and houses. Sliding doors were also a major issue in 48% of houses and 63% of apartments. For houses their most reported issue was poor or missing door seals. This was reported in 65% of houses.

The Chenath engine currently calculates air changes per hour using volume (ACH @ 50Pa). A further calculation method is being developed to output the air infiltration rate using surface areas and output a value at $m^3/hr.m^2$ @50Pa. The Chenath engine follows a slightly different calculation method than ISO 9972:2015, which creates a slightly different and generally more conservative result. 21 calculations of surface area and volume were made according to both the NatHERS and ISO 9972:2015 methods.

Overall, there was an average difference of 3.7% between ISO 9972:2015 and the NatHERS calculation method, with the NatHERS figures always being smaller. The difference was smaller for apartments and single-story houses, and greater for multi-story houses, from a minimum of 1.5% up to a maximum of 6.3%. Applied in a regulatory context, demonstrating compliance with a maximum leakage target in the design stage will therefore usually be more conservative when using the NatHERS method than when using the ISO 9972:2015 method. For this reason, if a dwellings design can meet a target in NatHERS it will by default show that it meets that target according to ISO 9972:2015.

A series of additional leakage tests were undertaken on specific aspects of dwellings that are suspected of having a significant impact on a dwelling's overall air tightness. HVAC ductwork was investigated with four main system types evaluated: ducted reverse cycle system with a ducted return register in the ceiling; a ducted reverse cycle system with a return duct mounted on a wall building cavity that served as ductwork; a bulkhead-mounted system that largely used wall/ceiling cavities as ductwork; and evaporative coolers that only had supply ductwork and no return air path. All systems tested were in detached homes, not apartments. The tests revealed the following:

- No duct system tested would have met requirements in the IECC 2021, but some would have met requirements in the older IECC 2009, the first in which testing was required.
- Duct air leakage losses are currently not part of NatHERS modelling calculations however this is probably a significant contributing factor in building energy use.
- Use of building cavities as ductwork can lead to energy loss, peak electrical demand, and possible occupant health consequences.
- Evaporative cooling systems have the potential for large performance penalties, most likely due to missing or ineffective dampers that should close when the systems are off. Where dampers are used, they should be of the motorised type.
- There is a major opportunity for energy savings in Australian housing by testing more ductwork to at least highlight the opportunity for savings and reform practice. Best practice would constitute duct testing as a regulatory requirement.

Overall, for each of the leaks identified during this study, a cost-effective solution is usually available to rectify the leakage point. Some of these are listed here:

Large discrete leaks – addressed through building code and supply chain development.

- Building cavities as supply ductwork
- Building cavities as return ductwork
- Bulkhead units without ductwork
- Vents over fridge

Larger leaks due to general absence of air barrier – addressed by trades training and incentives for air tightness testing.

- Cabinet over range hood
- Cabinet around oven
- Cavity sliding doors

Smaller leaks due to general absence of air barrier – addressed by incentives for air tightness testing rather than specific targeting.

- Power points
- Communications box

Product-related leaks – addressed through regulation or support of supply chain development.

- Bath fans
- Window units
- Sliding glass door units
- Solar tube

- Range hood
- Downlight

Smaller miscellaneous leaks – addressed by trades training.

- Access hatch
- Kitchen service penetrations

10 Recommendations

The study provides many insights into common performance problems. Some recommendations for addressing them include the following.

- **Introduce air tightness requirements**. Overall, NatHERS models air tightness well, showing good correlation with the actual measured values. However, variability was found and this has negative implications for energy use, moisture management, and indoor air quality. Some homes in this study were very leaky, with air permeabilities likely at least twice the assumptions in their NatHERS model, a condition that represents a compliance problem, while other homes, particularly some apartments, were shown to be extremely airtight but with no continuous ventilation, a condition that is a concern for occupant and building health. The National Construction Code (NCC) should work towards appropriate air tightness requirements for all climates.
- **Continuous ventilation**. Approximately 26% of dwellings in the study were tested below a permeability of 5 $m^3/h/m^2$ @ 50 Pascals (15.6% of Class 1 and 39.1% of Class 2). The NCC currently requires application of continuous mechanical ventilation when below this threshold. However, because these homes were not aware of, or aiming for a permeability rate, no continuous ventilation was installed. For many reasons, construction will continue its trend towards increased air tightness. The NCC should consider a mandatory requirement for continuous mechanical ventilation dwellings, particularly Class 2 dwellings. The aim is to reduce the concentration of interior moisture and other pollutants and their associated risk to occupant health. This would reduce the negative consequences of dwellings unintentionally achieving low air permeability results, while delivering occupant and building health benefits.
- **Air barrier installation**. The presence of an air barrier is a factor in air tightness of dwellings. While the NCC requires that materials used as sarking possess defined levels of vapour permeability, it does not currently explicitly require the use of an air barrier. An air barrier, whether a purpose-made product such a wrap or an inherently airtight material such as poured concrete, should be required on all dwellings. Air barrier materials may be classified through standards such as AS/NZS ISO 14857:2023.
- **Air barrier behind cabinetry and bulkheads.** Many of the larger leaks found in housing come from an absence of an interior air barrier. Ensuring full coverage on walls before installation of kitchen, bedroom, and bathroom cabinetry in new homes would greatly improve performance. In locations such as kitchens, the gaps caused by absence of this interior lining are the likely paths that pests such as insects, arachnids, rodents, and other pests.

- **Fully connected ductwork**. Ducted heating and cooling systems that used fully ducted distribution systems often performed well. However, where building cavities were used to extend or replace sections of ductwork, major performance penalties were observed and measured. The NCC should require that ducted systems are fully ducted and sealed, including to the final connection with the interior surface. Analysis must be conducted to support these changes.
- **Include modelled air tightness value on NatHERS certificate**. The air tightness value that has been used in the NatHERS model should be displayed on the NatHERS certificate.
- **Allow air tightness levels to be directly specified in NatHERS**. NatHERS models air tightness well and energy assessors should be able to directly nominate an air tightness level for a design and note the impact on the star rating. Any nominated air tightness level must be verified upon the building's completion with an air tightness test, before certification.
- **Link to ATTMA certificates**. Schemes such as the Air Tightness Testing and Measurement Association have test result verification that would pair well with a NatHERS rating where a nominated air tightness level has been specified. Once the building is completed, the NatHERS building details can coordinate with ATTMA's Lodgement verification system. Once the test is completed, a standard ATTMA certificate is issued for verification.
- **Simplify how NatHERS treats air tightness**. Eventually, the way NatHERS simulates air tightness should be simplified. Currently, penetrations in the envelope include exhaust fans, downlights, ceiling and wall vents, flues and chimneys. Many of these penetration types are rare or prohibited in new builds, while others are not significant contributors to air leakage. Downlights, for example, as found in this study were generally well sealed and were not identified as a leakage point, whereas HVAC ductwork and registers are significant leakage points that are not accounted for. Simpler and broader approaches should be considered, such as a simple nominated air tightness level, otherwise any assumption should be conservative. An option of allowing a specified air tightness level to be nominated that would then require verification via an air tightness test on building completion, as recommended earlier.
- **Education resources**. Education is needed to bring the building industry along with the necessary transition to improved building performance. The results from this study may provide a substantial basis for builders as well as NatHERS assessors. On site training or field walkthroughs would be an excellent opportunity to connect builders with real cost-effective improvements. Once air tightness is a fully functional part of NatHERS, training of assessors will also be required to educate them on its application responsibly.

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Appendix A – Survey

1. HouseID

2. Dwelling Type
    - House - detached
    - House - semi-detached
    - Townhouse attached
    - Townhouse end
    - Flat/Apartment - Ground floor
    - Flat/Apartment - Mid floor
    - Flat/Apartment - Top floor
    - Flat/Apartment - Over unconditioned space

3. Are building plans available?
    - Yes - copy obtained
    - No, but NatHERS assessment completed
    - No, but site measurements taken

4. Was air tightness a goal for this home?
    - No
    - Unknown
    - Yes - target unknown or undefined
    - Yes - target known (What was this target?)
5. Number of bathrooms
    - One
    - Two
    - Three
6. Bath 1 Ventilation Type
    - Intermittent extract
    - Continuous extract
    - Passive vents (no fans)
    - Unknown
    - Other

7. Bath 1 Ventilation infiltration control
    - Damper on fan unit
    - Damper at duct terminus
    - No damper
    - Unknown
    - Other

8. Kitchen Ventilation Type
    - Intermittent extract

- Continuous extract
- Passive vents (no fans)
- Unknown
- Other

9. Kitchen Ventilation infiltration control
    - Damper on fan unit
    - Damper at duct terminus
    - No damper
    - Unknown
    - Other

10. Ceiling conditioning (Select all that apply)
    - Warm roof
    - Cold roof
    - Cathedral ceiling

11. Roof/ceiling air barrier assembly
    - Exterior wrap/sarking present
    - Interior wrap/air barrier present
    - Plasterboard only
    - Concrete slab
    - Other

12. Wall exterior cladding assemblies (Select all that apply)
    - Brick
    - Weatherboard
    - EIFS (Render)
    - Metal
    - Other

13. Wall air barrier features
    - Exterior wrap/sarking present
    - Interior wrap/air barrier present
    - No wrap/sarking used
    - Curtain wall
    - Shopfront assembly
    - Unknown
    - Other

14. Wall framing (Select all that apply)
    - Timber
    - Metal
    - Concrete/block
    - Mass brick

- Other

15. Floor air barrier assembly (Select all that apply)
    - Concrete slab on grade
    - Concrete slab over other
    - Timber underfloor
    - Other

16. Building layout features (Select all that apply)
    - Attached garage
    - Garage under living space
    - Attached porch
    - Attached alfresco
    - Other

17. Number of downlights

18. Leakage points (Select the top 10)
    - Wall vents
    - Chimney
    - Gas heater
    - Bath fan
    - Poor damper on bath fan
    - Plumbing penetrations
    - Cabinets
    - Cuts or vents over fridge
    - Poor or missing door sweep - front or rear entry
    - Poor or missing door sweep - garage
    - Window - sliding
    - Window - double hung
    - Window - awning or casement
    - Trickle vents
    - Sliding glass door
    - Seal around windows
    - Trim around windows
    - Skirting missing seal
    - Missing skirting
    - Cavity sliding door
    - Leaky electrical panel
    - Ductwork
    - HVAC return cavity/plenum
    - Stairs
    - Evaporative cooler
    - Clothes dryer or vent termination
    - Downlights
    - NBN Box

- Electrical box
- Ceiling/roof access hatch
- Pet door
- Other

19. Heating/Cooling Systems in House (Select all that apply)
    - Split AC
    - Ducted AC
    - Ducted Heating
    - Ducted Evaporative Cooling
    - Wall mounted heater

20. Is apartment entry door from internal corridor?
    - Yes
    - No

21. Corridor door status
    - Good seal applied to door sides and top
    - Poor seal applied to door sides and top
    - No seal applied to door sides and top
    - Good seal applied to door undercut
    - Seal on door undercut does not fully reach floor
    - No seal applied to door undercut
    - Door closes firmly
    - Door closes loosely

22. Estimated average size (in mm) of unobstructed door undercut

23. Test in negative direction (Select all that apply)
    - Photographs of test equipment setup recorded
    - Photographs of building preparations, if any

24. Test in positive direction (Select all that apply)
    - Photographs of test equipment setup recorded
    - Photographs of building preparations, if any

25. Additional notes

Appendix B – Other leakage measurements

Many other leaks were measured to investigate their penalty. Some of these leaks are currently included in common energy models. The measurements may help assess whether software assumptions are reasonable or should be updated. Other leaks are examples where energy models often fail to appreciate the wide range and significance of other possible air leak paths. Table 13 lists a summary of the measurement results.

Table 13 Leakage measurement results for a variety of leakage points

Leak Category	Average m^3/hr @ 50 Pa	Minimum m^3/hr @ 50 Pa	Maximum m^3/hr @ 50 Pa	Number of separate measurements	Variability*
Cabinet over range hood	221.0	221.0	221.0	1	-
Cabinet around oven	150.4	27.4	232.2	5	55%
Cavity sliding door	125.9	50.4	414.0	6	113%
Vent over fridge	105.1	87.5	122.8	2	24%
Communications box	89.3	61.6	117.0	3	31%
Range hood	80.6	15.8	110.2	4	54%
Sliding window	77.4	67.0	87.8	2	19%
Laundry exhaust	44.3	34.6	52.2	4	17%
Bath Fan	42.9	28.1	81.4	23	31%
Access hatch	29.8	7.2	104.4	6	125%
Solar tube	22.7	22.7	22.7	1	-
Kitchen service penetrations	12.2	12.2	12.2	1	-
Downlight - dropped ceiling	7.3	5.4	8.6	3	23%
Smoke detector	5.5	4.0	7.9	7	25%
Audio speaker	4.8	3.6	6.5	3	31%
Downlight	4.8	2.5	7.2	30	24%
Surface mounted light	4.8	3.6	6.1	4	28%
Directional downlight	4.5	0.7	6.8	12	34%
AC control	4.0	4.0	4.0	1	-
Pendant	3.9	3.2	4.7	5	15%
Television outlet	3.2	3.2	3.2	1	-
Television outlet	3.2	3.2	3.2	1	-
Power point	3.0	0.7	4.0	8	38%
*std deviation as % of average value					

Some measurements were straightforward using the flow hood directly, such as those shown in Figure 46.

Roof access hatch	Solar tube	Communications box	Power point

			
Common downlight	Directional downlight	Downlight	Recessed downlight
			

Figure 46 Examples of individual items measured directly by flow hood

In the case of downlights, whether they were simple standard type, directional, surface-mounted, recessed, mounted in a drop ceiling or not, the leakage was very low. Although some houses had 50 or more of these fixtures, they should have little impact on the building's overall infiltration rate.

A common leak in the main study was bath fans. Major leakage could be demonstrated from many with fog or toilet paper. In this smaller portion of the study, only higher-quality fans, typically centrifugal type with an integrated damper, were present. They still showed some leakage, but it is expected that the problem typically is much worse in the general population.

Other common features may seem like a significant leak because they can be felt with the hand during a blower door test, but when measured, they are collectively small. Examples include discrete service penetrations that may feel larger than they are. It is also possible that the examples measured in this small study were less significant than normal. Fortunately, remediating these leaks is cheap and easy.

A very common leak is kitchen or bathroom cabinetry, see Figure 47. The problem isn't that cabinets themselves are not airtight – they aren't meant to be – it is that there is no solid air barrier material behind them before they are placed. An air barrier in this case can be something as simple as extra plasterboard sealed down to the subfloor surface before cabinets are installed. Leakage was measured from one example of this defect, and it shows the potential of the problem, at 221 m^3/h @ 50 Pa.

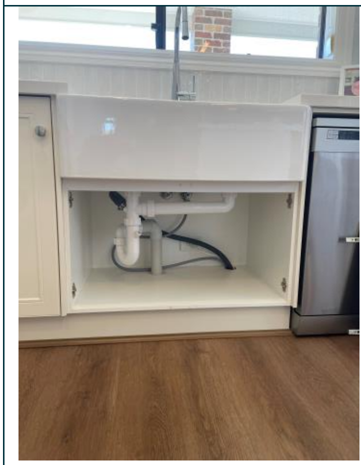
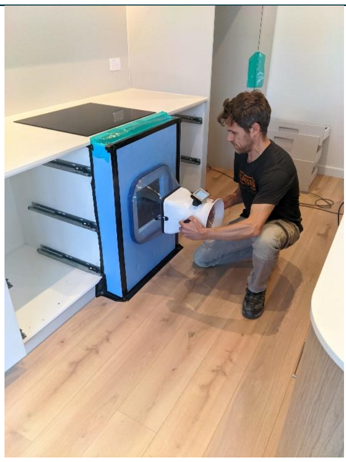
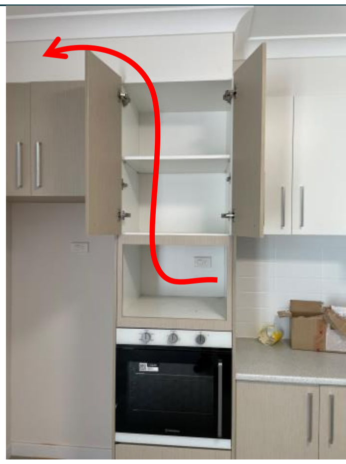
Kitchen utilities under sink	Variety of services	Sealing over cabinet and measuring with flow hood
		
Cabinet around range hood – no leaks	Cabinet around range hood	Measuring leak at holes for door hinges
		
Measuring leakage of cabinets around an oven	Observing leakage of cabinets around an oven	No solid blocking behind cabinets in another building in the main study. Plastic bags could be sucked from the cabinets into the roof.
		

Figure 47 Examples of leaks via kitchen cabinetry

Another common problem is a cavity sliding door (Figure 48). This leak is extremely common but sometimes variable. An average of 126 m^3/h @ 50 Pa was measured from 6 units, with a maximum of 414 m^3/h @ 50 Pa, more than 8 times the minimum of 50 m^3/h @ 50 Pa. Thus, an individual unit may not leak much, but potentially this is a very large fault. The force of the airflow from the unit with 414 m^3/h @ 50 Pa leakage was enough to repeatedly push the sliding door out of its housing in the wall.

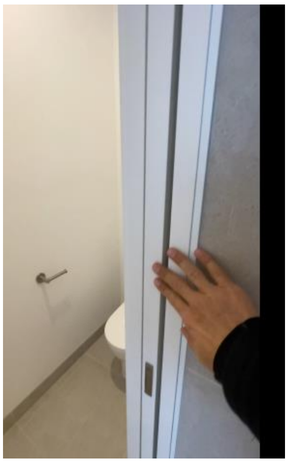
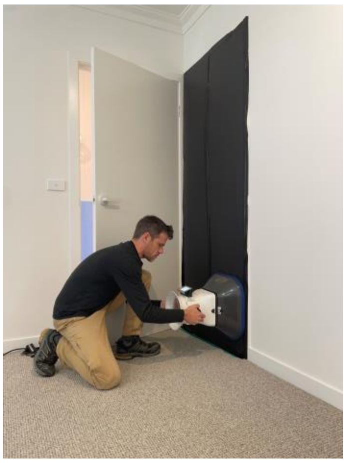
Typical cavity sliding door	Leakage from a door strong enough to push it out of the wall	Measuring leakage from the unit with masking to capture flow
		

Figure 48 Leakage from cavity sliding doors

One common practice with a negative effect is a vent cut over a fridge (Figure 49), presumably with the intention of enhancing refrigerator energy efficiency by improving airflow over a refrigerator. Unfortunately, this idea is misguided. Most refrigerator manufacturers recommend merely a 50-100 mm gap around the sides and top of the unit and make no mention of a need for a large gap to the roof space. In fact, because air from the roof space may be entering the home during the cooling months of summer due to stack effect in reverse, this practice may have the exact opposite effect as intended.

The average leakage measured on two homes with fridge vents provided was 105 m^3/h @ 50 Pa. Anecdotally, other homes in the main study had very large gaps that were estimated to leak as much as 500 m^3/h @ 50 Pa, but no similar examples were found in this sample of homes. During a blower door test, so much leakage was demonstrated that plastic bags could be sucked up into the hole.

Vent over fridge in this sample	Custom capture hood to measure leakage from fridge vent	Large vent cut into cabinets over fridge from home in main study
		

Figure 49 Ventilation holes for refrigerator

One category not related to build quality but more to product supply chain is the leakage of window and door units (Figure 50). In Australia, leakage of fenestration is a metric that is not required to be reported. Measuring leakage from units will help draw attention to the matter. Two sliding casement window units were measured. They had 67.0 and 87.8 m^3/h @ 50 Pa, respectively. For an entire house with many similar units, the total could be significant. Measuring leakage from installed windows is difficult because differentiating between leakage coming from the unit and leakage coming from the installation around the unit can be difficult. The two specimens tested were ideal in that they had no observable leakage from the enclosure they were installed in, so the number is probably fairly representative. Other window and sliding door units were not nearly as amenable to in-situ testing, so this was only performed twice.

Casement sliding window	Masking and measuring flow from window installation	Sliding doors, not tested
		

Figure 50 Leakage from window and door units

Other leaks were too small, oddly-shaped, or too diffuse to measure directly (Figure 51). Examples include some cabinetry, gaps along skirting, and a very typical absence of a seal at the bottom of a wall before carpeting is installed. These leaks show on infrared inspection and can be readily indicated with fog tools, but they are difficult to measure.

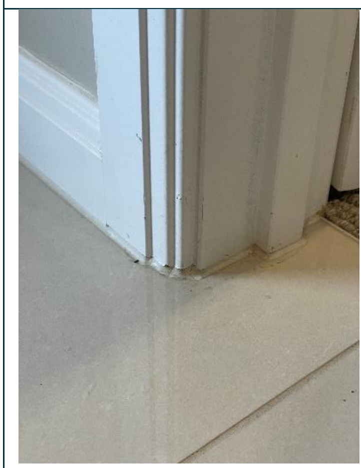
Kitchen cabinet	Gap at corner of cabinet	Bedroom cabinet
		
Bathroom cabinet with leak that could not be easily measured		
		
Skirting in one house with seal to floor	Skirting in house next door with no seal to floor	A door leak, not measured.
		
Leakage along base of wall	Leakage along skirting	Gap was not sealed before carpet was installed

Figure 51 Examples of leakage points identified, but too difficult to measure

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