The Innovation Hub

for Affordable Heating and Cooling

Product Testing Evaluation Report

LLS3 Hivve Transportable Classrooms: Impact of Heat Recovery Ventilation on Energy Use and Indoor Air Quality

27 May 2022

University of Wollongong

About i-Hub

The Innovation Hub for Affordable Heating and Cooling (i-Hub) is an initiative led by the Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH) in conjunction with CSIRO, Queensland University of Technology (QUT), the University of Melbourne and the University of Wollongong and supported by Australian Renewable Energy Agency (ARENA) to facilitate the heating, ventilation, air conditioning and refrigeration (HVAC&R) industry's transition to a low emissions future, stimulate jobs growth, and showcase HVAC&R innovation in buildings.

The objective of i-Hub is to support the broader HVAC&R industry with knowledge dissemination, skills-development and capacity-building. By facilitating a collaborative approach to innovation, i-Hub brings together leading universities, researchers, consultants, building owners and equipment manufacturers to create a connected research and development community in Australia.

This Project received funding from ARENA as part of ARENA's Advancing Renewables Program.
The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.

Lead organisation

University of Wollongong (UOW)

Project commencement date

1 December 2021

Completion date

30 June 2022

Date published

27 May 2022

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VERSION HISTORY

Revision	Version details	Prepared By	Revision Date	Reviewed By	Approval Date
1	Released for comment	D Daly & C Pickup	27/05/2022	G. Kokogiannakis	27/05/2022

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1 EXECUTIVE SUMMARY

There has been a growing awareness on the adverse impacts on inadequate ventilation and poor indoor air quality. COVID-19 has drawn public attention to the issue of adequate ventilation in the built environment, and in particular to ventilation in school classroom. Previous studies (e.g. (Rajagopalan, Andamon and Woo, 2022),(Haddad *et al.*, 2021)) have identified issues of insufficient fresh air in learning spaces, the need for increased ventilation in classroom, and the importance of using energy efficient strategies to deliver the amount of required fresh air. Many classrooms have had mechanical cooling retrofitted, with the typical approach being to install a split-system air-conditioner with no mechanical ventilation. Some recent programs (e.g. cooler classrooms in NSW) are requiring con-installation of demand controlled ventilation (DCV) systems (i.e. fans supplying unconditioned outdoor air) with CO_2 monitoring. Although DCV can improve ventilation, there is a substantial energy cost to condition the fresh air during heating and cooling seasons

Heat Recovery Ventilation offers a potential solution to this issue. Heat Recovery Ventilators (HRVs) use the energy in conditioned exhaust air to precondition incoming fresh air, allowing increased ventilation while mitigating the increased heating or cooling demand. The benefits of HRV, compared with DCV, increase as the external conditions get more extreme (hotter or colder), as there is a greater temperature difference between exhaust and supply air.

Transportable classrooms are a common feature of schools across Australia; these buildings typically have poor thermal performance. Hivve offers a transportable classroom package with many additional features designed to improve the thermal comfort and sustainability of these buildings, including higher performance thermal envelope relative to minimum standards, an energy efficient split system air-conditioning unit, a rooftop PV generation system, with the option of integrated battery storage. Previous i-Hub testing has provide an evaluation of the thermal envelope and heating system installed in a Hivve transportable (i-Hub, 2021).

The current report provides an evaluation of two Hivve classrooms that had HRV retrofitted, in Sydney and Canberra (St Felix and Majura Schools respectively). The current evaluation was designed to test the effectiveness of HRV systems, as well as the implication of the additional energy use for ventilation in grid connected and off-grid classrooms. The evaluation was significantly impacted by COVID-19 related supply chain issues. Procurement of the HRV units commenced in early 2022 with installation planned for summer 2021/22 school holidays, however there were substantial delays in receiving the HRV units by the supplier, and installation was not completed until the autumn school holidays (April 2022). This has resulted in i) a very short period for evaluation, limiting the ability to account and correct for differences in operation during side-by-side comparisons and ii) the evaluation occurring during a mild shoulder season, with only modest requirements for heating or cooling. This has presented significant challenges in evaluating the energy implications of HRV systems. A continuation of this technology evaluation, encompassing winter 2022 and summer 2022/23 has been in-principle agreed between UOW and the ACT education directorate, and this additional data will be invaluable in quantifying the impact of HRV units on energy use and thermal comfort, and the impact on energy availability of the solar battery system.

The current evaluation has explored the impacts of the HRV on energy and ventilation for a period of one month, and has produced a number of useful findings:

1. The installed HRV units (Daikin VAM1000GJVE) have a stable energy consumption of 0.59 kW during operation, compared with a nameplate power of 0.84 kW.
2. The HRV systems were effective at controlling CO_2 levels within the test classrooms. For example, before the HRV was installed, 77% of days had at least one hour with a mean CO_2 concentration greater than 1000 ppm; there were no days after the HRV was installed that met this criteria. During the same period all other classrooms at Majura saw an increase in days with high CO_2 events, despite operating under COVID-19 ventilation protocols.
3. Demand controlled operation of the HRV unit based on CO_2 concentration, as implemented in Majura, is a preferred method in comparison with scheduled operation as implemented at St Felix. The use of 800 ppm as a threshold value appears appropriate, as it was effectively able to limit the occurrence of CO_2 concentrations above 1000 ppm. During the short evaluation period, operations based on CO2 monitoring resulted in significantly reduced average daily run-time compared with scheduled continuous operation (2.2 hours vs 8 hours) and therefore significantly lower energy consumption.
4. Both scheduled and demand controlled operation of the HRV aligned well with periods of solar generation, allowing for onsite renewables to provide the required energy.
5. Single day comparisons of HRV vs non-HRV classrooms during a cold day identified lower CO_2 levels and a warmer internal temperature for the HRV equipped classrooms, with similar AC consumption. However, based on the current evaluation it is not possible to ascertain the impact the HRV has on energy usage for heating and cooling unless a longer evaluation takes place that covers the winter and summer seasons. Given the short and mild evaluation period, there was significant diversity in the operation of AC between classrooms, and the related internal temperatures. It was therefore not possible to determine an accurate estimate of the impact of the HRV on energy consumption for heating or cooling. It is expected that these occupancy related differences will become less significant during colder or hotter periods that will be encountered during the planned extension of the current project, and demand for heating or cooling becomes more uniform.

2 INTRODUCTION

2.1 Background

There is a growing body of evidence linking thermal discomfort to reduced cognitive performance. The BPIE (2018) review identified a learning performance improvement for reduced overheating hours, concluding: Every 1°C reduction in overheating increases students' learning performance by 2.3 %. This is similar to findings in academic literature (e.g. Wargocki & Wyon (2013), Wargocki et al., (2019)). In a study of 50 adults, Griffiths and Boyce (1971), found that performance was progressively impaired as temperature increased or decreased from 18.3°C, in the range 15.6°C to 26.7°C. Pilcher et al. (2002) reviewed four studies within the temperature range of 10.0-18.3°C, and concluded that exposure to cool environments, of less than 18.3°C, had the most negative effect when compared with neutral and hot temperature exposures. Given the impact of thermal comfort on student performance, properly accounting for the ability of the whole building and HVAC system to deliver thermal comfort in a learning space is essential.

While the effect of thermal comfort has apparent impact on the learning performance of afflicted students, consideration of student safety is of primary concern. Covid-19 has impacted the requirements of learning spaces, with education departments across Australian enacting policies to ensure the safety of students undertaking their primary and secondary education. Steensen Varmings independent report for School Infrastructure NSW (Steensen Varming, 2021) indicates that sufficient ventilation of fresh air (10L/s/person) for classrooms can be achieved through opening windows, in keeping with various Covid-19 and CO_2 recommendations and standards outlined within the report (e.g. WHO (2021), NCC (2019), etc.). This is a similar policy to the ACT Health Guidelines (ACT Government, 2021), where fresh air will be maximised "using mechanical controls, such as opening windows and doors". Both reports recognise that temperature considerations will impact these policies, with Steensen Varming (2021) outlining that "…with rising ambient temperatures, the reliance on natural ventilation will lead to thermal comfort issues in classrooms". The report adds that on hotter days, the air conditioner may be run to provide some cooling but will not provide the same relief as it would for a sealed envelope.

To maintain some level of thermal comfort, additional energy expenditure is required, placing a greater strain on the electrical grid. While some Hivve classrooms have been designed to function off-grid through the integration of solar PV, battery storage technologies and a highly efficient thermal envelope, the implementation of Covid-safe policies encourage atypical functionality of HVAC systems, and negating improvements to passive thermal performance by requiring windows to remain open during school hours.

2.2 Problem statement

As schools start to transition from gas towards zero emissions technologies, the electrical grid connection capacity at the local substation and main switch board is placed under increased pressure. These additional strains are further compounded by COVID-19 ventilation policies being enacted by schools to maintain indoor air quality conditions (IAQ) in classrooms, ensuring a well-ventilated space for students.

The Hivve transportables installed at St. Felix have already established that the systems in place are capable of meeting net-zero/net-positive energy contributions under typical operation. Given the policies enacted by both ACT and NSW education sectors due to COVID-19, these transportables are no longer operating under typical conditions, and may require a larger than normal energy expenditure to adhere to ventilation policies. These polices (windows open, AC running) may be sufficient to operate classes in a safely ventilated manner but place further strain on the electrical grid (or microgrid). It is therefore important to further study the relationship between ventilation and energy use, storage and generation, especially during the peak demand periods of summer and winter.

2.3 Technology overview

Hivve transportables offer a transportable classroom package with higher performance thermal envelope, including double glazing, and energy efficient AC system (split system at Majura, ceiling cassettes at St. Felix). Hivve transportables typically include PV generation, with optional battery storage, reducing their reliance on electricity grid and providing a potential means of offsetting energy requirements. The inclusion of a Heat Recovery Ventilator (HRV) further reduces the potential energy usage of the classroom, while also providing fresh air to the enclosed building envelope.

These zero-emission/net-positive energy contributions are particularly attractive to schools where electrical grid connection is at capacity and adding further classroom loads would otherwise require a substantial upgrade to the electrical supply.

Hivve transportables include a smart building control and monitoring package (Hivve iQ) to manage the indoor learning conditions. It also features several alert settings, that notify the user when indoor air quality (IAQ) is poor, as well as general energy usage data, available for viewing.

2.4 Objective

The objective of this project is to evaluate the overall energy, thermal, and indoor air quality performance of the Hivve transportable classroom package, specifically:

1. Can the installation of a HRV unit provide equivalent or improved ventilation to classroom occupants when compared to existing COVID-19 ventilation policies in schools (i.e. windows open, AC operational).

2. Can the installation of a HRV unit provide a measurable saving in energy consumption while maintaining comfort conditions and improved ventilation in comparison to current COVID-19 ventilation policies in schools?

Additional performance testing to determine the relative impact of the installation of a HRV on IEQ energy consumption during more typical operation periods (i.e. with windows closed during heating and cooling operation) was unable to be completed in this testing period, due to COVID-19 risk management protocols. Insights will be sought from historic data, however, change of use for a new school year will make this comparison difficult.

3 Test description

3.1 **Site information**

The testing will take place across two separate school sites, Majura Primary School in Canberra (ACT) and St. Felix's Catholic Primary School in Bankstown (NSW). Both sites have two double Hivve Classrooms installed, with a differing layout. The Majura site has the classrooms installed in parallel (i.e. side-by-side), whereas the Bankstown site has the classrooms facing one another (as seen in Figure 3-1).

Figure 3-1: Hivve Transportables at Majura Primary (left) and St. Felix (Right)

3.1.1 Majura Primary School

Majura Primary School has two identical double Hivve transportable buildings placed side-by-side (as seen in Figure 3-2). Each building consists of two mirrored classrooms surrounding a staff office and a breakout room, shown in further detail in Figure 3-3.

Figure 3-2: Majura Primary with Hivve transportables circled and labelled

The Hivve transportables at Majura have previously undergone testing through LLS2: ACT schools' establishment and operation (LLS2, 2021), with instrumentation having already been installed. The floorplan of the rooms and location of existing sensor installation locations for this testing is shown in Figure 3-3, with the existing sensors being utilised for the testing scheme proposed for LLS3.

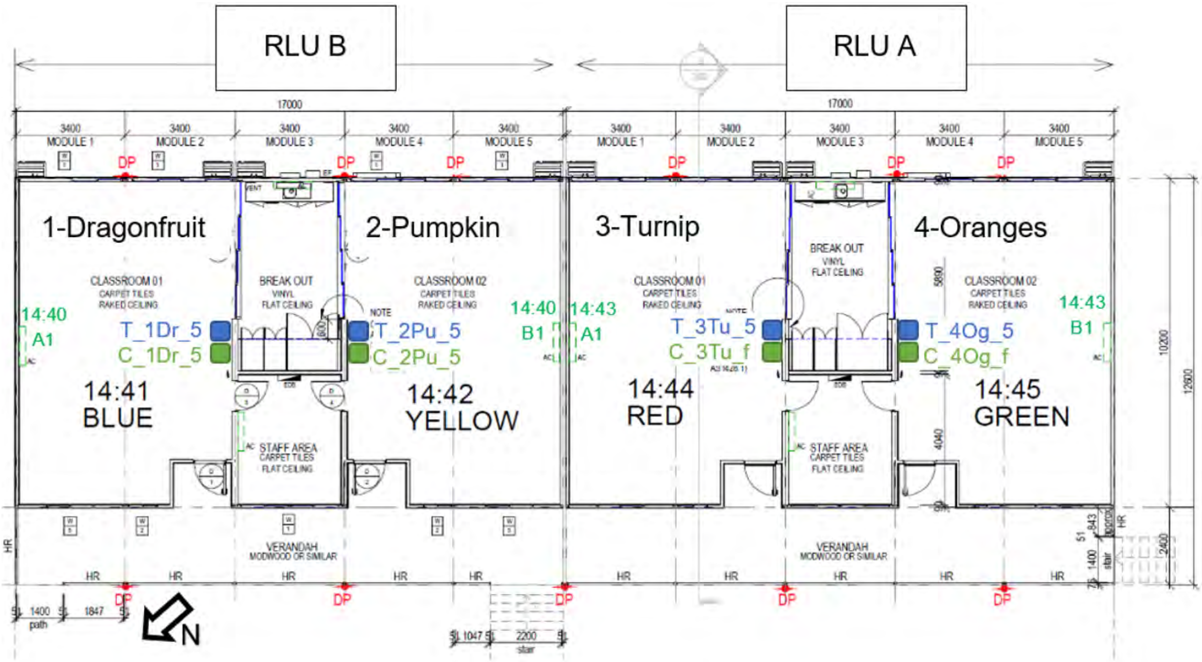

Figure 3-3: Hiwe Majura RLU floor plan

3.1.2 St. Felix's Catholic Primary School

As seen in Figure 3-1 (right), two identical double Hive transportable buildings have been installed at St. Felix, with these classrooms being 100% off-grid. Each transportable building consists of two mirrored classrooms separated by a partition wall as shown in Figure 3-4. The approximated positioning of the transportables on the school grounds is shown in Figure 3-5.

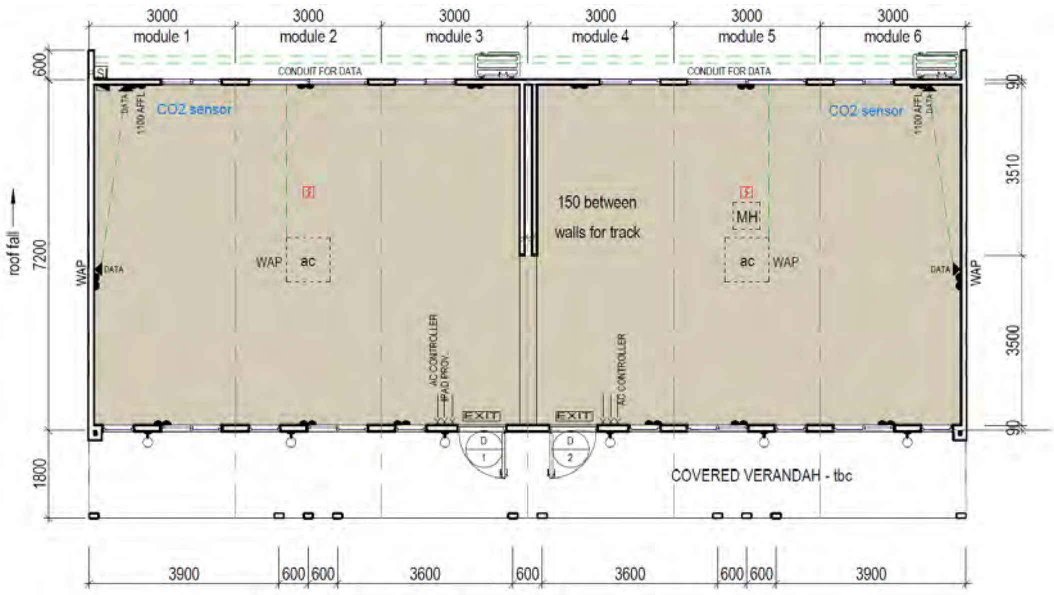

Figure 3-4: Hivve St. Felix Floorplan

Figure 3-5: St. Felix Catholic Primary School with the indicative positioning of the Hivve transportables, and an aerial image showing installed location.

3.2 Description of tested technology

One HRV unit will be installed in one of the Hivve transportable classrooms at both Majura and St. Felix. All Hivve classrooms at each site have an identical respective setup (i.e PV, battery storage, AC system etc.) excluding the HRV. The details of each classrooms systems for their respective site are indicated in Table 1.

The thermal envelope of Hivve transportables is built to meet NCC minimum insulation requirements for the ceiling. Wall insulation specification is bolstered, and double-glazed windows are added. Sub-floor insulation is included to meet NCC minimum insulation requirements.

A stand-out feature of the Hivve transportables is the PV generation and battery storage systems. Hivve's building control and monitoring package is notably specified at a quality suitable for a living laboratory (see Table 2: Sensor list and accuracy), requiring only relatively minor calibration checks to participate in a performance evaluation.

Table 1 - Comparison of specifications between the three transportable types and test sites

Technology	Majura	St. Felix
Insulation - ceiling	R_t 3.7 with an enclosed air gap to meet Section J.	R_t 3.7 with an enclosed air gap to meet Section J.
Insulation - walls	R_t 2.7	R_t 2.7
Insulation – sub-floor	R_t 2.0 (to meet Section J)	R_t 2.0 (to meet Section J)
Windows – size, glazing, location/ orientation	Double glazed, aluminium frames, flyscreens.	Double glazed, aluminium frames, flyscreens.
Window covering	Double roller blinds.	Double roller blinds.
External Shading	Covered front veranda 2400 deep, NW facing	Covered front veranda 1800 deep, E and W facing or respectively facing transportables
Technology	**Majura**	**St. Felix**
Floor area (total internal)	168 m^2	124 m^2
Ceiling height	Raked ceiling from 2600 to 3140.	2850 flat ceiling.
Volume	527 m^3	353 m^3
Ceiling fans	4 x 1200 per classroom. Fwd/Rev, var spd.	-
Split system A/C **Model:** **Year of manufacture:** **Heat** (output/COP): **Cool** (output/EER):	Daikin FTXM95PAVMA/ RXM95PAVMA 2020 10.3 kW/3.36 9.4 kW/3.421[1]	Daikin FCA125CVMA/ RZAC125CV1 2020 14 kW/3.86 12.5 kW/3.54
PV	Yes (10 kW)	Yes (18 kW)
Battery Storage	27 kWh RLUA 13.5kWh RLUB	4x 13.5 kWh Tesla PowerWall 2
Smart monitoring and control	Hivve iQ system	Hivve iQ system
HRV	Daikin VAM1000GJVE	Daikin VAM1000GJVE

[1] https://reg.energyrating.gov.au/comparator/

4 Methodology

4.1 Test Approach and Description

A series of side-by-side energy and IEQ performance tests are designed to provide a controlled comparison of data. The HRV has been adequately sized to service one classroom with a sufficient volume of fresh air (10L/s/person), with this room being compared to classrooms operating under equivalent circumstances. Potential confounding factors are listed below, before detailing the methodology of each performance test.

4.2 Potential confounding factors

Site-specific discrepancies:

- *Solar gains* are anticipated to impact the performance of each transportable diversely at each site. The Majura transportables all have identical orientation with similar front-oriented shading, though solar gains will impact the end classrooms asymmetrically due to their exposed external surfaces. St. Felix has two sets of classrooms, facing east and west. Due to the veranda installed at the entrance of each building and the shading structures installed in between, solar gains will impact each building differently.
- *Local Weather:* There is a local weather station installed at the Amaroo site (near Majura) as part of the existing living lab baseline study. Both Hivve locations have external temperature sensors installed as part of the monitoring system. This local external temperature data will be used in the analysis, supplement by BOM data or Amaroo weather station data as required.
- *Technology-specific issues:* Differences in terms of the delivery of heat from the AC systems will be investigated but this is not expected to be a factor of difference between classrooms in each location.
- *Utilisation (occupancy patterns)*: frequency of use and number of occupants in each classroom may be different.
- *Device settings and locations:* AC setpoint controller temperature calibration and sensor locations may introduce differences between measured indoor temperatures.

4.3 Test procedure - occupied operational performance evaluation

Evaluate the energy required to achieve and maintain thermal comfort, and the related CO_2 concentrations, for a sealed thermal envelope with normal operation.

In the HRV classroom, two alternative HRV operation modes will be trailed, demand controlled operation based on CO_2 monitoring (threshold at 800 ppm) will be implemented in Majura, and scheduled operation (8am – 4pm) implemented at St Felix.

The teacher in this classroom will be advised to close windows and doors when heating or cooling is in operation, with HRV providing sufficient ventilation of fresh air in accordance with NSW (Steensen Varming, 2021) and ACT (ACT Government, 2021) education sector recommendations. They were encouraged to use the AC to maintain comfort conditions as usual. **Note:** The occupied sealed envelope test will only be conducted for rooms which contain an installed HRV, to remain compliant with the recommendations of the ACT (ACT Government, 2021) and NSW (Steensen Varming, 2021) education sectors, and provide sufficient ventilation.

The evaluation will consider the impact of the HRV in comparison to historical energy requirements for the period in which Covid-safe policies have been in effect, as well as in comparison to similar Hivve classrooms for an equivalent testing period.

Supply chain issues (largely related to the high demand for HRVs in response to COVID-19) resulted in extended delays in installation. Final installation occurred on 21st April for St Felix, and 24th April for Majura. These delays have resulted in i) a considerably shorter evaluation period than originally planned, and ii) an evaluation period that has occurred during the shoulder season, with modest heating and cooling requirements.

4.4 Instrumentation Plan

Table 2: Sensor list and accuracy

Criteria	St. Felix	Majura
Electrical Energy Sensor	**Carlo Gavazzi EM280-72D** True RMS; IEC62053-21 Class 1 Instrument (better than combination of Class 1 meter and Class 0.5 of EN60044-1 CT); kWh/5 min	**Carlo Gavazzi EM280-72D** True RMS; IEC62053-21 Class 1 Instrument (better than combination of Class 1 meter and Class 0.5 of EN60044-1 CT); kWh/5 min
Indoor Temperature Sensor	**Carlo Gavazzi SHSUCOTHL** ±0.5° (0.1 resolution)	**Carlo Gavazzi SHSUCOTHL** ±0.5° (0.1 resolution)
Outdoor Temperature Sensor	**Carlo Gavazzi BSI-TEMANA-U** 0.5°C	**Carlo Gavazzi BSI-TEMANA-U** 0.5°C
Indoor Humidity Sensor	**Carlo Gavazzi SHSUCOTHL** ±5% (0.1% resolution)	**Carlo Gavazzi SHSUCOTHL** ±5% (0.1% resolution)
CO2 Sensor	**Carlo Gavazzi SHSUCOTHL** 0-2000 ppm ±50 ppm (±2% of value) Non-dispersive infrared; 2 ppm CO2/°C, 20 ppm/year drift	**Carlo Gavazzi SHSUCOTHL** 0-2000 ppm ±50 ppm (±2% of value) Non-dispersive infrared; 2 ppm CO2/°C, 20 ppm/year drift
Local weather	Site external temperature	Amaroo site weather station used.

5 RESULTS

5.1 Canberra: Majura

The HRV unit was installed in Building RLUB, Blue Classroom on the 21st March 2022, and fully commissioned on the 24th April; the adjacent classroom (separated from the Blue by a sliding partition) was Yellow. As installed photos of the HRV system are provided in Figure 5-1.

Figure 5-1. As installed images of the HRV unit at Majura in the ACT.

The evaluation period ran from the 1st February 2022 to 13th May 2022, with the post implementation period from the 26th of April, giving a total of 12 school days with the HRV in operation. During the pre-HRV period the mean outdoor temperature was 16.9 °C, with a mean daily max of 22.6 °C and a mean daily minimum of 11.9 °C; during the post-HRV period the mean outdoor temperature was 11.9 °C, with a mean daily max of 16.5 °C and a mean daily minimum of 7.5 °C. This substantial temperature difference has important implication in terms of the energy used for heating and cooling; in order to mitigate the impact both pre-and post and side by side comparisons are used in the current evaluation.

The energy and environmental conditions post installation for the HRV classroom are provided in Figure 3-1. The HRV unit for Majura was configured to run at full capacity whenever the CO_2 concentration in the space went above 800 ppm. There are many days when the unit is effectively switching on at concentration above 800 ppm, and off again shortly after when concentrations are reduced below this level. In most cases run time is relatively short, however on several occasion the unit runs for much of the day. The average daily run time is 2.2 hours, or 27.5% of the day. The CO_2 levels rarely exceeds 1000 ppm, and there are only 25 minutes when the concentration exceed 1200 ppm. Typical school occupancy patterns are reflected in the CO_2 concentration profile during this time, other than the 9 – 11th of May, during which the classroom does not appear to be in use. The air-conditioning (AC) unit is rarely operated during the post installation period in the HRV classroom; in total there are only two days with 1 hour of operation, and 1 day with 2 hours of operation. In all cases the AC is used for heating.

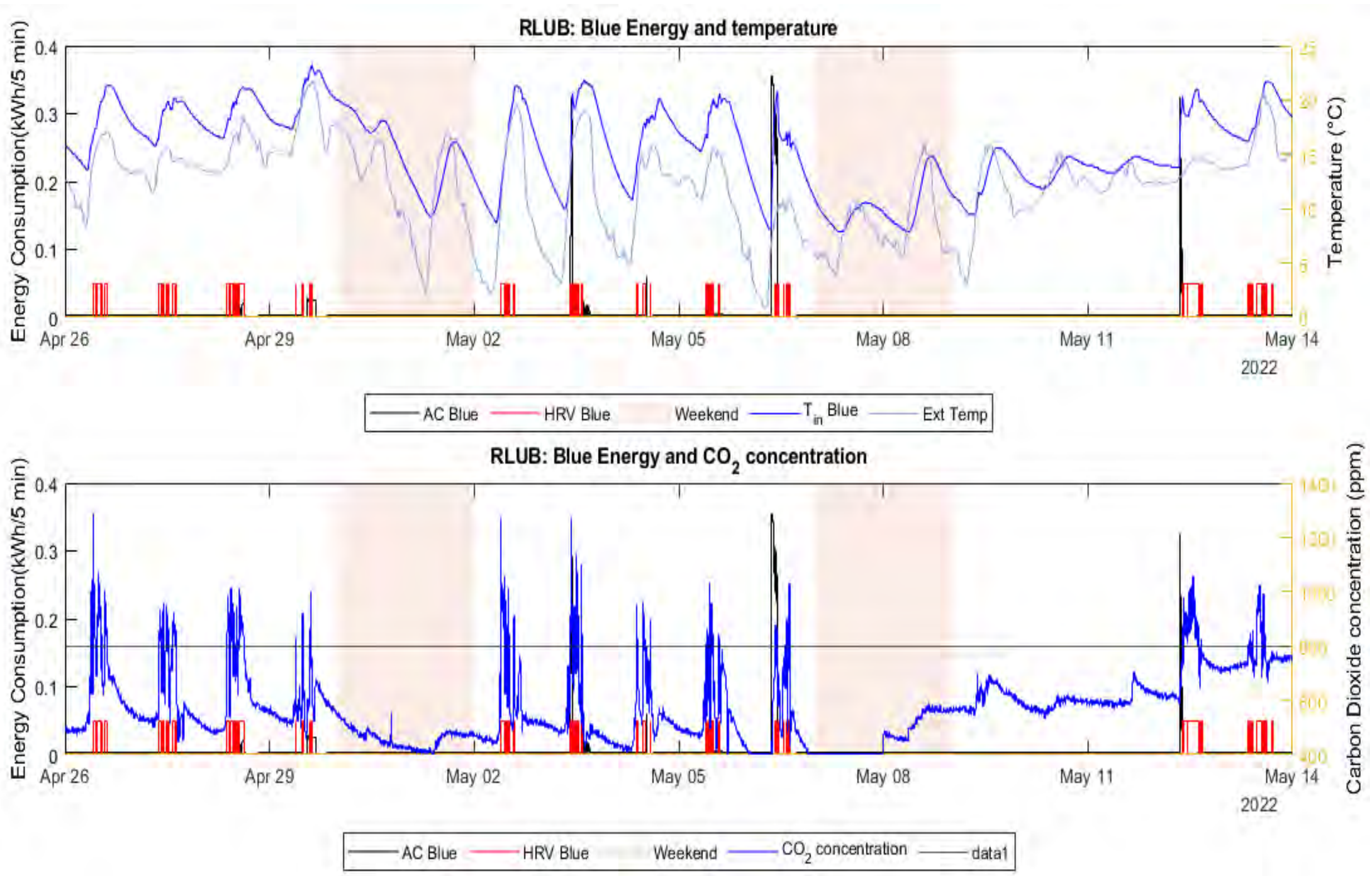

Figure 5-2. Energy, temperature and carbon dioxide concentration from the classroom with the HRV installed for the post-installation period.

A historic comparison for the Blue classroom is presented in Figure 5-3. This shows the last school week in the pre-installation period, and the first full week in the post installation period. The classroom had the same use in these two periods, and it is expected that occupancy levels were similar.

A clear change in the amount of time in which the CO_2 concentration is above 800 and 1000 ppm can be clearly observed. In the post-HRV period the concentration rarely exceeds 1000ppm (with the HRV unit commencing operation once the CO_2 level exceeds 800 ppm); in contrast, in the week shown prior to the installation of the HRV unit the CO_2 level is regularly above 1200 ppm. It is worth noting that windows were required to be always opened during this period due to COVID-19 risk management protocols, which would suggest that the observed concentrations are lower than would be expected during typical operating conditions (historical data was not available for Mjura). The two weeks shown are both relatively mild, with daytime temperatures typically in the low 20's. During periods with more extreme external conditions, the energy penalty of operating split-system air-conditioning with windows open would be much higher, and the full advantage of a HRV, in terms of both energy savings and control of CO_2 levels, is expected to be clear.

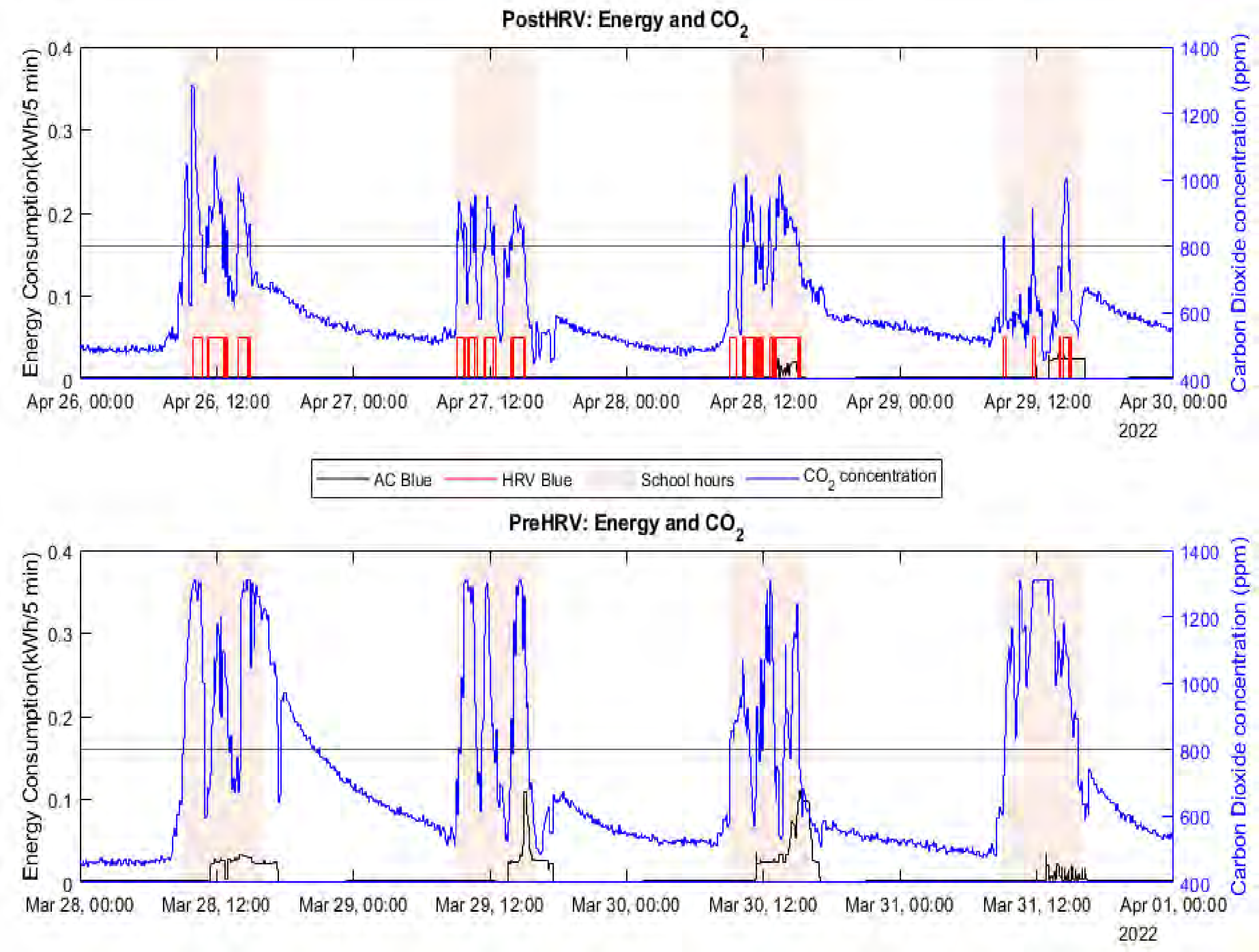

Figure 5-3. Historic time series, showing energy for AC and HRV, and carbon dioxide concentration for the last school week of pre-HRV data, and first school week of post-HRV data in the Blue classroom.

A side-by–side comparison of Blue (HRV) and Yellow (adjacent) classroom during the coldest week in the post-installation period, is shown in Figure 5-4. The energy for AC in the adjacent classroom (Yellow) is substantially higher than the HRV classroom (Blue). This is likely due to operational differences between the teachers in these spaces, as the additional energy input for AC usage in Yellow (mean of 7.5 kWh/day vs 2.0 kWh/day for Blue) results in substantially higher indoor temperatures during the morning period. The CO_2 concentration in Yellow classroom is relatively similar to blue, although there is one instance (~9-10:30 AM, 2 May) where CO2 concentration exceeds 1200 ppm for an extended period. As these are adjacent spaces, connected via a sliding partition, there is likely to be some degree of air mixing, and the status of the partition is uncertain during this testing period.

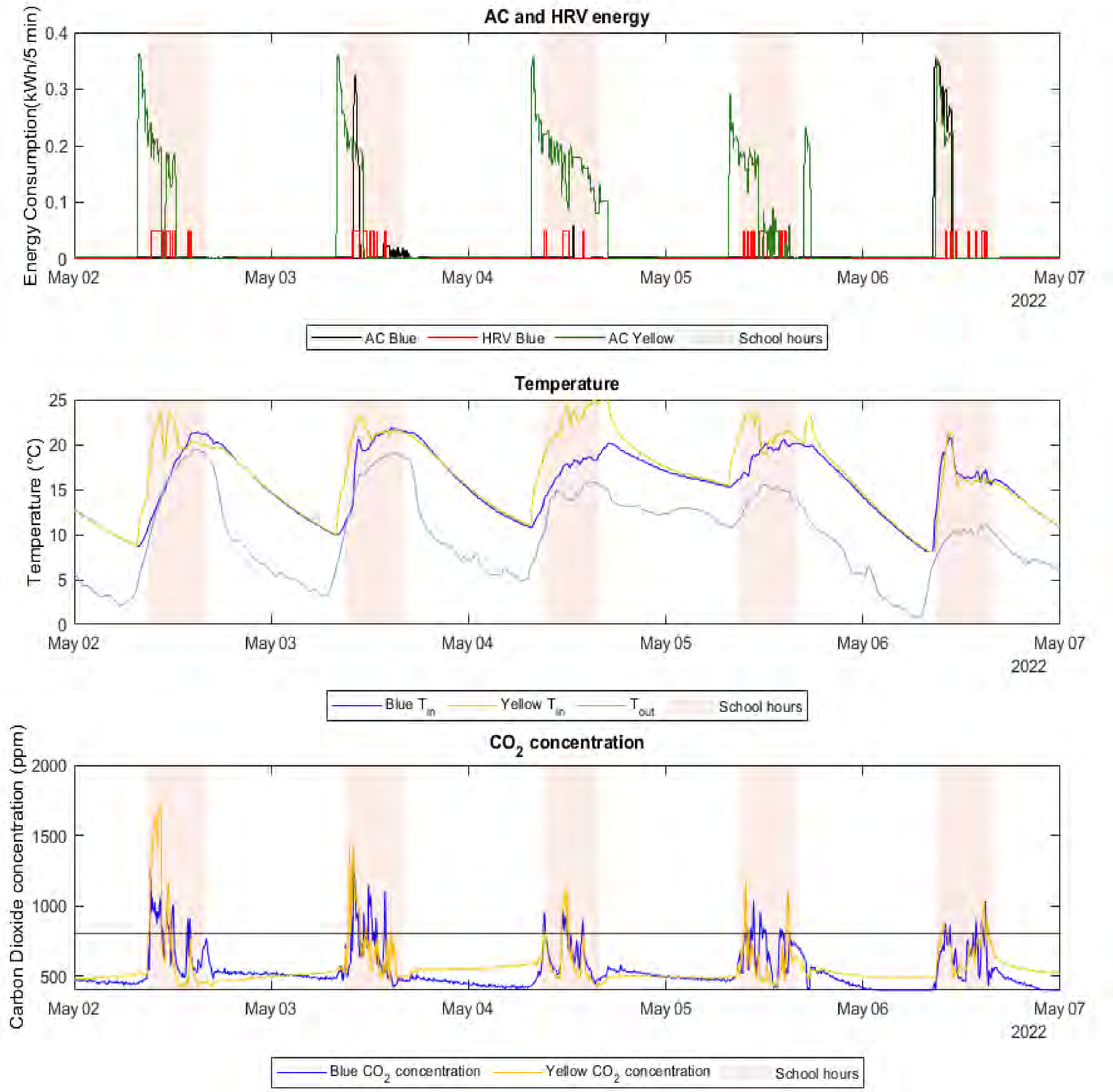

Figure 5-4. Side by side comparison of energy for AC and HRV, temperature and CO_2 concentration for Blue (HRV) and Yellow (adjacent) during the coldest week in the evaluation period.

The classrooms in the second Hivve building (Red and Green in RLUA) are not connected to the HRV classroom. A side-by-side comparison of these spaces is presented in Figure 5-5. The results for CO_2 concentration show that the classroom with the HRV installed consistently provides acceptable CO_2 concertation, and all other classrooms exceed the recommended limits for various amounts of time. For the week shown, in school hours Blue is above 1000 ppm 3.8% of the time, compared to 10%, 26.7% and 55.7% for Yellow, Red and Green respectively.

Considering the temperature and energy profiles of AC usage across the spaces, clear differences can be observed. Blue is typically both the coolest space, and the space with the lowest AC energy consumption. Over the period shown in Figure 5-5, Blue consumed 10.0 kWh for AC and 5.2 kWh for the HRV; Yellow consumed 37.6 kWh for AC, Red 16.7 kWh, and Green 9.5 kWh. These differing energy inputs correspond to substantially different internal conditions, with Blue recording a mean temperature during school hours of 18.0 °C, compared to 20.5 °C, 20.1 °C, and 20.2 °C for Yellow, Red and Green respectively. In this short testing period, it is difficult to disentangle the role of occupant preferences and behaviour in the operation of the AC unit with the impact of the HRV unit in order to ascertain the energy impacts of the HRV on AC usage. It is important to note that teachers were advised to continue using the AC unit to maintain comfort according to their own preferences.

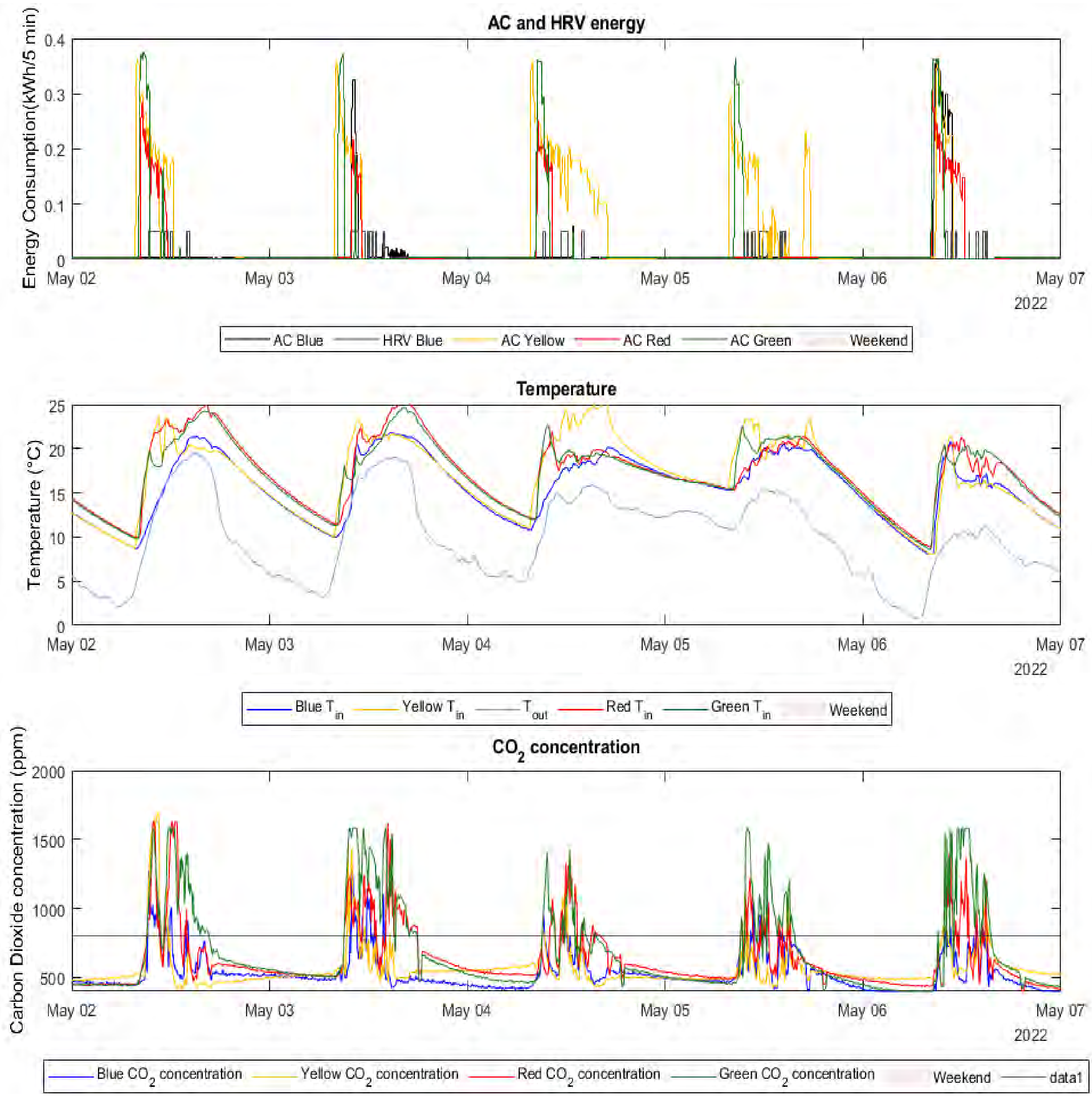

Figure 5-5. Side by side comparison of energy for AC and HRV, temperature and CO_2 concentration for Blue (HRV), Yellow (adjacent), Red and Green classrooms during the coldest week in the evaluation period.

A summary of the various comparisons considered above is provided in Table 3. This summarises a number of important metrics for the pre-HRV period (1/02/2022 – 8/04/2022) and the post-HRV evaluation period (26/04/2022 – 14/05/2022).

Table 3. Summary of results for Majura classroom, showing data from weekdays between 9am and 3pm (i.e. school hours)

		RLUB				RLUA			
		Pre_HRV		Post_HRV		Pre_HRV		Post_HRV	
		TEST	**CONTROL**	**TEST**	**CONTROL**	**CONTROL**			
		Blue	**Yellow**	**Blue**	**Yellow**	**Red**	**Green**	**Red**	**Green**
Mean Tout		**21.9**	**21.9**	**16.8**	**16.8**	**21.9**	**21.9**	16.8	**16.8**
Mean Tin		**21.8**	22.9	**17.8**	19.7	22.6	22.1	19.3	19.5
Mean ΔT (in -out)		**-0.8**	0.1	**0.8**	2.8	0.1	-0.2	2.3	2.5
Mean CO2 concentration(ppm)		**842**	674	**708**	664	712	802	816	968
Average daily hours above:	800 ppm (hrs/school day)	**2.7**	1.7	**3.2**	2.2	1.7	2.3	3.2	3.7
	1000 ppm (hrs/school day)	**2.1**	0.8	**1.1**	1.0	1.1	1.5	2.2	3.2
	1200 ppm (hrs/school day)	**1.3**	0.3	**0.2**	0.4	0.5	0.9	1.5	2.6
% of days with at least one hour with mean CO2 over 1000 ppm		**77%**	17%	**0%**	29%	45%	27%	79%	64%
Mean AC consumption (kWh/Day)		**1.7**	**1.4**	**0.9**	**4.7**	1.2	1.4	1.9	1.2
Mean HRV consumption (kWh/day)		**-**	-	**1.3**	-	-	-	-	-

During both pre- and post-installation period, AC energy consumption was modest, with a maximum average daily usage of 4.7 kWh for Yellow. This is largely due to the transition season, with little need for mechanical heating or cooling to maintain comfort. The HRV unit consumed on average 1.3 kWh/school day, corresponding to an approximate average run time of 2.2 hours/day. The HRV consumption was substantial relative to the energy used for space conditioning; again, this is likely to be due to the mild outdoor conditions, and further testing in colder conditions is necessary to evaluate the energy impacts of the HRV.

There is clear evidence of the impact on CO_2 concentrations the HRV has. Considering mean CO_2 concentration during school hours, a strong improvement was observed for Blue (and a slight improvement for Yellow), whilst both Red and Green saw increased concentrations in the colder post-installation periods. More importantly, the installation of the HRV unit substantially reduced the occurrence of periods with CO_2 levels above 1000 ppm.

For the HRV classroom, there was an increase in hours with at least one 5-minute period with CO_2 concentration above 800 ppm (average of 2.7 hr/d pre-, vs 3.2 hr/d post-HRV), but a reduction in hours with at least one period above 1000 ppm (2.1 vs 1.1. hr/d) and 1200 ppm (1.3 h/d vs 0.2 hr/day). This suggests that the HRV when controlled using CO_2 monitoring is capable of effectively limiting spikes in CO_2 concentration. All other (non-HRV) spaces showed an increase in number of hours with at least one 5-minute period above each threshold in the post-installation period.

Another measure of problematic CO_2 spiking in classrooms is the number of days for which there is at least one hour in which the **mean** CO_2 concentration is above 1000 ppm. In the pre installation period, the Blue classroom recorded at least 1 hour with a mean CO_2 above 1000 ppm on 77% of the days; there were no days meeting this threshold after the installation of the HRV unit. Again, all other classrooms showed an increased occurrence of this metric in the in the post-installation period.

5.2 Bankstown: St Felix

The HRV unit was installed in Building 5 Green Classroom (5G) and was commissioned and in operation from the 24th of April 2022 (with the first school day after installation being 26th of April 2022).

Figure 5-6. Installation photos for St Felix, showing the supply (left) and return (right) vents connected with the underfloor HRV unit.

An overview of the St Felix evaluation period is shown in Figure 5-7. Additional energy monitoring was installed during the installation of the HRV unit, to separately meter air-conditioning consumption for the post-HRV evaluation period. During this work an error was identified that invalidated pre-upgrade energy consumption data, meaning only side by side comparisons are available.

The external temperature during the evaluation period was relatively mild, with overnight temperature rarely dropping below 10 °C, and daytime temperature only once exceeding 30 °C. The HRV unit at St Felix was operated on a fixed schedule, at full capacity from 8am to 4pm Monday to Friday. This is in contrast to Majura HRV which operated when $C0_2$ exceeded 800 ppm. During operation the unit has a consistent and stable energy consumption of 590 Watts. CO_2 concentration rarely exceeded 800 ppm in room 5G, and only exceeds 1000 ppm for one 5-minute period. In contrast 5W exceeds 1000 ppm on 6 of the 19 school days and reaches 2000ppm for several hours on one of these days (shown in Figure 5-10). Air-conditioning was regularly used during the post-HRV evaluation period, with significant usage on 13 of the 19 school days, and an average of 4 kWh consumption on the days it was used.

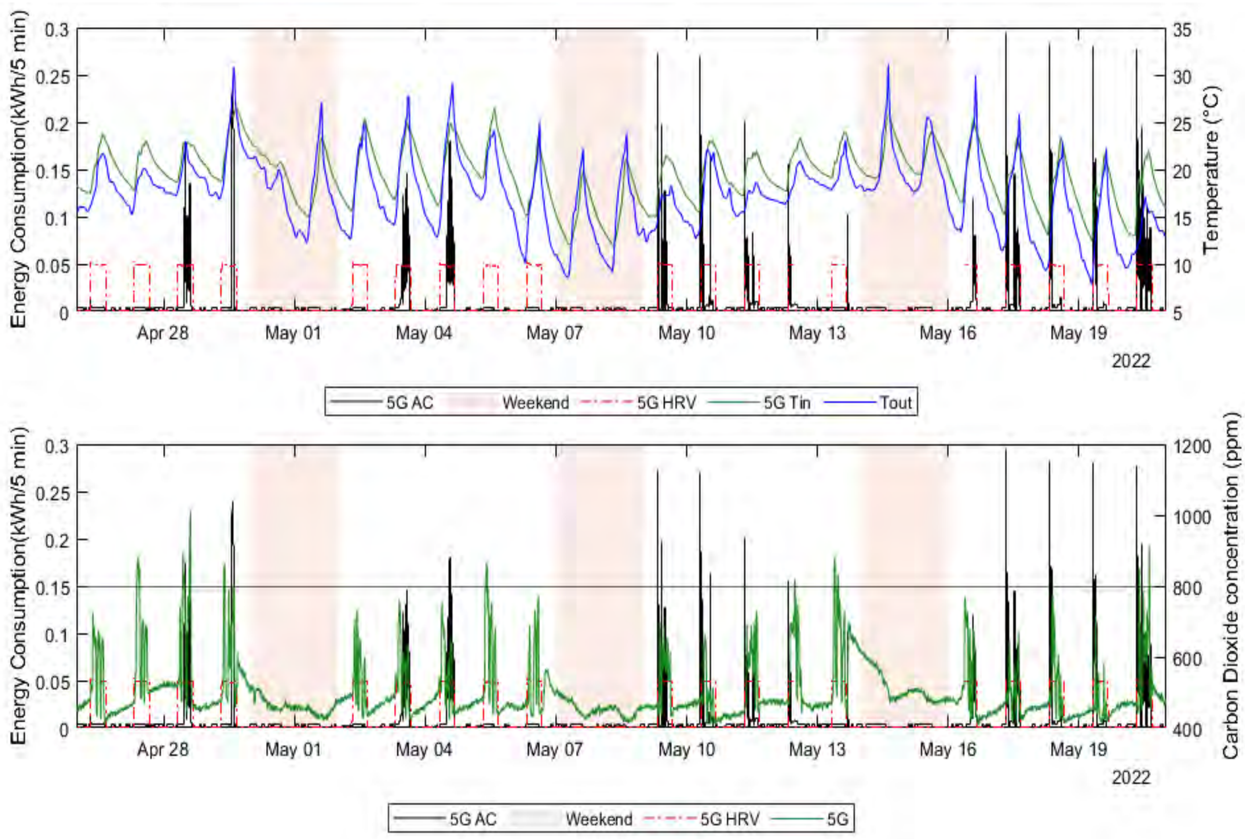

Figure 5-7 Energy, temperature, and carbon dioxide concentration from the classroom with the HRV installed for the post-installation period

A historic comparison for the 5G classroom was not able to consider energy usage for the air-conditioning system, as the air-conditioning energy meter was only installed concurrently with the HRV unit. Further a historic metering installation issue was identified during HRV installation, which invalidated energy use data collected during 2022. However, it is interesting to consider the energy and CO_2 data from the previous 2 years (2020 and 2021), to gauge the impact of the recently introduced COVID-19 ventilation protocols, which require windows to be open in all spaces without mechanical ventilation. 2021 and 2021 data is shown for 5G in Figure 5-8 and Figure 5-9; it is important to note that the usage of 5G changed between 2021 and 2022, making direct comparison between these periods of limited use.

The CO_2 concentration data shown in Figure 5-8 and Table 4clearly shows that the COVID-19 ventilation protocols were effective in reducing periods with high CO_2 concentrations. During the period with ventilation protocols in place (Term 4, 2021), there were an average of 7 minutes per day above 1000 ppm for 5G. This was comparable for the other Hivve transportable classroom; 9 minutes, 8, minutes and 7 minutes for 5W, 6G and 6W. During the same period in the year prior, this value was substantially greater: 30 min, 87 minutes, 189 minutes and 210 minutes for 5G, 5W, 6G and 6W respectively. Given the improvement in CO_2 concentration, it would be expected that substantial additional energy may have been required for air-conditioning, however this is not observed in either Table 4 or Figure 5-9. The full reason for this are uncertain, however, summer 21/22 was very mild, and it is likely that there was substantially lower demand for cooling than in previous years.

Table 4. Summary of impact of COVID-19 ventilation protocols on CO2 concentration and energy for ST Felix classrooms.

	Mean daily time with CO_2 above 1000 ppm (minutes)		Room energy use (kWh)		Mean T_{out} school hours	
	2020	2021	2020	2021	2020	2021
5G	30	7	29	18.5	25.4	23
5W	87	9				
6G	189	8	23	12.3		
6W	210	7				

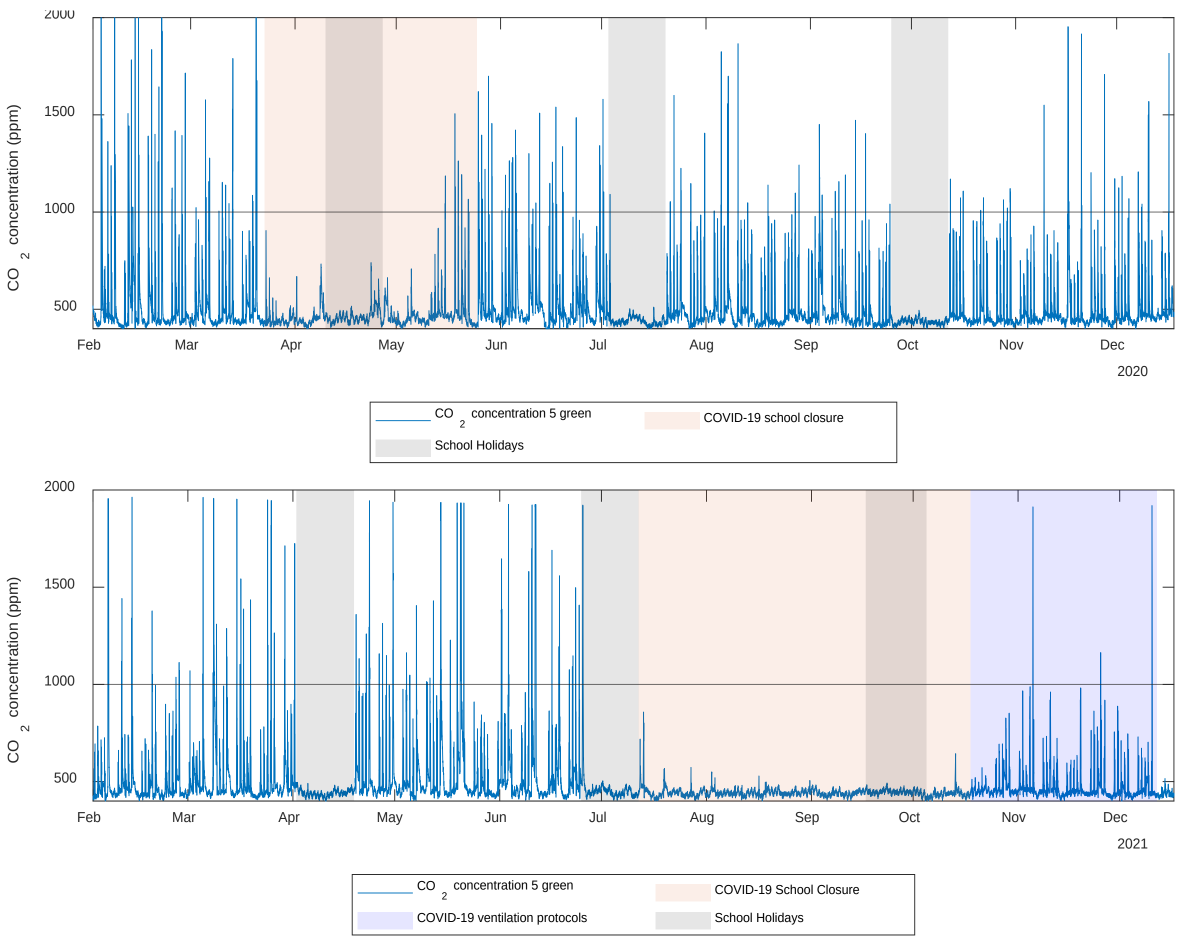

Figure 5-8. Two years of historic CO_2 concentration readings for 5G, with school holidays, COVID-19 induced interruptions, and the period with COVID-19 ventilation protocols highlighted.

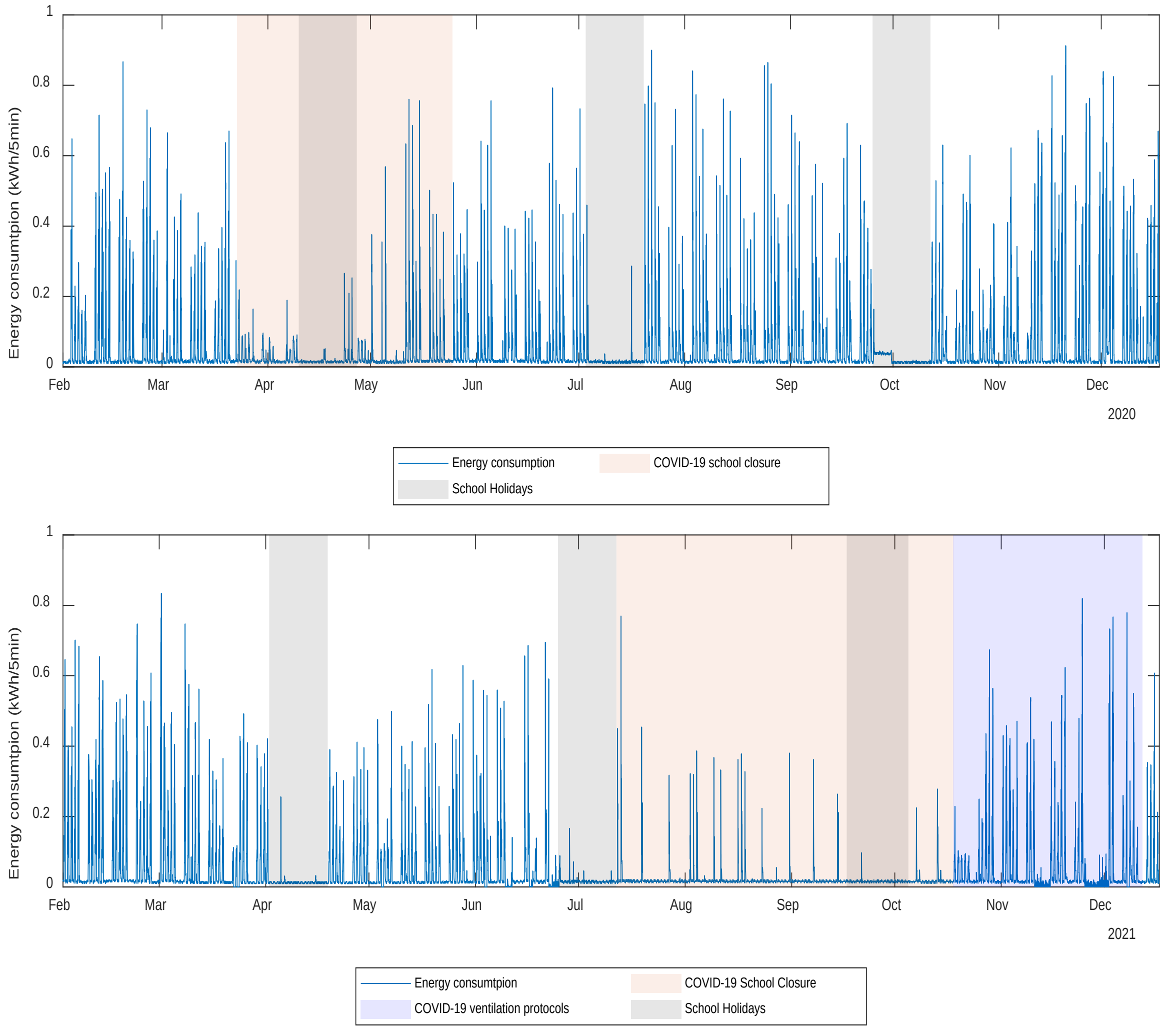

Figure 5-9. Two years of historic total energy consumption for 5G, with school holidays, COVID-19 induced interruptions, and the period with COVID-19 ventilation protocols highlighted.

A side-by–side comparison of 5G (HRV) and 5 White (5W) (adjacent) classroom during the first two weeks in the post-installation period, is shown in Figure 5-10 and Figure 5-11. Throughout both weeks room 5G typically maintains a higher internal temperature compared to 5W (mean of 21.7 °C and 20.8 °C during school hours, respectively). The AC is operated much more frequently in room 5G compared to 5W. Over the post-HRV period, the AC in 5G is used of twice as long as the AC in 5W (mean of 1.8 hrs/weekday, vs 0.9 hrs/weekday), and consumed more than twice the energy (49 kWh, vs 27 kWh). Energy use for the HRV unit was also significant over this period, 88.5 kWh, or 4.7kWh.weekday, due to the extended run time. Typical school occupancy patterns can be observed in the CO2 concentration profile during this time, however there are very few events where the CO2 exceed 1000 ppm in either classroom. During school hours, 5G has a mean CO2 concentration of 582 ppm, and 1 5 minute period above 1000 ppm, compared with a mean of 771 ppm, and 326 five-minute periods above 1000 ppm (27 hours, or an average of 1.4 hours per day. There is a clear and major issue with IAQ in classroom 5W on each Friday during the evaluation period. For example, on the 6 May 2022, the CO_2 exceeds 1000 ppm for 6.5 hours, and exceeds 1800 ppm for 1.3 hours. Given the uncertainty in operation during this short evaluation period, it is difficult to ascribe the lower CO_2 and higher internal temperature to the HRV alone, and a longer analysis period during warmer and colder external temperature periods is expected to clarify the results.

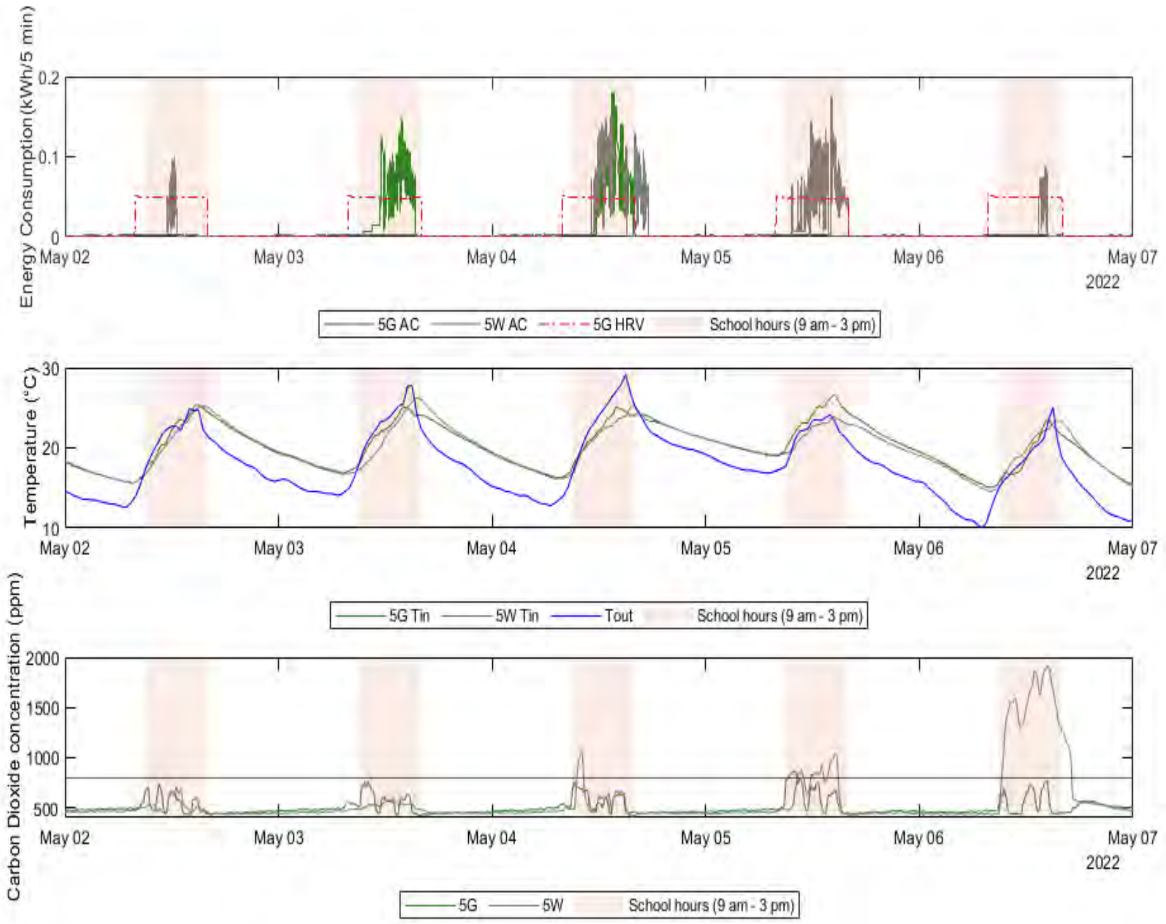

Figure 5-10. Side by side comparison of energy for AC and HRV, temperature and CO2 concentration for 5G (HRV) and 5W (adjacent) during the 1st week in the evaluation period.

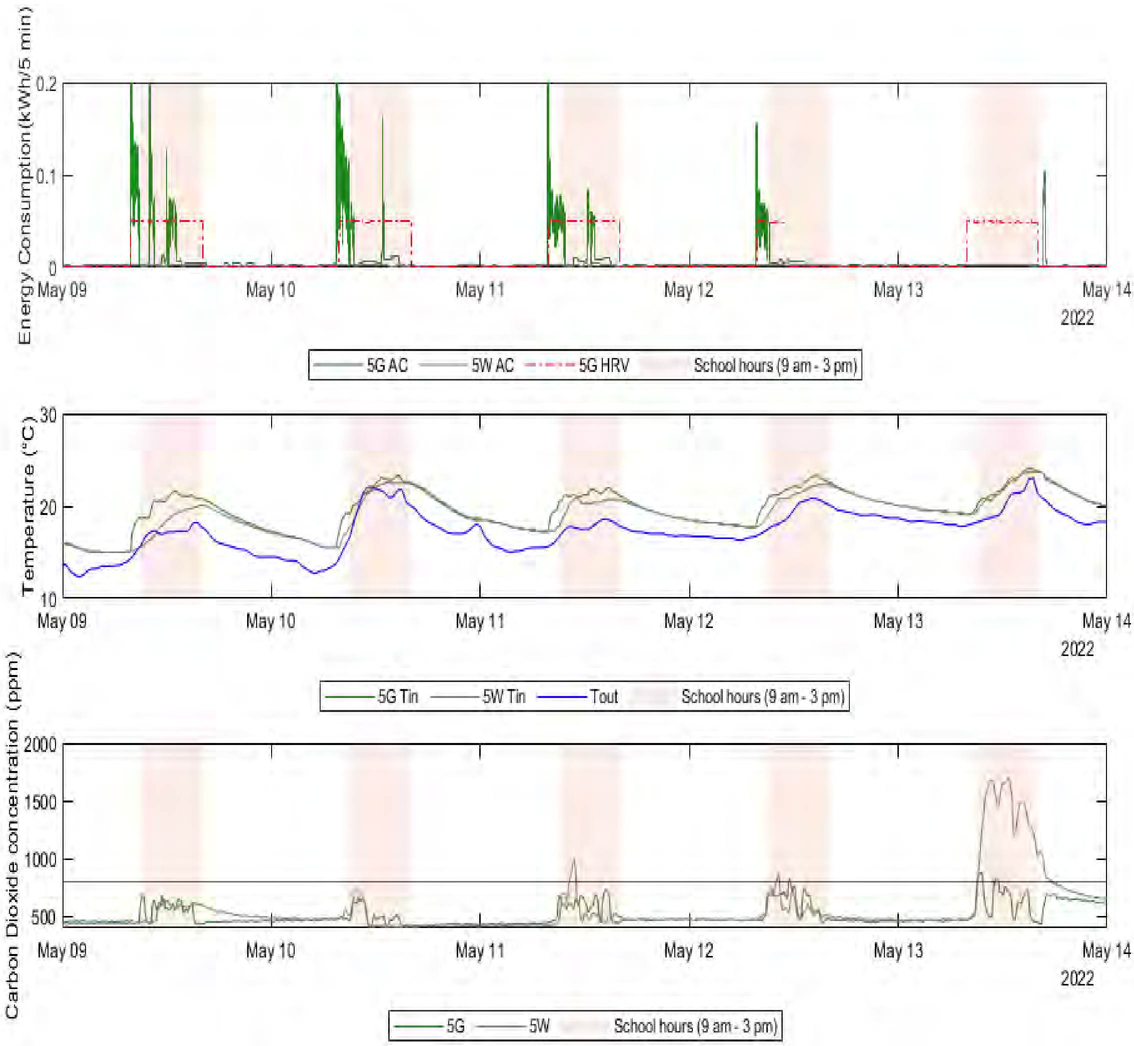

Figure 5-11 Side by side comparison of energy for AC and HRV, temperature and CO2 concentration for 5G (HRV) and 5W (adjacent) during the (coldest) 2nd week in the evaluation period.

Some insights into the impact of the HRV on energy consumption can be gained by looking at a single day in which both 5G and 5W used air-conditioning to maintain similar conditions; an example is shown in Figure 5-12. On this day the mean internal temperature between 9 AM and 6 PM was 22.7 in 5G and 22.2 in 5W. Both classroom used the AC for similar periods (4.1 hours for 5G and 4.6 hours for 5W), and 5W used slightly more energy (5.3 kWh vs 4.1 kWh for 5G); during the day the HRV unit consumed an additional 4.7 kWh. The CO_2 concentration in 5G remained below 800 ppm for the entire day, 5W exceeded 100 ppm for 25 minutes during the morning. This example shows that i) the HRV appears to reduce the energy requirements for air-conditioning when compared with a classroom that (likely) had open windows, but also that ii) the HRV energy usage in significant, in comparison to air-conditioning. It is important to note that this was a relatively mild day, which mean the HRV energy recovery benefits will be modest, and that the HRV was not operated using demand control, which may substantial reduce run-time.

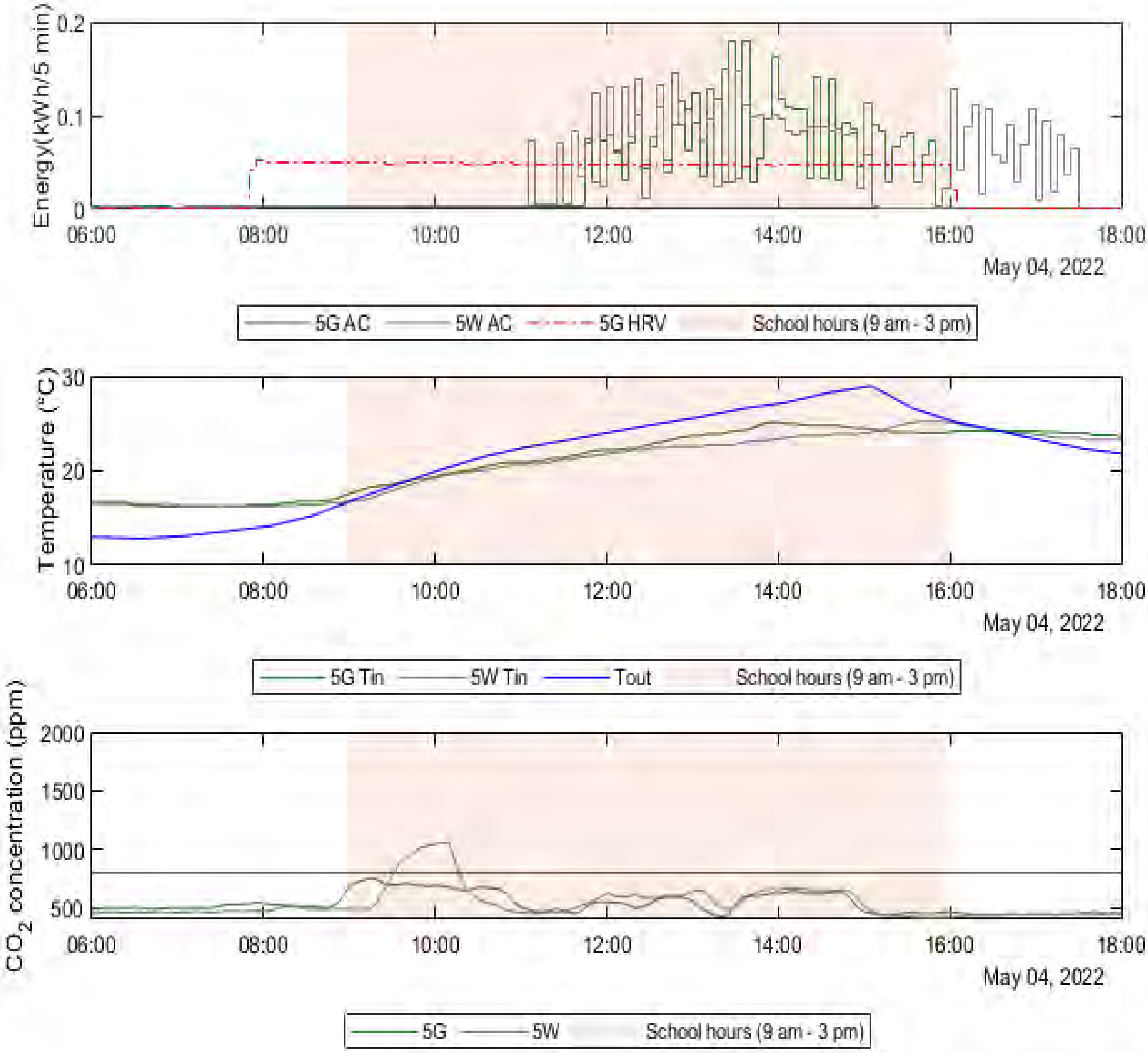

Figure 5-12. Energy, Temperature and CO_2 for 5G and 5W on a day with similar internal temperatures.

The classrooms in the second Hivve building 6W (6W) and 6G (6G) are not connected to the HRV building (5G & 5W), being a fully independent structure. A side-by-side comparison of these spaces for the coldest week in the evaluation period is presented in Figure 5-13. The CO_2 concentration in both 6W and 6G does not appear to be problematic. For the full evaluation period, during school hours school hours 5G was above 1000 ppm for only one five-minute period, 5W was above 1000 ppm for 20% of the period (27 hours), and 6G and 6W were above 1000 ppm for 2.6 and 2.7 % of the period. Only total energy consumption for 6G and 6W (i.e. no sub-metered AC consumption), and it is difficult to compare this to the sub-metered AC load for 5G and 5W. Usage appears to be higher for these space (i.e. a combined total of 14.2 kWh/day for Building 6, compared with an average of 2.6 kWh for AC in 5G and 1.4 kWh in 5W0, however there are likely to be significant operational differences that are difficult to ascertain without sub-metered data.

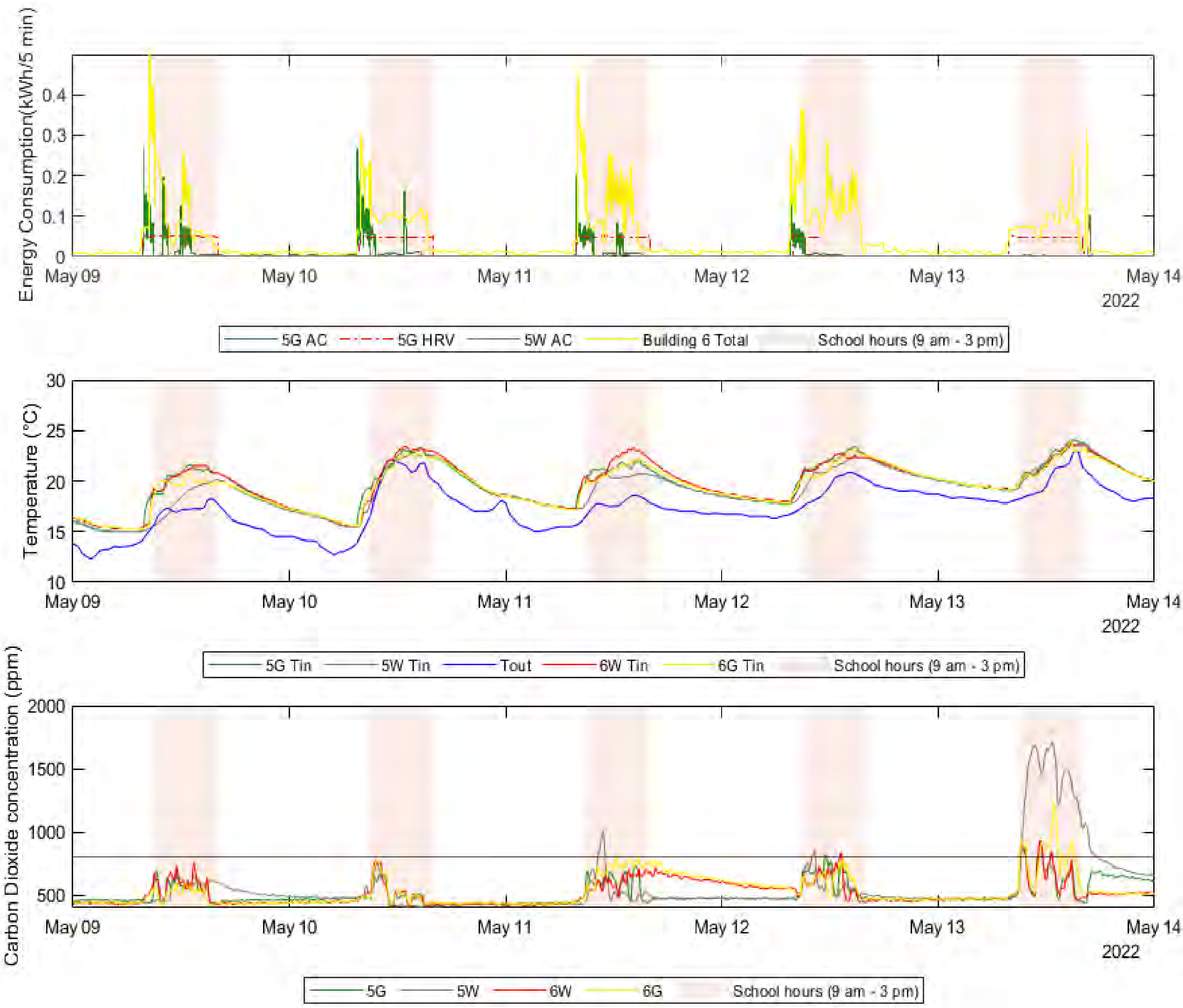

Figure 5-13 Side by side comparison of energy for AC and HRV, temperature and CO2 concentration for 5G (HRV), 5W (adjacent), 6G and 6W classrooms during the during the (coldest), 2nd week in the evaluation period.

6 CONCLUSION

This report has presented an evaluation of the effectiveness of HRV systems in providing appropriate ventilation (assessed using CO_2 concentration as a proxy), as well as the implication of the additional energy use for ventilation. The evaluation was significantly impacted by COVID-19 related supply chain issues, with significant delays in procurement of the HRV units. This resulted in a relatively short evaluation period that also occurred in a relatively mild shoulder season with minimal heating and cooling requirements. The energy recovery benefits of a HRV unit are related to the indoor to outdoor temperature difference, and these benefits are difficult to quantify during mild periods when natural ventilation does not have a substantial energy penalty.

The current evaluation has conducted both pre- and post- and side-by-side evaluation of two HRV units installed in Hivve transportables in Bankstown (St Felix) and Canberra (Majura). Within the constraints of the evaluation period, there are several important findings.

The HRV unit has a stable and consistent energy consumption during operation (~0.6 kW). When scheduled operation is used (St Felix HRV was operated at 100% from 8am-4pm) the energy consumption of the HRV unit can be significant, approximately 4.8 kWh. During this mild shoulder season, this can be a substantial end use relative to air-conditioning. In contrast, the use of demand- controlled operation based on CO_2 monitoring (Majura HRV operated whenever CO_2 concentration exceeded 800 ppm) substantially reduced run-time (from 8 hours to an average of 2.2 hours/day) and consequently the energy consumption (1.3 kWh/day). Both operation modes were able to effectively control CO_2 concentrations below 1000 ppm, with the results clearly highlighting a difference in CO_2 concentrations with the non-HRV classrooms. For example, at Majura, before the HRV was installed 77% of days had at least one hour with a mean CO_2 concentration greater than 1000 ppm; there were no days after the HRV was installed that met this criteria. During the same period all other classrooms at Majura saw an increase in days with high CO_2 events, despite operating under COVID-19 ventilation protocols.

Establishing the benefits of energy recovery from HRV in reduced AC loads was more difficult to establish during the evaluation period, due to the mild external conditions. There was some evidence of energy savings at Majura, however it is difficult to ascribe these savings to the HRV due to large discrepancies between classrooms in the operations of the AC system. Similarly, considering a single day of information from St Felix some potential savings were observed, however these were much lower than the energy used for the HRV in the single period. Again, the mild conditions make this assessment inconclusive.

In both scheduled and demand controlled operation the HRV operates during solar PV generation period, providing lower CO_2 levels within the rooms without the need for grid energy. With the cost of grid energy rising considerably in 2022, utilising onsite renewables and decreasing energy consumption is highly desirable. A continuation of this technology evaluation, encompassing winter 2022 and summer 2022/23 has been in-principle agreed between UOW and the ACT education directorate, and this additional data will be invaluable in quantifying the impact of HRV units on energy use and thermal comfort, and the impact on energy availability of the solar battery system.

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