Investigating Indoor Air Quality in Arrowtown using Hau-Haus (2019)

A CONA Progress Report

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Contents

Tables

Figures

Executive summary

Over a decade's worth of monitoring by Otago Regional Council has shown that whilst air quality in Arrowtown in summer is amongst the best anywhere in New Zealand, during winter it is amongst the worst. Whereas air quality in other towns has improved over that time, poor air quality persists in Arrowtown, and several other towns like it where solid fuel burning for home heating is common.

"Community Observation Networks for Air", or CONA, is a NIWA research initiative begun in 2015. It aims to explore how enhanced community-scale air monitoring networks, enabled by new low-cost technologies, and monitoring in the home in particular, can increase engagement with air quality issues, improve public understanding of the science, and promote or accelerate reductions in emissions or other actions to improve air quality in places like Arrowtown.

After pilot studies elsewhere, NIWA brought the CONA project to Arrowtown in 2019. This report is the second in a series covering the 2019 Arrowtown field study. It covers the results of an initial analysis of data from a network of prototype **indoor** air quality sensors. A separate report (Part One) covers **outdoor** air quality.

Thirty "Hau-Hau" prototype indoor air quality sensors developed by HauHau Ltd for NIWA were deployed in Arrowtown homes in 5 phases from June to October, successfully collecting 1 – 3 weeks of data from 70 homes. Although not all sensors worked as intended, sufficient high-quality data was captured to gain new insights into indoor air quality, whereas the study also provided valuable insight into instrument failures that will be used to inform future upgrades. For a subset of 28 homes where indoor and outdoor PM concentrations were high enough, it was possible to estimate the relative contribution of indoor and outdoor emissions sources to indoor air quality, albeit with some uncertainty.

We draw the following conclusions with a high certainty:

- There was a very large variation in indoor air quality (represented by concentrations of particles smaller than 2.5 microns, i.e. $PM_{2.5}$) between homes, ranging from 1 to 22 $\mu g\ m^{-3}$.
- In the relatively small sample of homes for which it could be calculated (28), on average, pollution from outdoor sources (which infiltrated into the home) made a larger contribution to indoor $PM_{2.5}$ sources (average 57 % from July – October), than indoor sources, with the contribution from outdoor sources increasing (to an average of 82 %) in mid-winter.
- As outdoor air quality varied hugely across the town (see Part One report), it follows that this dominant outdoor source was the main cause of the large variation in indoor air quality between homes.
- The contribution of indoor sources also varied substantially, but no particular geographical pattern is apparent at this time.

The following conclusions have a degree of uncertainty and will be the subject of ongoing research.

- The proportion of outdoor pollution that penetrated indoors varied from 16 – 61%, with an average of 35%. In other words, being continuously indoors would provide an

occupant an average reduction in exposure of 65% relative to being outdoors (at the same location).

- Homes with a lower air exchange rate – i.e. those that were more airtight – tended to have higher levels of outdoor-sourced air pollution inside the home on average (infiltration factor), and vice versa. These higher infiltration factors were more likely to be recorded in the north and east of the town. This implies that it is the rate at which polluted air is removed from the home, especially in the late evening and overnight, that determines the overall exposure of occupants to outdoor smoke,
- A few homes fell outside of this general pattern. These 'outlier' homes did not appear to be geographically clustered but were spread across the town, and the reasons why they behaved differently is currently unknown. However, they may give clues to ways in which indoor air quality can be inadvertently worsened, or deliberately improved.
- Air cleaning technologies may be an effective means of improving indoor air quality in Arrowtown, but there are many factors regarding the home and how it is heated and ventilated, which might enhance or undermine that effectiveness. Further research, particularly based on experimental trials in real Arrowtown homes, is required to understand these effects.

1 Introduction

1.1 Air quality in Arrowtown

Air quality has been measured continuously in Arrowtown by Otago Regional Council (ORC) since 2006, with the monitoring site moving from Arrowtown School to Arrowtown Recreational Reserve in 2014. These measurements have shown that whilst air quality in Arrowtown in summer is amongst the best anywhere in New Zealand, during winter it is amongst the worst. Over the last decade air quality has exceeded the National Environmental Standard between 16 and 46 days per winter every year.

Studies to date have indicated that Arrowtown's poor air quality is overwhelmingly caused by emissions from burning wood for home heating. Consequently, demanding rules for woodburning appliances have been established for Arrowtown (and other towns) by Otago Regional Council. Despite this, whereas long-term improving trends in air quality are apparent in many New Zealand towns and cities over the last decade and a half, this is not so in Arrowtown where air quality has changed little in that time.

We are aware of no previous study of indoor air quality in Arrowtown, or indeed any similar town in Otago or Southland. Studies of air quality inside New Zealand homes have been scarce and limited to date.

1.2 NIWA's role

NIWA (the National Institute for Water and Atmospheric Research) is a Crown Research Institute that carries out scientific research into a range of environmental topics related to water and air. It has no official role in air quality monitoring or management, but often acts as a scientific advisor.

However, NIWA does use part of the MBIE Strategic Science Investment Fund to conduct a research programme entitled "Impacts of Air Pollutants". This programme aims to help Regional Councils, agencies, businesses and the NZ public in developing understanding of air quality, expanding the scope and utility of air quality monitoring and improving the scientific evidence base for policymaking and everyday decision-making.

1.3 Community Observation Networks for Air

"Community Observation Networks for Air", or CONA, is a NIWA research initiative begun in 2015. It aims to explore how enhanced community-scale air monitoring networks, enabled by new low-cost technologies, can increase engagement with air quality issues, improve public understanding of the science, and promote or accelerate reductions in emissions or other actions to improve air quality.

Although the principles developed in CONA are designed to be applied to any air quality issue, to date the initiative has focussed on domestic home heating emissions as New Zealand's priority air quality issue. The relative failure of the National Environmental Standards and regional air plans to effect real improvements in air quality in towns like Arrowtown is most likely due to financial barriers, with other political and cultural forces at work. However, a hypothesis underlying the CONA approach is that these barriers may be compounded by lack of clear evidence on effective and successful solutions, particularly for householders and owners. The CONA initiative aims to develop means to generate more localised and accessible information for the community. The aim is to better inform and motivate actions that the community can take, providing rapid feedback to evaluate and refine those actions.

The heart of the CONA initiative is a series of winter field studies in small New Zealand towns. Each study has used its host town to develop new technologies or methods, whilst simultaneously improving the understanding of air quality in that town. As CONA has developed, "daughter" projects have emerged where some of the better developed CONA technologies have been used either on a research or commercial basis (Table 1-1).

Table 1-1: CONA field projects to date.

	Main CONA project	"Daughter" projects
2015	Rangiora	
2016	Rangiora	
2017	Rangiora	
2018	Alexandra	Gisborne, Hobart
2019	Arrowtown	Motueka, Christchurch, Kellogg (Idaho)

1.4 Scope of this report

This report is the second in a series covering the Arrowtown 2019 CONA field study. This was the first year that a CONA study was conducted in Arrowtown. It covers the results of an initial analysis of data from a network of prototype indoor air quality sensors ("Hau-Haus") developed by HauHau Ltd for NIWA within the 'CONA' initiative. Other reports will cover other aspects of the Arrowtown 2019 study – specifically ambient (outdoor) air quality and home-heating behaviour and emissions.

2 Arrowtown measurement campaign, 2019

2.1 Overview and goals

The Arrowtown 2019 campaign featured the following elements:

- Up to 48 prototype ambient air quality sensors (ODINs) deployed in a distributed grid across the town to better understand variation in air quality
- 30 prototype indoor air quality sensors (Hau-Haus) deployed for up to 3 weeks inside 86 homes.
- Measurements of woodburner use in selected homes.

This report primarily covers the Hau-Haus.

The main goals relating to the Hau-Haus and indoor air quality were:

- Technical:
  - First field trial of the Hau-Haus
  - First trial of the use of an app to provide real-time data for the research team and householders.
- Local air quality:
  - Characterise indoor air quality in a wide range of homes across Arrowtown
  - Combine these data with data from our network of outdoor air sensors (ODINs) to attempt to characterise the relative contribution of indoor and outdoor sources to indoor air quality.

2.2 Indoor monitoring – Hau-Hau

The Hau-Hau (pronounced 'Hæʊ Hæʊ[1]') is a low-cost air quality monitor. The devices used in this study correspond to an advanced prototype developed by Dr Khalid Arif at Massey University. The Arrowtown 2019 campaign was the first CONA field study in which Hau-Hau sensors were used. The version used in Arrowtown in 2019 had the following characteristics:

- Simultaneously measures particulate matter in two size ranges: $PM_{2.5}$ and PM_{10}
- Also measures air temperature, relative humidity and carbon dioxide.
- Records measurements once every minute.
- Stores data to an onboard SD card.
- Powered by a phone charger (micro-USB connector).

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[1] Using Oxford dictionaries pronunciation guide. https://www.oxfordlearnersdictionaries.com/about/english/pronunciation_english

- The device’s operation is indicated by a multicoloured light and it does NOT have any data display.
- An Android™ application is used as the main data display mechanism and the only way to change the configuration of the device. The initial version of this app had serval weaknesses leading to the app being changed and updated during the field campaign.
- If setup correctly, through the app, to connect to a WiFi hotspot, data is sent immediately to a cloud server.

2.3 Outdoor monitoring - ODIN

The analysis in this report also makes use of outdoor air quality data captured using ‘ODIN’ monitors.

The Outdoor Dust Information Node (ODIN) is a low-cost air quality monitor. It is developed by NIWA and at the time of writing should be considered as an advanced prototype. The version used in Arrowtown in 2019 had the following characteristics:

- Simultaneously measures particulate matter in three size ranges: PM_{10}, $PM_{2.5}$ and PM_1 (i.e. particles with an average size smaller than 10 μm, 2.5 μm and 1 μm respectively)
- Makes measurements at a user-defined time interval, usually every 1 – 5 minutes.
- Also measures air temperature and relative humidity.
- Stores data to an onboard SD card.
- Where adequate 2G mobile phone coverage is available, data is sent immediately to a cloud server.
- Powered by a combination of solar panel and lithium-ion battery.

2.4 The Arrowtown 2019 air monitoring network

2.4.1 Outdoor air – ODIN network

Due to resource limitations, the Network was deployed in four phases over winter 2019. ODINs were installed on streetlight poles as a preference (courtesy of Queenstown-Lakes District Council), with wooden power poles (courtesy of Aurora Energy) and private property also being used. The aim was to install a regular rectangular grid with even coverage across the town, insofar as available infrastructure and permissions made this possible. Table 2-1 summarises the network in each phase.

Table 2-1: The 4 phases of ODIN deployment.

Phase	Start	End	Total number of ODINs in place	Average spacing between ODINs
1	29th May	2nd July	22	340 m
2	3rd July	20th Aug	22	340 m

Phase	Start	End	Total number of ODINs in place	Average spacing between ODINs
3	21st Aug	10th Sep	37	240 m
4	11th Sep	24th Oct	47	170 m

2.4.2 Indoor air – Hau-Hau network

Thirty prototype Hau-Hau units were available for the study. A process was developed in which Arrowtown householders were invited to host one unit in their homes for a period of approximately 3 weeks. Potential users were recruited via social media, local press and through a town meeting and asked to register via an online form, which included the requirement for the applicant to provide consent. Once registered, participants could withdraw from the study, and have any data collected in their home withdrawn also, at any time.

In total, 85 homes (6 % of all homes in the town) were registered for the study. One withdrew, and Hau-Hau were deployed in 84 homes. Installations were conducted over 5 phases, as summarised in Table 2-1. Due to a range of instrumental failures of logistical difficulties (see section 3 for more details) some homes were sampled in more than one phase. Homes within the main part of Arrowtown were prioritised for the earlier phases, when home heating emissions were still strong enough to degrade outdoor air quality in the town. A small number of homes in outlying areas were reserved for phase 5 so that deployments were prioritised in the town when outdoor concentrations were highest providing insight into infiltration.

Table 2-2: The 5 phases of Hau-Hau deployment.

Phase	Start	End	Number of new homes sampled	Number of homes re-sampled	Total number of samples
1	30th May	1st July	26	0	26
2	3rd July	21st July	9	15	24
3	23rd July	19th August	14	8	22
4	20th August	4th September	19	2	21
5	5th September	17th October	17	4	21
TOTAL			85	29	114

2.5 Indoor air quality modelling

A modelling approach has been applied to data from some homes to estimate the contribution of indoor and outdoor emissions sources to indoor concentrations. The approach is based on simulating the indoor-outdoor exchange of polluted air over the time-step between measurements.

The indoor-outdoor exchange is assumed to be proportional to the difference between indoor and outdoor concentrations and the "air exchange rate". Thus, higher concentrations outdoors will cause infiltration and lower concentrations outdoors will cause exfiltration. The air exchange rate is actually a composite parameter incorporating the rate at which air that can enter or leave the home (how ventilated or leaky it is) and the rate at which particles are removed from the air (e.g. by settling on surfaces or removed by filtration). In our model outdoor concentrations of $PM_{2.5}$ are allocated to each home by calculating the average concentration from the four nearest ODINs to that home for every 5-minute period. During most sampling sessions there are periods when the contribution of indoor sources to indoor air quality is equal, or close, to zero. These periods are initially identified by a combination of a change detection algorithm (which identifies sudden increases in indoor concentration not matched by outdoor concentrations), an "initial guess" model that simulates outdoor contribution, and some manual expert correction. These periods are used to establish the average air exchange rate of the property by finding the value giving the smallest error between measured and modelled indoor $PM_{2.5}$. This air exchange rate is then used to simulate indoor concentrations due to infiltration only during those periods when indoor sources, expected to be mainly cooking and smoking, are significant. The process is then repeated, which improves the identification and removal of indoor source "events", until the simulation 'converges' on a stable result. Finally, the difference between simulation and observation is then the contribution of indoor sources.

This method incorporates assumptions and requirements that introduce uncertainty into the results, including:

- It assumes air exchange properties are constant in time, whereas air exchange may reduce at night when windows and doors are more likely closed or may vary if the home has a sophisticated ventilation system or may be increase by strong winds.
- It requires outdoor concentrations to vary significantly and relatively rapidly in order to model the home's "response".

The main consequence of these limitations is that the reliable modelling is not possible for samples where outdoor concentrations are too low or too invariable. The uncertainty in the results has not yet been quantified.

3 Findings part 1 – Performance and validity of the Hau-Haus

3.1 Hau-Hau performance

The Hau-Hau is still a device in development. The Arrowtown 2019 campaign was the first in which it was used in the field by the NIWA team and we expected to find some issues with its deployment, use and performance.

Overall, the Hau-Hau fleet had a data recovery rate[2] of around 51% but individual instrument's data recovery varied from 0% to 100%. Operating failures were due to four broad reasons that will be expanded on in the following sections:

- Hau-Hau functioned well, but users struggled with the app, preventing correct configuration and real-time data access.
- Hau-Hau functioned well, but users did not have it operating for the full intended 3-week period.
- Hau-Hau failed to record data (see further details below)
- Hau-Hau recorded incorrect data (see further details below).

3.1.1 Issues with the app

The app had effectively two functions:

1. to allow users to connect the Hau-Hau to their home WiFi to enable real-time data to be sent to our servers.
2. to view real-time data extracted from our servers.

Due to time constraints, the app was not tested by us before this study. This meant that several issues were found during the Arrowtown campaign relating to both software bugs and unanticipated user needs.

- **App availability**: At the start of the study the app was only available through a direct download from a Google drive via an emailed hyperlink, which was a barrier for some users.
- **User interface design**: Some users found the screen hard to read or misunderstood the instructions because the expected workflow was not intuitive for them.
- **Robustness issues**: The app, particularly at the beginning of the campaign, was unable to recover from some failures, requiring the users to start the setup process several times which lead to some units not connecting to a WiFi hotspot and therefore no real-time data.

Some of these weaknesses were addressed through software updates during the campaign, while others will be addressed in future upgrades.

3.1.2 Incomplete monitoring record

The study was designed to enable the collection of a minimum of three weeks' data from each home. However, the amount of data retrieved was often less than this. This was mainly due to delays

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[2] Data recovery was calculated against the **total** number of ours that the units were at the relevant address from the moment it was delivered to the moment it was retrieved.

between the Hau-Hau being designated to a home, arriving at the home, the householder receiving the Hau-Hau and it being switched on. Similar delays could occur between the householder being informed that their study phase was over, and the monitor being retrieved or delivered to the collection point.

Also, a power cut, which affected the whole town, led to a data gap, but all Hau-Haus successfully restarted logging once power was returned. However, insufficient time was allowed in the device's firmware for the home wifi to restart and to re-establish connection with the Hau-Hau leading to the loss of real-time data for some units.

3.1.3 Faults on the Hau-Hau

The Hau-Hau devices were, in general, very robust and reliable, operating without much trouble as long as their power wasn't disrupted. However, some units experienced the following hardware faults:

- **Corrupt SD cards**. A small number of units had, at the end of the campaign, corrupted memory cards. This only mattered for those units that were not connected to a WiFi hotspot and were logging data locally only.
- **Power connector broken**. The first version of the microUSB connector on the Hau-Hau was very fragile and several of those early units were sent back to be repaired with a new, more robust, connector.
- **Internal connectors loose**: Some units had data gaps that when reviewed in our lab were found to be due to internal connectors being loose or misaligned. Some of those failures can be related to transport while others were assembly issues. These units were removed from the study.
- **Sensor problems**: On a couple of units, their dust sensor seemed to report wrong data, but no obvious issue was found when the units were assessed in the lab. These units were removed from the study.

3.1.4 Hau-Hau data recovery rates

As a net result of these failures, the total data recovery rate (compared to 100 % recovery from all homes) was 51 %. A recovery rate of 100 % was achieved for 7 samples (in most cases a 'sample' equates to a home, except where homes were sampled more than once). Data recovery of above 75 % was achieved for approximately one third of samples. Data recovery between zero and 75 % was achieved for another third, and data recovery of zero occurred in another third.

Table 3-1: Hau-Hau data recovery for each phase of the study.

Phase	Total number of homes sampled	Number of homes with >7 days valid data
1	26	13
2	24	16
3	22	17

Phase	Total number of homes sampled	Number of homes with >7 days valid data
4	21	11
5	19	13

3.2 Hau-Hau data validity

Ideally, the validity of the data collected by the Hau-Haus can be through co-location with reference instruments. As NIWA took delivery of the Hau-Haus in April 2019 there was insufficient time to conduct a co-location experiment. As such, the data remains unvalidated. A co-location experiment is proposed for 2020 after which the data and results in this report will be adjusted if necessary.

4 Findings part 2 – Indoor air quality in Arrowtown (winter 2019)

4.1 What the Hau-Hau measures, and what's in the air in our homes

In this report "indoor air quality" is represented by concentrations of particulate matter smaller than 2.5 micrometres (μm), i.e. $PM_{2.5}$, as measured by the Hau-Haus. Outdoor air quality can be assessed by comparing concentrations of $PM_{2.5}$ with ambient air quality standards but these standards are considered inappropriate for assessing indoor air. In fact, there are no air quality standards or guidelines which are generally considered applicable in the home.

Common sources of $PM_{2.5}$ in the home in towns like Arrowtown include woodsmoke from home heating, particles generated by cooking (especially when food gets burnt), and cigarette smoking. Many sources may also be present in some homes. The chemical composition of these particles, and their toxicological effect may vary widely. The evidence from health research is that all exposure to airborne particulate matter in any environment is potentially harmful, especially for vulnerable people, like infants and children, the elderly, foetuses, and those with pre-existing respiratory and cardiovascular illness.

The Hau-Hau also measures the gas carbon dioxide (CO_2). At the concentrations usually observed in homes exposure to CO_2 is harmless. However, if high concentrations persist, some exposed people can experience symptoms such as drowsiness, loss of concentration, etc.

Measurements of CO_2 in buildings have another function – they give an indirect indication of the degree of air tightness or ventilation. Human breath contains CO_2 (it also arises from burning natural gas). In an occupied, poorly ventilated, airtight building levels of CO_2 will rise higher than in a more ventilated building. Similarly, once unoccupied (or occupants are asleep, which reduces the CO_2 emission rate) levels of CO_2 will fall faster in a well-ventilated building. Poor ventilation is a cause of other forms of poor air quality, including dampness (which promotes growth of mould), and accumulation of other gaseous pollutants released in the home, which can often include volatile organic compounds associated with solvents, furniture, building materials and cleaning materials, cigarettes, candles, gas and liquid fuel stoves, etc.

4.2 Summary of indoor air quality observed in Arrowtown, 2019

To consider a sample to be 'valid' we required that it was at least 7 days long. This is an arbitrary requirement based on our experience that a minimum of 7 days' data is necessary for the data to represent 'typical' conditions in most homes. Of the 85 homes sampled, data from 50 met this criterion.

Our focus is on winter conditions. Although 17 homes were successfully sampled in phase 5, 14 of which returned valid samples, this phase began on 10th September when outdoor PM concentrations were very low. And we therefore do not consider phase 5 representative of winter conditions. Furthermore, several homes sampled were outside Arrowtown, far from the ODIN grid, and no outdoor PM data was available. For these reasons data from phase 5 is excluded from our analysis and will be presented elsewhere.

Across the whole study sample-average **outdoor** $PM_{2.5}$ concentrations ranged from 0.4 – 54.2 $\mu g\ m^{-3}$, with a mean of 14.9 $\mu g\ m^{-3}$ and **indoor** $PM_{2.5}$ concentrations ranged from 0.5 – 21.9 $\mu g\ m^{-3}$, with a mean of 9.8 $\mu g\ m^{-3}$.

Figure 4-1 and Figure 4-2 show how sample-average $PM_{2.5}$ concentrations outdoors and indoors respectively varied though each phase of the study. A strong decline in outdoor concentrations is seen as winter gave way to spring. Although there was also a decline in indoor concentrations it is much less marked.

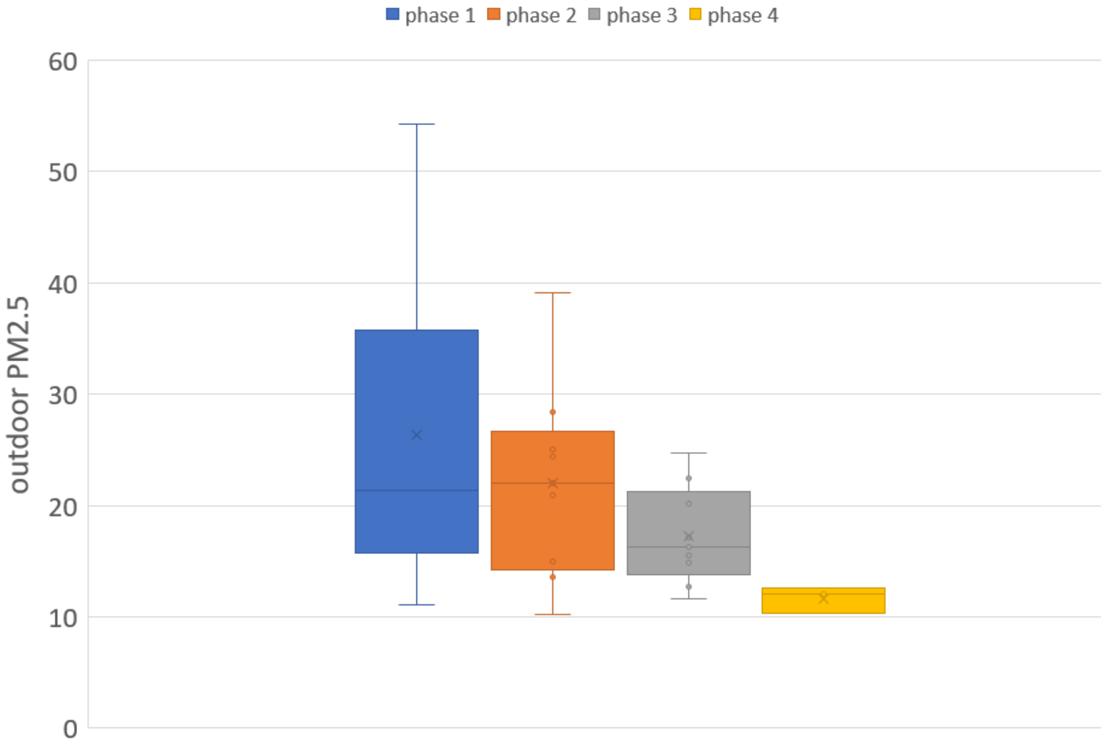

Figure 4-1: **Range of sample-average $PM_{2.5}$ concentrations outside the study homes for each phase.**

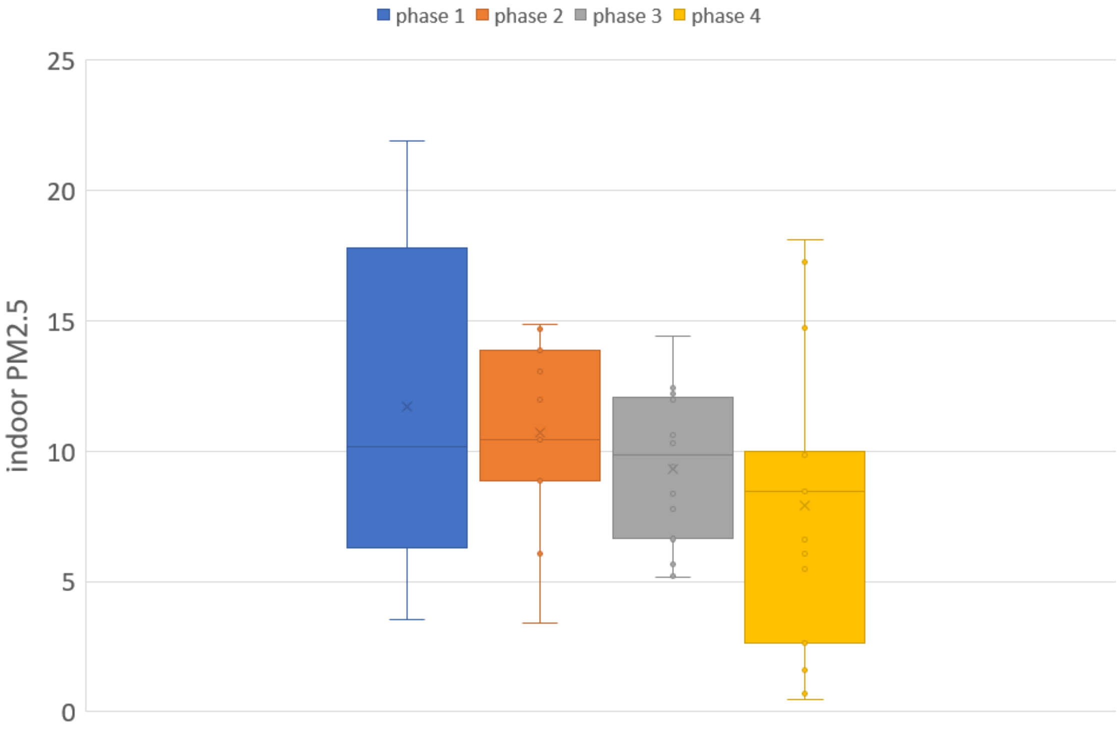

Figure 4-2: **Range of sample-average $PM_{2.5}$ concentrations inside the study homes for each phase.**

4.3 Homes where indoor and outdoor source contributions can be estimated

The modelling approach that splits measured indoor PM into an indoor-sourced and an outdoor-sourced component requires a minimum amount of data containing variation in outdoor PM levels over time, and a minimum amount of outdoor PM. At this stage we have chosen to use an average of 10 $\mu g\ m^{-3}$ as a threshold. With lower concentrations there is clearly less infiltration to observe and model uncertainty substantially increases. Further research may allow us to lower the upper PM threshold thereby allowing infiltration factor to be estimated for more homes.

Due to data losses (see section 3.1) and low outdoor PM levels to the north and west of the town, and in the later phases of the study, we were able to estimate indoor and outdoor source contributions for 32 out of 112 samples (covering 28 out of 84 homes). Figure 4-3 indicates how the number of valid samples gradually reduced as the study progressed.

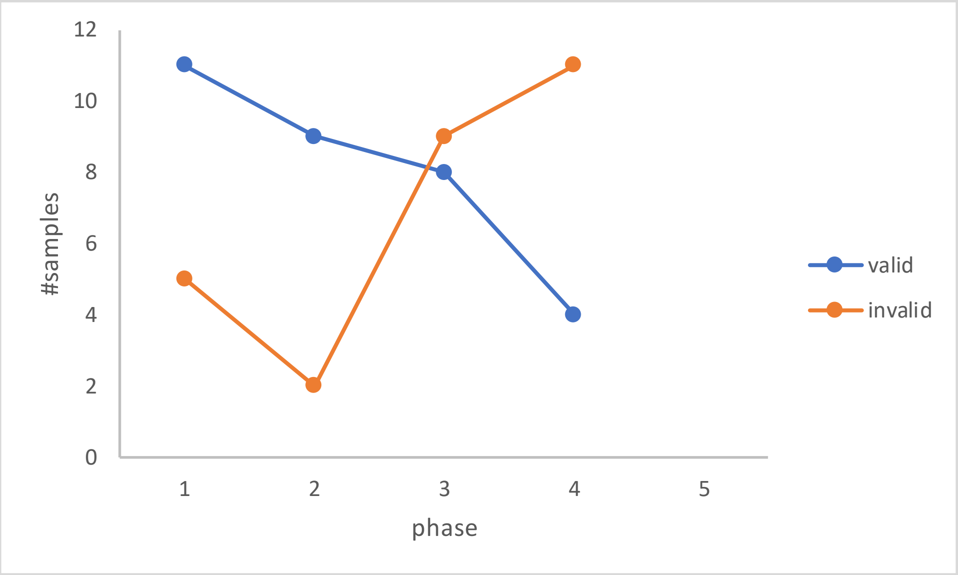

Figure 4-3: **Number of valid and invalid data samples for source apportionment modelling per phase.**

4.4 Indoor emissions

4.4.1 Variation in sample-average results

Figure 4-4 shows the distributions of sample-average concentration of $PM_{2.5}$ attributed to indoor sources for each house-sample. There appeared to be a small reduction in concentrations moving from winter to spring. In phases 1 to 3 (ending in mid-August) there appeared to be a minimum contribution of around 4 µg m^{-3}.

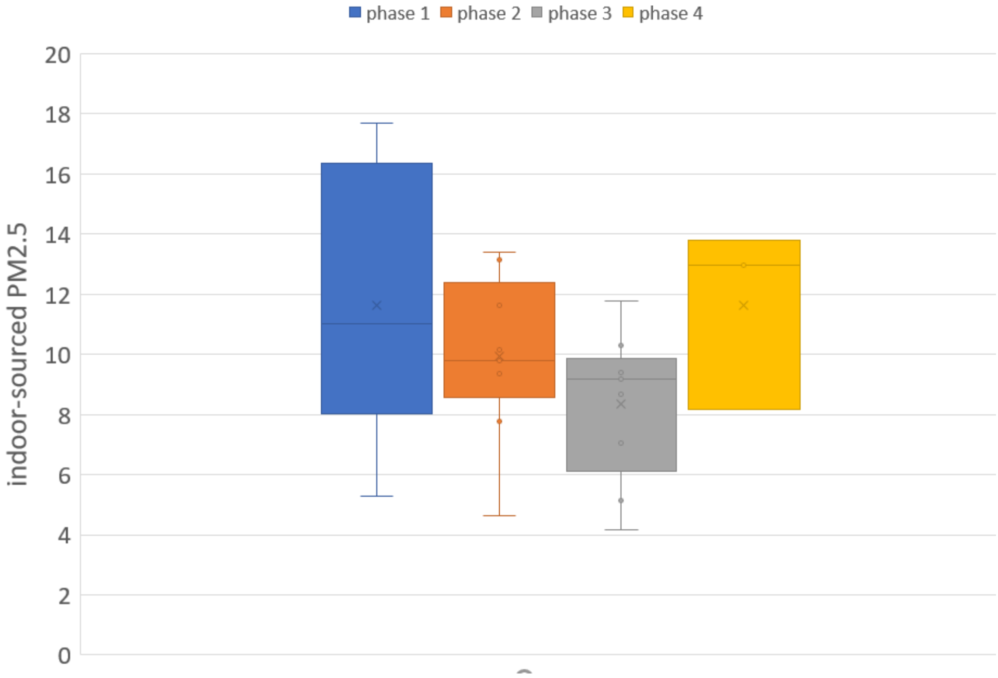

Figure 4-4: **Range of sample-average concentrations of $PM_{2.5}$ measured indoors and attributed to indoor emission sources for each phase.**

4.5 Infiltration of outdoor smoke

4.5.1 Infiltration factor

The infiltration factor is the fraction of outdoor-sourced PM, averaged over the whole sample, that is measured inside the home. A value of 0 would indicate zero infiltration, i.e. the home is totally isolated from outdoor pollution. A value of 1 would indicate total infiltration, i.e. zero protection from outdoor pollution.

Sample-average infiltration factor has been calculated for the model-valid samples in the study.

4.5.2 Variation in infiltration

Figure 4-5 shows the distributions of sample-average concentration of $PM_{2.5}$ present indoors but attributed to infiltration of smoke from outdoor sources for each house-sample. In general, the range in concentrations between homes was roughly proportional to, and approximately double the average concentration across homes for each phase. Both the range and average steadily fell during the duration of the study.

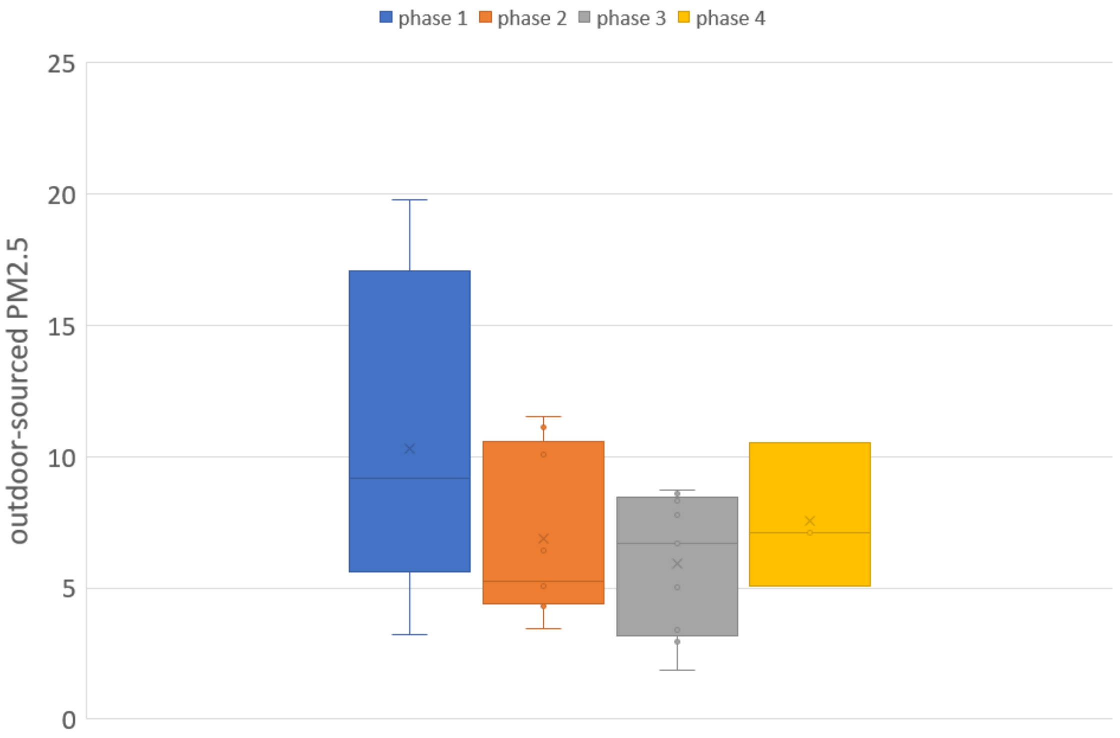

Figure 4-5: Range of sample average concentrations of indoor $PM_{2.5}$ attributed to outdoor emission sources.

Figure 4-6 shows the range in infiltration factor for phases 1 to 3 (the results for phases 4 and 5 possess a large uncertainty due to low concentrations). Infiltration factor ranged from 0.16 to 0.61. The mean infiltration factor across the whole study was 0.35.

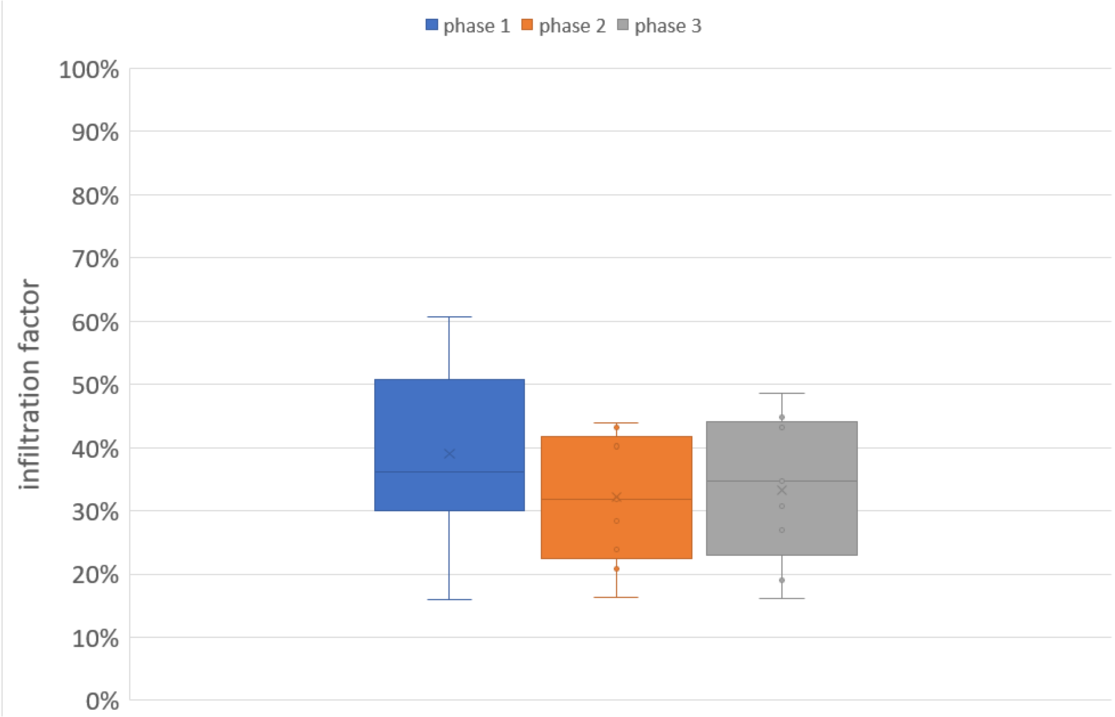

Figure 4-6: Range of sample-average infiltration factors for each phase.

4.5.3 Variation in infiltration between homes

Figure 4-7 shows a map indicating the average infiltration factor for each home with a valid sample. The figure appears to show a weak gradient with higher infiltration factors to the north and east and lower to the south and west.

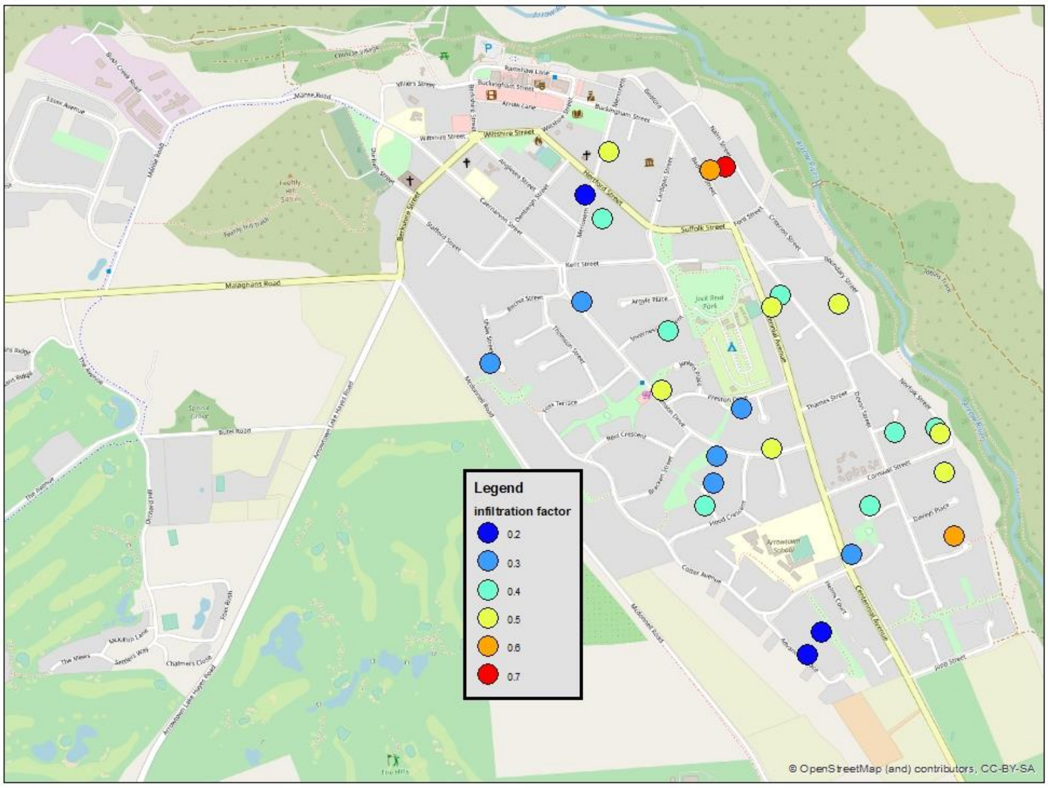

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Figure 4-7: Sample-average infiltration factors.

4.6 Relative contributions of indoor and outdoor sources

The relative contribution of indoor and outdoor sources to indoor $PM_{2.5}$ varied substantially between homes, and varied seasonally (Figure 4-8 and Figure 4-9). In phases 2 to 5 outdoor sources contributed around 40 – 80 % (mean of 57 %) and indoor around 20 – 60 % (mean of 43 %). In the phase 1 (midwinter) the contribution of outdoor sources was higher at 50 – 100 % (mean 82 %).

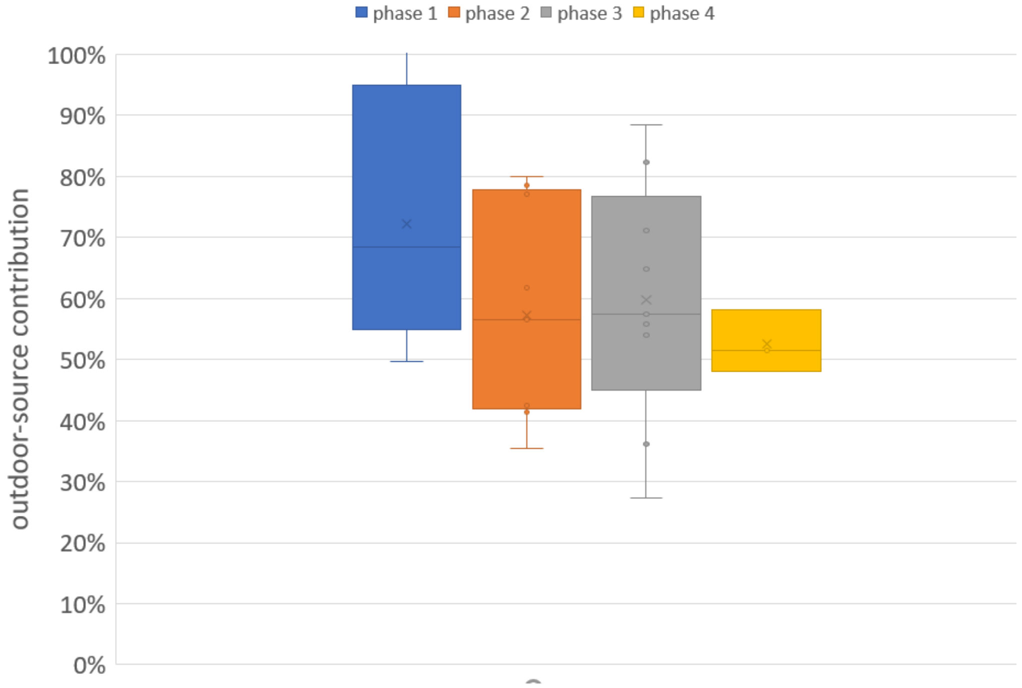

Figure 4-8: **Range of sample-average contributions of outdoor sources to indoor $PM_{2.5}$ concentrations.**

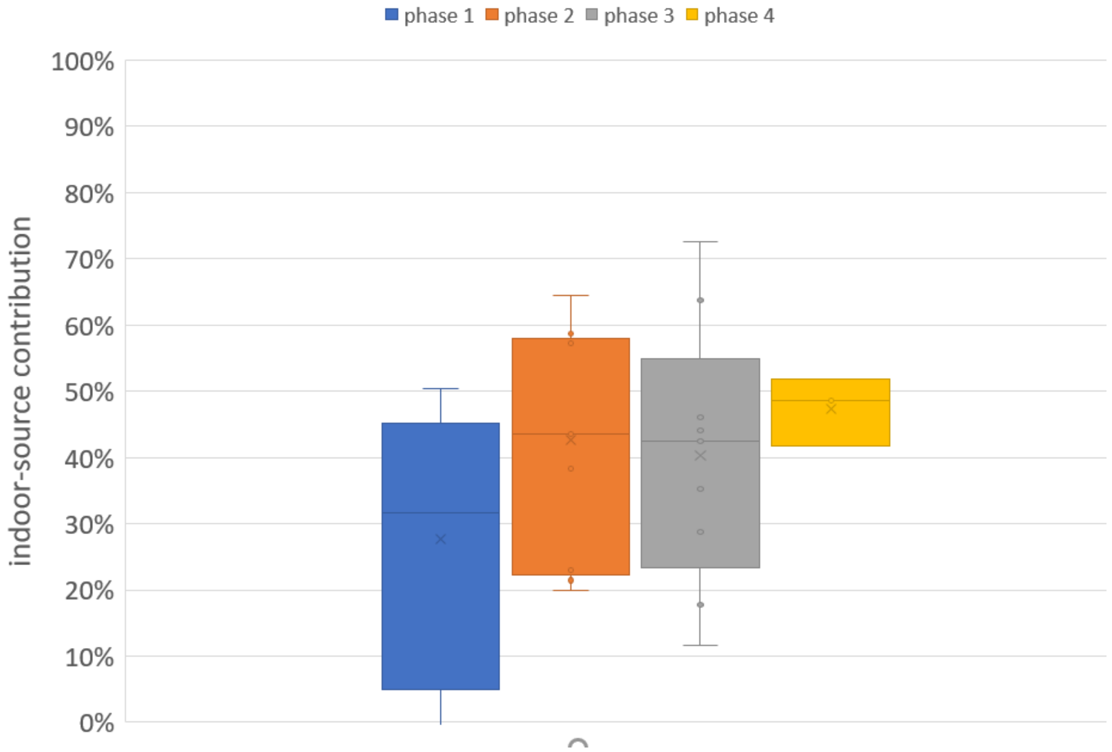

Figure 4-9: **Range of sample-average contributions of indoor sources to indoor $PM_{2.5}$ concentrations.**

5 Discussion and outstanding research issues

5.1 Why do some homes provide better protection from outdoor smoke than others?

With full modelling assessments only available for 28 homes, and given the wide variety in the size, design, layout and use of homes, we are not yet able to draw firm conclusions. However, generally, our analysis to date suggests that homes that exhibited a lower air exchange rate – i.e. were more sealed – tended to have a higher infiltration factor, leading to poorer indoor air quality overall, and vice versa.

This result may seem counter intuitive. One may expect a lower air exchange rate would prevent infiltration of smoke from outside. This would generally be true if the outdoor pollution load was constant. In Arrowtown, however, **even the more sealed homes still had significant outdoor-indoor air exchange** and the outdoor pollution level was quite dynamic – rising and falling rapidly. Our initial analysis on this restricted number of homes suggests that the dominant mechanism driving higher indoor concentrations of outdoor-sourced smoke in homes – when averaged over several days – was the “trapping” of polluted air within the more well-sealed homes. This is especially so late in the evening and overnight when outdoor concentrations are falling rapidly meaning that indoor concentrations can be higher than outdoor. Whereas smoke would more readily enter leakier homes, it would also be removed from these homes just as readily.

However, a few homes fell outside of this general pattern. Two homes had relatively high net infiltration despite high air exchange rates. Seven homes also had lower net infiltration despite being relatively well-sealed. Reasons for this are currently under investigation. These ‘outlier’ homes did not appear to be geographically clustered but were spread across the town. They also represented a wide range of property ages and sizes. Nevertheless, the existence of these outliers suggests that they may have some feature or be used in such a way that can potentially increase their protection from polluted outdoor air.

In order to draw firmer conclusions, further research is required including collecting data from more homes and capturing corroborating data using other methods.

5.2 Can homes be designed or used to optimise indoor air quality, comfort and cost?

Our tentative conclusion is that, when averaged over a week or longer, indoor air quality is worse in more well-sealed homes due to trapping of polluted air that will inevitably infiltrate into the home. This basically implies three solutions:

- Prevent the initial infiltration
- Increase the removal of polluted air from the home once it has entered
- Clean the air *in situ* using air filtration in the home

The first method is very difficult to achieve. In this study we observed infiltration of smoke into even the most well-sealed of homes.

Increased ventilation once the indoor air is polluted, and especially once outdoor concentrations are falling (which, in Arrowtown, is typically from around 7pm in the west to 11pm in the east) may be effective but needs to be balanced against the potential loss of heat from the house.

Indoor air filtration is becoming increasingly popular. Our results imply it is likely to be relatively effective in the more well-sealed homes in Arrowtown, although exactly how effective depends upon many complex factors including the airflow in the home.

Leakier homes appear to be exposed to less smoke in the long-term but can be exposed to higher short-term (e.g. hourly) concentrations. For these homes, upgrades to make the home more well-sealed may reduce these peak concentrations, but not the total long-term dose for the occupants, which may even rise. Indoor air filtration may be suitable for some leakier homes, but its effectiveness will diminish as leakiness increases.

The existence of apparent ‘outlier’s in the data – homes which do not conform to the general trend – indicates the potential for solutions that could be applied to other homes. Our research aims to explore this further in the future.

5.3 Might air cleaning technologies provide a suitable solution?

Whereas previously restricted to industrial uses, air cleaning appliances are now increasingly available for household use. A variety of air cleaning technologies are available either as stand-alone appliances costing approximately $100 - $1000, or may be incorporated into air conditioning, heat recovery and ventilation systems. Some devices now have air quality sensors incorporated into them. Appliances have been in particularly high demand in Chinese cities and in locations badly affected by wildfire smoke.

Air cleaning appliances are an attractive option because they are generally effective at cleaning the air that passes through them and are cheaper and easier to run and install than making major changes to the fabric of the building. Also, if a house owner is investing in a more comprehensive air ventilation system, it may be a minor additional cost to install air cleaning into the system.

Air cleaners are generally an efficient and effective way of cleaning the air that passes through the device, its overall effectiveness for the home depends on how long it takes for the air in the house to pass through the cleaner, relative to the rate at which cleaned air is being replaced by more polluted air. This, in turn, depends on the air infiltration rate of the home, the rate and route by which air circulates through the home and the air flow rate through the cleaner. The latter determines the size, energy consumption and noise generated by the cleaner, each of which the user is likely to want to minimise. The effectiveness of an air cleaner is very dependent upon not just the exact design and state of the home in which it is intended to be used, but also the preferences and behaviours of the householders. Furthermore, experimental evidence of air cleaner effectiveness in different localities, where the air pollution profile is likely to be quite different, may be quite different to places like Arrowtown, where there is a very specific pollution profile of overnight woodsmoke.

In summary, we suggest that air cleaning technologies are likely to offer a viable and attractive solutions for improving indoor air quality in places like Arrowtown, but that actual performance, and optimal use, cannot be predicted. Carefully designed field experiments should be conducted to determine where, when and how air cleaners might be most, and least effective.

5.4 Does participation in indoor air quality monitoring boost engagement with air quality solutions?

This 2019 study was not set up to address this question directly, although the possibility was part of the study's motivation. The relative ease with which 86 householders were recruited, and the fact that many waited up to 5 months to receive their Hau-Hau without withdrawing from the study, suggests that participation in the study was an attractive option for a significant number of people. Whether or not the experience has changed attitudes or motivated people to consider behaviour change or investment in an air quality solution will be studied in the future.

5.5 Summary of ongoing research and future research needs

Our conclusions at this stage are rather tentative. In order to achieve robust conclusions, the following is recommended:

- Further analysis of existing data (expanding to temperature, humidity and CO_2 data) with the goal of finding corroborating evidence.
- Conduct a thorough co-location experiment to understand inter-instrument variability and instrument responses to differences between homes, and between indoor and outdoor environments.
- Collecting a larger dataset, especially covering more homes, and particularly in more polluted locations at the most polluted times of the year.
- Improving the modelling, including validation and calculation of uncertainty.
- Further investigation of 'outliers' – how can they be predicted and what is causing them to behave differently?
- Experiments to test hypotheses generated to explain inter-home difference, and to test the efficacy of potential solutions, such as indoor air cleaners.
- Investigate whether participation in the study can lead to a change in attitude, behaviour, or willingness to act towards air quality solutions.
- Conduct carefully controlled trials of air cleaner technologies in the context of Arrowtown's air pollution profile and range of building types.

6 Implications for stakeholders

6.1 Where you live is the primary determinant of indoor air quality

Results from this study clearly indicate that there is a higher risk of poor indoor air quality in the south-east of the town and a lower risk towards the north-west. This is driven by infiltration of smoke derived from home heating from the outdoor environment into the home. As discussed in our companion report on outdoor air quality, there is a big difference in outdoor levels of $PM_{2.5}$ across Arrowtown, with highest concentrations towards the south-east. Our data so far indicates that smoke from outdoors penetrated into all of the homes in our study, although there was a tendency for polluted air to become more trapped in more airtight homes leading to higher indoor concentrations when averaged over a few days.

Indoor sources of air pollution were common to many, but not all homes in the study. The contribution of indoor sources (which may include cooking and smoking) tended to give rise to brief periods of high concentration, compared to infiltration of smoke which gave longer periods of lower concentration.

6.2 Air quality, housing quality, energy, climate and equity

Poor indoor air quality matters because, when Arrowtown's air quality is worst, most of its population are indoors. Our data shows that being indoors offers only limited protection. However, unlike in the case of the management of industrial pollution, the relationship between polluter and polluted is complex, and therefore the question of who is responsible for funding and implementing solutions is also unclear. Poor air quality in towns like Arrowtown can be viewed as a consequence of an inefficient and un-coordinated approach to home heating. The use of an indoor air cleaner may be an effective way of improving air quality in one home, but would it be effective for all homes to operate an air cleaner? Air cleaners do not address outdoor air quality and do not address the problem at its source – solid fuel heating appliances. A more effective and holistic long-term solution for the town might be to reduce excessive heating demand through improved home insulation, coupled with a commitment to the ultimate removal of all solid fuel appliances.

Common barriers to implementing solutions that are more effective for the community as a whole typically include:

- Lack of fora to host public discourse
- Lack of local data-based evidence
- Considering only a narrow set of goals

In general, we recommend that solutions are implemented within a local strategy that seeks to achieve goals agreed across the community, such as:

- Fewer cold and damp homes
- Minimised energy consumption, and carbon and greenhouse gas emissions
- Prioritising risk reduction for more vulnerable persons
- Equitable cost-sharing

7 Summary of conclusions

The following conclusions have a high certainty.

- There was a very large variation in indoor air quality (represented by concentrations of particles smaller than 2.5 microns, i.e. $PM_{2.5}$) between homes, ranging from 1 to 22 μg m^{-3}.
- In the relatively small sample of homes for which it could be calculated (28), on average, pollution from outdoor sources (which infiltrated into the home) made a larger contribution to indoor $PM_{2.5}$ sources (average 57 % from July – October), than indoor sources, with the contribution from outdoor sources increasing (to an average of 82 %) in mid-winter.
- As outdoor air quality varied hugely across the town (see Part One report), it follows that this dominant outdoor source was the main cause of the large variation in indoor air quality between homes.
- The contribution of indoor sources also varied substantially, but no particular geographical pattern is apparent.

The following conclusions have a degree of uncertainty and will be the subject of ongoing research.

- The proportion of outdoor pollution that penetrated indoors varied from 16 – 61%, with an average of 35%. In other words, being continuously indoors would provide an occupant an average reduction in exposure of 65% relative to being outdoors at the same location.
- Homes with a lower air exchange rate – i.e. those that were more airtight – tended to have higher levels of outdoor-sourced air pollution inside the home on average (infiltration factor), and vice versa. These higher infiltration factors were more likely to be recorded in the north and east of the town. This implies that it is the rate at which polluted air is removed from the home, especially in the late evening and overnight, that determines the overall exposure of occupants to outdoor smoke,
- A few homes fell outside of this general pattern. These 'outlier' homes did not appear to be geographically clustered but were spread across the town, and the reasons why they behaved differently is currently unknown. However, they may give clues to ways in which indoor air quality can be inadvertently worsened, or deliberately improved.
- Air cleaning technologies may be an effective means of improving indoor air quality in Arrowtown, but there are many factors regarding the home and how it is heated and ventilated, which might enhance or undermine that effectiveness. Further research, particularly based on experimental trials in real Arrowtown homes, is required to understand these effects.

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