The Innovation Hub

for Affordable Heating and Cooling

Product Testing Evaluation Report

Hivve Sustainable Modular Classrooms Envelope and Heating tests

19 November 2021

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.

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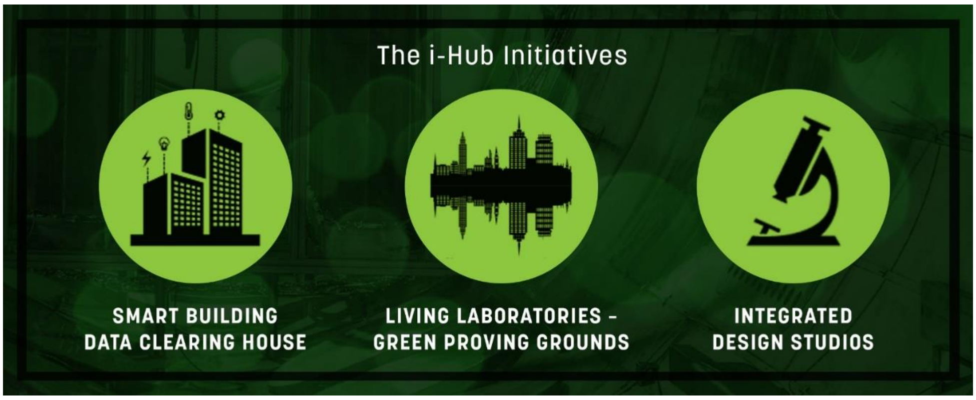

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Table of contents

This report should be read in conjunction with:

- Living lab manual: which details the specifics of the ACT Education Living Laboratories including the living lab boundaries, equipment within the facilities, monitoring equipment, and building schematics. The latest version can be downloaded via https://cloudstor.aarnet.edu.au/plus/s/f4xCnqxgfi6lyXJ/download.
- REETSEF: which defines the KPIs and methods of evaluation to be used to assess the impact of a technology upgrade on the value of renewable energy to an educational facility under the i-Hub living laboratory activity stream. The latest version can be downloaded via https://cloudstor.aarnet.edu.au/plus/s/J5TE6le6NnK5uIR/download

1 EXECUTIVE SUMMARY

The control of internal conditions within school classrooms is an important issue, with much focus on achieving appropriate temperatures for effective learning, and more recently, ensuring sufficient fresh air for learning and COVID risk minimisation. Providing these internal conditions through heating, ventilation and air-conditioning requires substantial energy, and has significant environmental implications.

Transportable classrooms are a common feature of schools across Australia. These classrooms can be moved from schools to school to assist in dealing with fluctuating demographics. The buildings are typically lightweight construction with basic thermal envelope specification to meet the minimum standards at the time of construction. Historically, they were designed with operable windows, shading and electric wall heaters to provide thermal comfort, however new transportables are equipped with multiple split system AC for heating and cooling, and major projects are underway to retrofit split-systems to existing buildings.

Hivve offers a transportable classroom package with many additional features designed to improve the thermal comfort and sustainability of these buildings. Features of a Hivve transportable include:

- Higher performance thermal envelope relative to minimum standards, notably including double glazing;
- An energy efficient split system Air-conditioning unit;
- Rooftop PV generation, with the option of integrated battery storage;
- A monitoring and controls systems to manage energy use and indoor environment.

A number of Hivve transportables have been installed in schools around Australia, including two at Majura Public School in the ACT. The current technology evaluation report presents the results of an as-built performance evaluation of the thermal envelope and HVAC system of the Hivve transportables located at Majura, in comparison with the transportables buildings located at the i-Hub living laboratory sites, namely Amaroo and Fadden schools. The comparison of transportables included an older building with a very modern efficient AC unit at Fadden, and two more recently constructed transportables at Amaroo that appear identical yet have remarkably different energy performance; one has an efficient AC and good thermal envelope, while the other is around five years older and has a poorer thermal envelope and a less efficient AC unit.

A series of tests were undertaken, designed to test firstly the building thermal envelope and heating system in combination, and then to test the performance of the building envelope with no active heating or cooling. The tests were undertaken during a COVID induced lock-down, in which there was no occupancy in the buildings. This allowed direct comparison that would not otherwise have been possible, as the usage and occupancy profiles of each transportable are substantially different.

The active heating test included setting the air-conditioning system in each transportable to heat to a set-point of 25 °C and identified several items of interest. Firstly, of the three standard

transportables (i.e. not Hivve transportables), two had issues with one of their twin AC units which meant they could not achieve the set point temperature. In one case (Fadden), one unit would regularly trip due to a faulty control board on the outdoor unit (diagnosed during the evaluation period). In the other case (Amaroo B13) the unit was not achieving the set point temperature, but using substantial energy. As a result of these issues, a valid comparison was only able to be made with Amaroo B14, which was a more modern building, with wall, ceiling and under-floor insulation and a high-efficiency Air-conditioning unit with a COP comparable to the Hivve units. Over the course of the 9 day testing period of continuous heating in September, the Hivve transportables used 13% and 2% less energy to maintain 25 °C when normalised by floor area, and 15% and 5% when normalised by heated volume.

The free running test returned a valid comparison for all the transportable buildings, as there was no reliance on active heating. After a period of normalisation, all external doors and windows were closed and the blinds shut, and the internal conditions monitored for a period of 10 days. The test was conducted in late September to early October, and external conditions were clearly still within the heating season. The results confirmed the impact of the improved thermal envelope for the Hivve buildings, with both Hivve transportables showing higher mean, minimum and maximum temperatures during this period when outside temperatures in Canberra were low. The Hivve transportables also showed a lower diurnal temperature variation.

This technology evaluation has evaluated the in-situ performance of the thermal envelope and HVAC system installed at Majura public school, in comparison to typical transportable buildings installed within the Fadden and Amaroo living laboratory. Notably, key features of the Hivve offering, namely the renewable energy system and Hivve IQ monitoring and controls systems, were not evaluated in this test, although a brief summary of their performance during the test period is included. A proposed future evaluation will explore in detail these renewable energy systems, and the performance of the building during occupied periods.

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. Consideration should be given to improvement in both summer and winter performance, and performance across the entire school day. Technology considerations include careful assessment of the thermal envelope (e.g. insulation and air-tightness), heating and cooling capacity, methods of control, thermostat locations, and distribution systems (see i-Hub (2021) for further detail on the Whole of Life assessment guide for technology replacement decisions).

Transportable classrooms are widely used in schools across Australia often because of the need to address issues around fluctuating demographics. Transportables are typically of lightweight construction with basic thermal envelope specification to meet the minimum standards at the time of construction.

The baseline data from this living laboratory, i-Hub (2021a), contrasts the performance at Amaroo School of transportable classrooms of lightweight construction and poor thermal envelope against the heavyweight concrete slab and concrete block wall construction of a main school building with in-slab heating (see Figure 1). It can be seen that the indoor temperatures of B13 and B14 (transportable) follow the outdoor temperature much more closely overnight, compared to Building 8. However, the transportable classroom temperatures rise much more quickly in the morning, whilst Building 8 classroom temperatures tend to take many hours to heat up before reaching the minimum thermal comfort threshold. Due to the occupancy schedule for schools, HVAC daily energy use profiles are typically well matched to PV generation profiles, without the use of sophisticated load shifting or scheduling. This means that overall improvements to HVAC or building thermal efficiency would be expected to closely correspond to reduced need for onsite generation to achieve net zero operation.

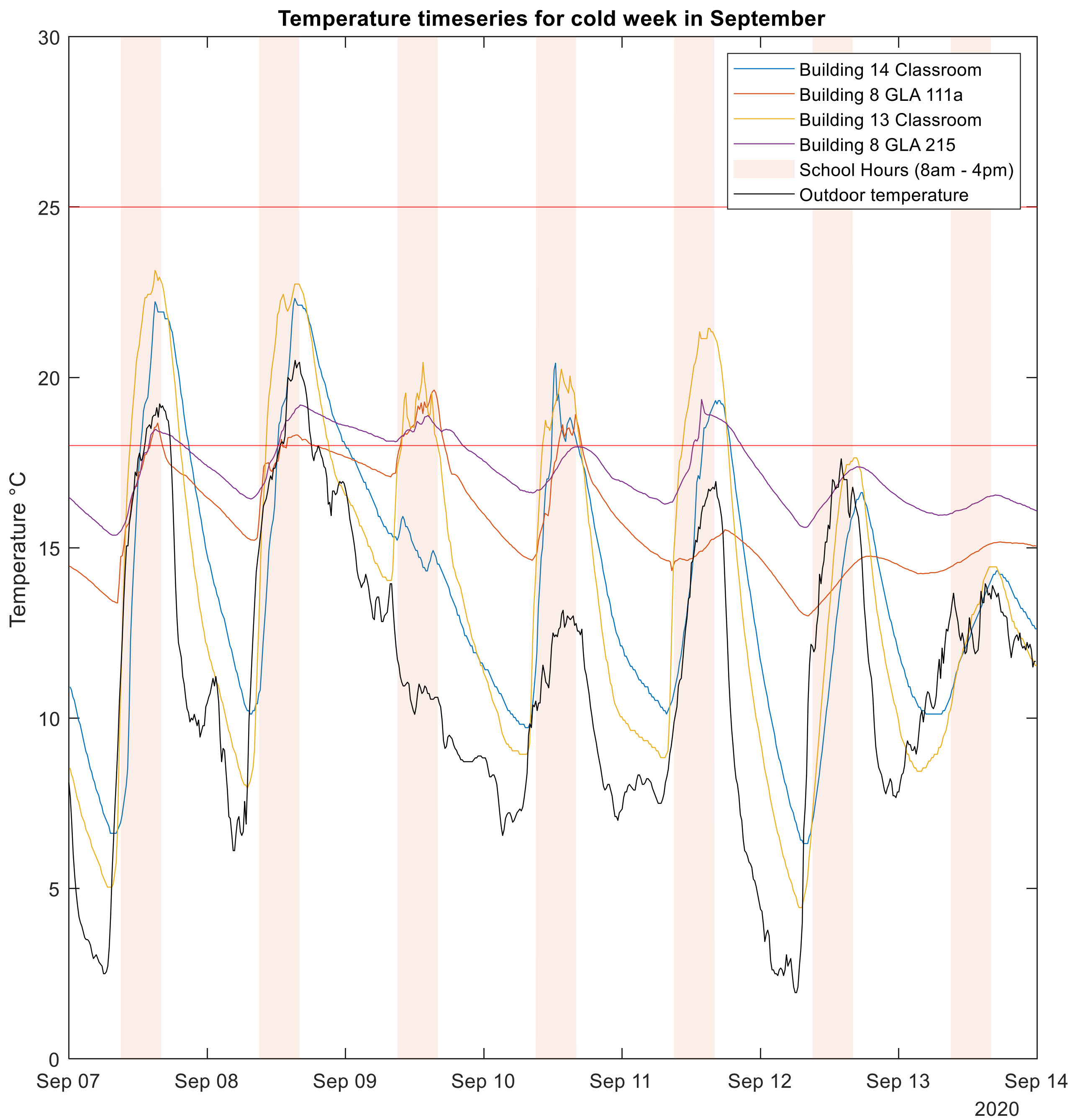

Figure 1. Amaroo School temperature performance comparing two transportable classrooms (B13 and B14) with Building 8 (heavy weight construction) for comparison.

2.2 **Problem statement**

Transportable classrooms are widely utilised in Australian schools as a flexible solution to changing enrolment levels. However, transportable classrooms may have tended to be viewed as lower cost temporary solutions, with accordingly lower performance thermal envelope and energy efficiency. In practice, many older transportable buildings remain in place as a long-term classroom provision.

As ACT Schools start to transition from gas heating to zero emissions technologies, the electrical grid connection capacity at the local substation and main switch board is placed under increased pressure and adding transportable classrooms will increasingly exacerbate this problem.

The unique occupancy schedules of the schools sector requires a flexible transportable classroom solution that delivers improved indoor thermal comfort to support learning outcomes with best value for money energy performance.

2.3 **Technology overview**

Hivve transportables offer a transportable classroom package with higher performance thermal envelope, including double glazing, and energy efficient split system AC. Hivve transportables typically include PV generation, with optional battery storage. This zero emissions and net positive energy contribution is 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 energy consumption is high, as well as general energy usage data, available for viewing.

2.4 **Objective**

The objective of this project is to evaluate the overall thermal envelope and HVAC performance of the Hivve transportable classrooms compared to the other transportable classrooms within the ACT Schools living laboratory. The evaluation covers the whole thermal aspects of the Hivve technology package including the AC split system combined with thermal envelope.

3 Test description

3.1 Site information

The testing will take place across three separate school sites in Canberra, ACT including two Hivve transportable buildings at Majura Primary School and existing i-Hub Living Laboratory transportable classrooms at Fadden Primary School and Amaroo School, shown on the satellite map in Figure 2.

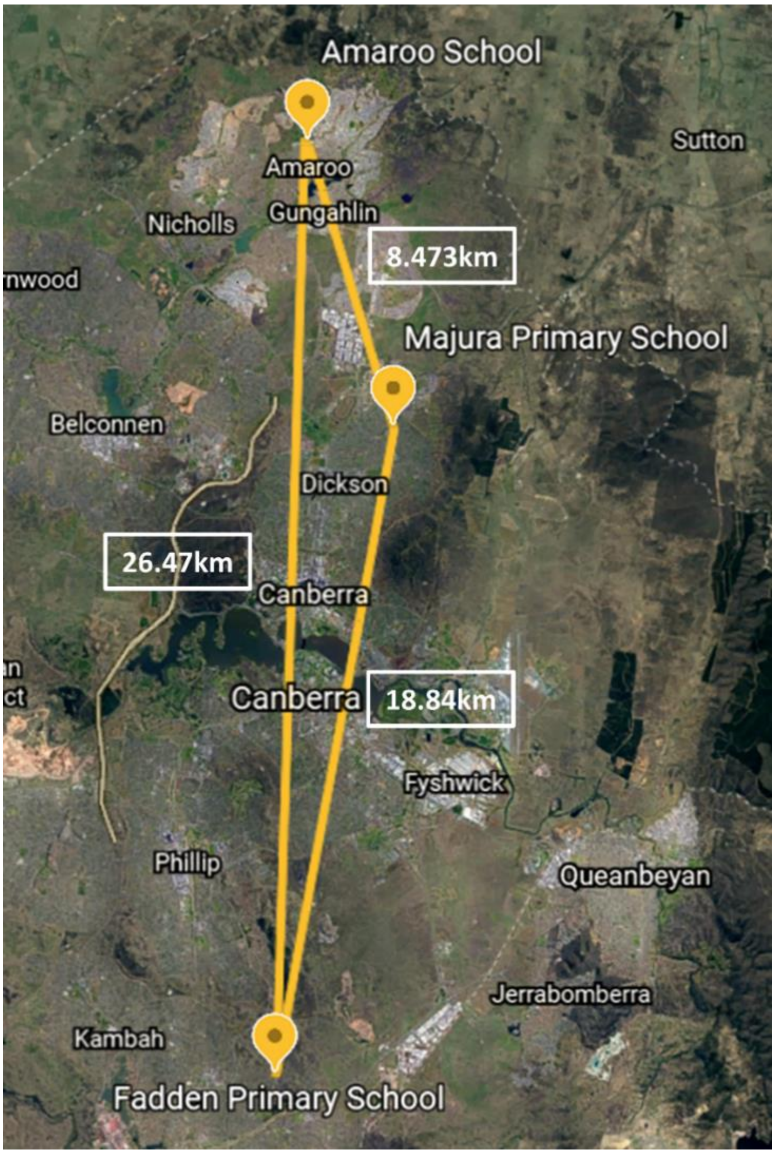

Figure 2: Location of schools with distances shown

3.1.1 Majura Primary School

Majura Primary School has two identical Hivve Transportable buildings, shown in Figure 3. Each building consists of two mirrored classrooms, a staff office and a breakout room, shown in Figure 4.

Figure 3: Majura Primary with Hivve transportables circled and labelled

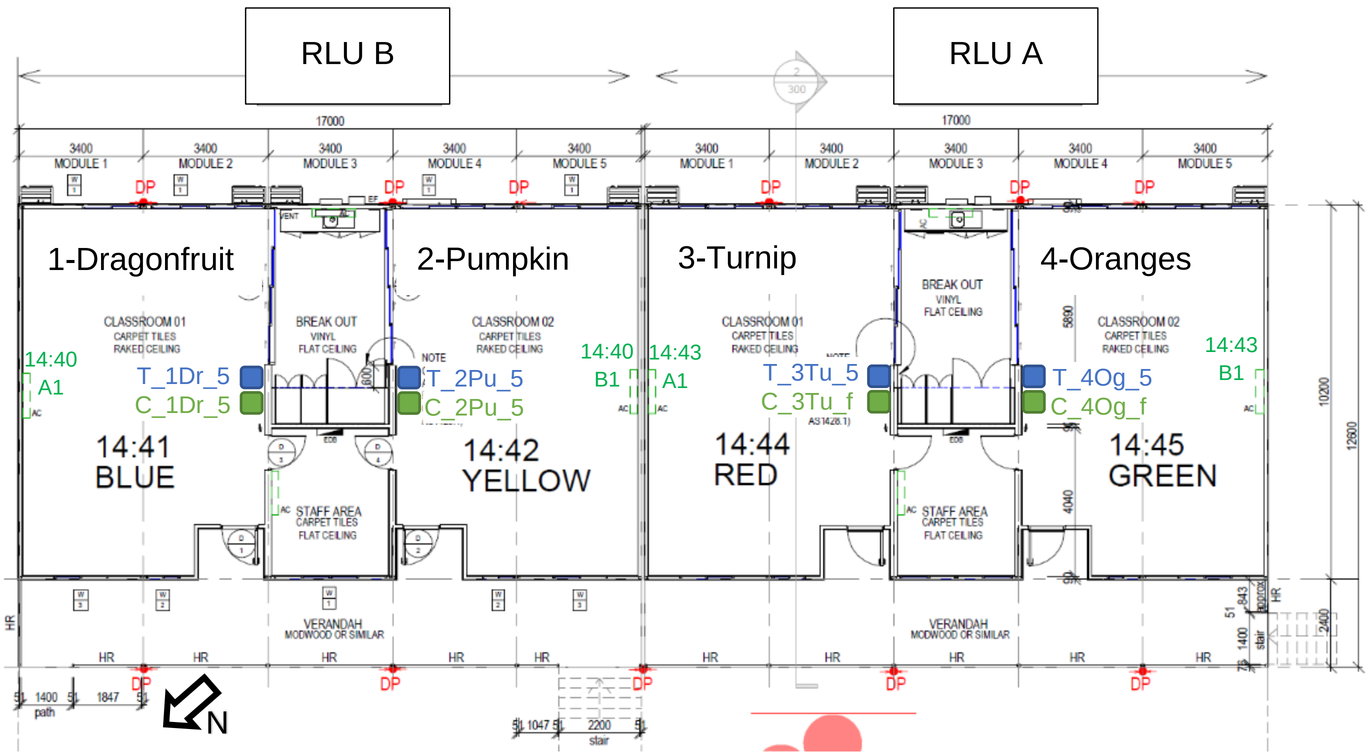

Figure 4: Hivve Majura RLU floor plan

3.1.2 Amaroo School

Amaroo School living laboratory includes two transportable buildings: B13 Preschool and B14 Music Room of equivalent design and orientation side-by-side (see Figure 5 and Figure 6). Each building has a single classroom with integrated office, storage and bathrooms (Figure 7).

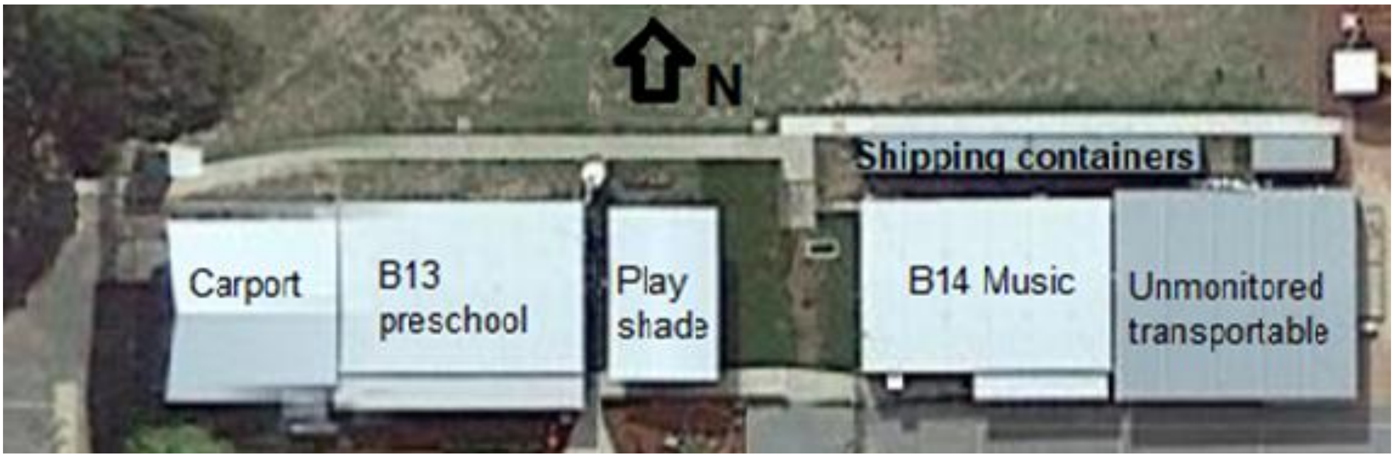

Figure 5: Amaroo transportables site layout B13 and B14 side-by-side with surrounding shade

Figure 6: (a) B14 north side windows with full louvre external shading; (b) B14 north side partial low shading by shipping container, and west side high windows unshaded; B13 east side shade structure; north windows partial height shade louvres; west carport shade.

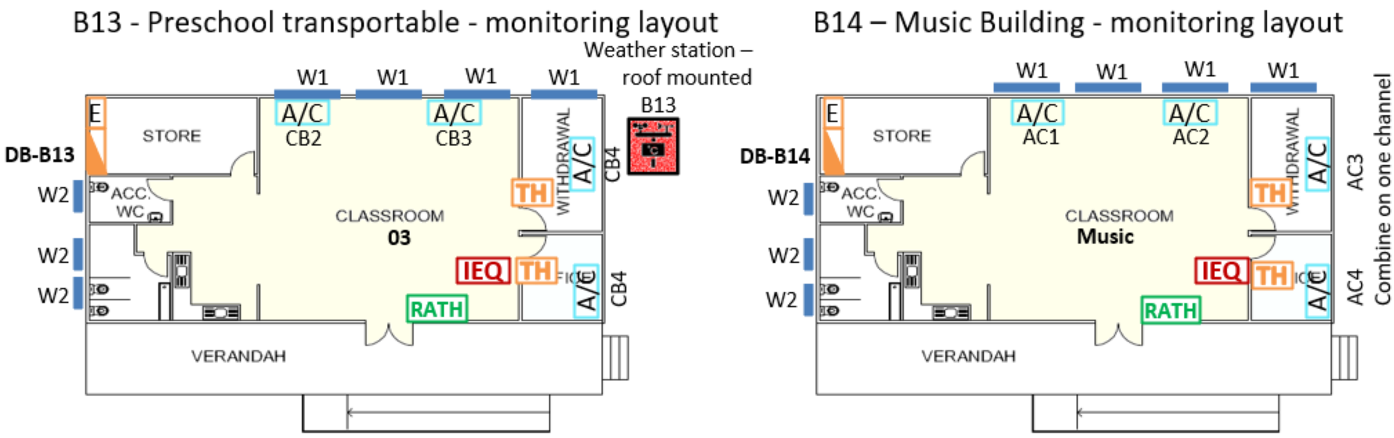

Figure 7: Floor plan for Amaroo transportable buildings B13 (left) and B14 (right)

3.1.3 Fadden Primary

Fadden Primary has a single transportable 'Namadgi', which has two mirrored classrooms. The office and storeroom have no internal connection to the classrooms (Figure 8 and Figure 9).

Figure 8: Fadden 'Namadji' transportable site plan and orientation with shade sails on the northwest

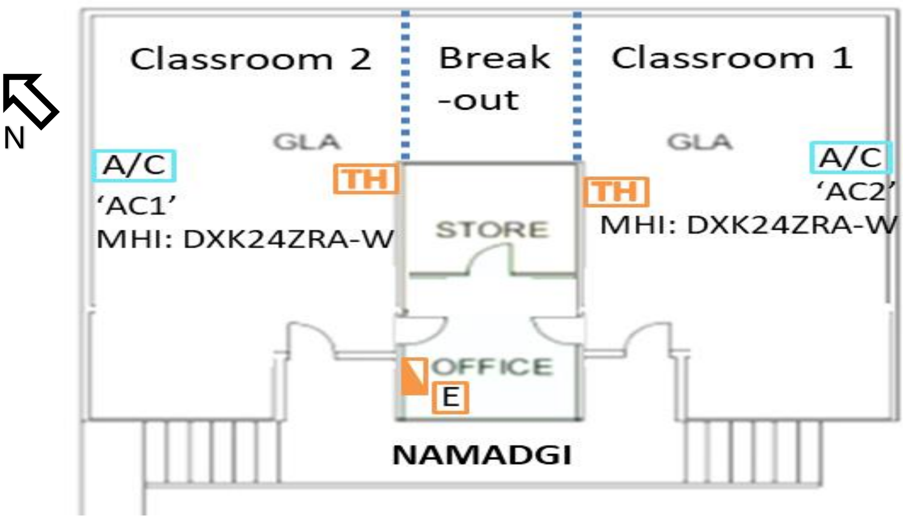

Figure 9: 'Namadji' floor plan

3.2 Summary of tested technology: Hivve transportables

The Hivve transportable package offers improvements over typical transportables in a range of different areas as detailed in Table 1.

All of the tested transportables had split system AC systems. The Hivve split system AC units were comparable to Amaroo B14. The Fadden AC systems had been recently replaced with much more efficient units. Amaroo Building 13 had a much older pair of AC units, with slightly lower rated COP.

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 (Hivve iQ) is notably specified at a quality suitable for a living laboratory, requiring only relatively minor calibration checks to participate in a performance evaluation. The Hivve iQ system provides a future-flexible platform for delivering further IEQ performance improvements. Assessment of the performance impact of these energy systems and Hivve iQ smart controls are planned for a separate i-Hub living lab technology trial and were not considered in this evaluation.

An important note regarding the various tested transportables is that they had markedly different floorplans. Fadden and Majura had two classroom and a small breakout space, whilst both buildings at Amaroo had one classroom and an office, withdrawal, storeroom and facilities. It was therefore not possible to compare these units normalised by student numbers.

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

Technology	Hivve	Amaroo		Fadden
Insulation - ceiling	R3.7 with an enclosed air gap to meet Section J.	Present but inaccessible ceiling space to estimate R value.		R2.0
Insulation - walls	R2.7	Present (estimated R1.5)		Present (estimated R1.5)
Insulation – sub-floor	R2.0 (to meet Section J)	B13: None	B14: Present	None
Windows – size, glazing, location/ orientation	Double glazed, aluminium frames, flyscreens.	Single glazed aluminium windows.		Single glazed Al; double sided (black/silver) screens
Window covering	Double roller blinds.	Metal venetian blinds.		Roller blinds (classrooms); venetians (office);

External Shading	Covered front veranda 2400 deep, NW facing	Fixed horizontal slats on north windows		None
Floor area (total internal)	168 m^2	156 m^2		139 m^2
Ceiling height	Raked ceiling from 2600 to 3140.	2690 flat		2690 flat
Volume	527 m^3	274 m^3		374 m^3
Ceiling fans	4 x 1200 per classroom. Fwd/Rev, var spd.	None		2 x 1500; summer only; 3 speed.
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]	(B13): ME MSHA26WV (2 off) 2004 8.0 kW/2.94 7.2 kW/2.69[2]	(B14): Tosh' RAS24N3KV ZA (2 off) TBC 8.1 kW/3.31 7.1 kW/3.16[1]	MHI: DXK24ZRA-W 2019 8.00 kW/3.96 7.1 kW/3.86[1]
PV	Yes (10 kW)	No		No
Battery Storage	27 kWh RLUA 13.5kWh RLUB	No		No
Smart monitoring and control	Hivve iQ system	None		None

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

[2] https://www.mitsubishi-electric.co.nz/product/nlaproduct.aspx?item=68927i

4 Methodology

4.1 Test Approach and Description

To compare Hivve transportable units with standard ACT transportable units, a Measurement and Verification Protocol (MVP) would typically be employed for a period of one year of the old transportable before replacement and a further year of the Hivve transportable after replacement of the old building. Alternatively, a side-by-side comparison method could be used. The practical cost and logistics of a whole building technology makes these assessment methods impractical to implement within the constraints of the i-Hub living laboratory budget and COVID restrictions.

A series of unoccupied building characterisation tests were designed to be synchronised across all three sites to provide controlled comparison data. These unoccupied tests were designed to overcome the project schedule and budget constraints above as well as to address the confounding factors as listed below.

4.2 Potential confounding factors

Site-specific discrepancies:

- *Solar gains* are expected to be the greatest confounding factor for the performance comparison. Orientations are indicated in the site layouts in Section 2. The Amaroo transportables both have the rear of the buildings facing north, whereas the Fadden transportable has the rear facing northeast and the Majura (Hivve) transportables have the rear facing southeast. Site-specific shading is indicated in the satellite images in Section 3.1. Notice the variations between Amaroo B13 (half height external louvre awnings) and B14 (full height louvre awnings) in Figure 6, as well as different east and west shading.
- Local Weather: There are local weather stations installed at the Fadden and Amaroo sites as part of the existing living lab baseline study, while consideration of the most appropriate source of external conditions for Majura is included in Section 5.1.
- Time synchronization of tests across disparate sites was crucial.

Technology-specific issues:

- *Sensor accuracy and location*: The existing Hivve temperature sensors are integrated with the wall controller and may be exposed to direct solar gains, so additional pre-calibrated temperature, humidity and CO_2 sensors were installed.

Occupant behavioural discrepancies (no impact on current tests):

- *Utilisation*: Amaroo test building B13 room is a preschool classroom, where the door is often left open throughout the day and B14 is a music room, with intermittent use, while the Fadden and Majura transportables are more typical junior school classrooms. This was the key reason to preference unoccupied testing.
- *AC setpoint controller temperature calibration and sensor locations* will introduce discrepancies between measured indoor temperatures during the unoccupied heating tests.

- *Different pre-conditioning of indoor thermal mass:* The first stage of the test is designed to precondition the buildings to similar outdoor conditions.

The methodology of each unoccupied building performance test is detailed below. Significant effort was put to coordinate the precise starting and finishing times of the tests between all three sites. This was achieved by constant communication with the schools' BSOs.

4.3 Test procedure

4.3.1 Start up period

This test was used to determine the total energy and the time required to recover to the temperature set point after a system failure. It is was also a method for starting all sites from similar conditions.

Indoor conditions were normalised to outdoor conditions for four hours with all AC units turned off, external windows and doors opened and internal doors opened.

The AC start up performance tests commenced simultaneously at midday with all classroom AC split systems switched on to 25 °C, in heating-only mode and maximum fan speed. Staff room and withdrawal space AC units were left switched off. External windows and doors were closed and internal doors were all left open. Internal blinds were closed to minimise solar gains effects.

4.3.2 Active stable heating energy test *(10 day during heating season)*

This test methodology is similar to a co-heating test, except that the existing split AC systems are used to maintain the space temperature instead of an electric resistance heater. This means that instead of evaluating the thermal envelope performance, this test evaluates the combined performance of the AC and thermal envelope in terms of the total electrical power (kW/m^2 and kW/m^3) required to maintain constant indoor temperature for a range of fluctuating outdoor temperatures.

This test was conducted as a continuation of the start up test without interruption or change of conditions.

4.3.3 Heating failure response test *(3 hours nominal)*

The results may be used to calibrate a building thermal model under conditions similar to the total failure of the heating (AC) system.

This test was conducted as a continuation of the active heating energy test without interruption or change of conditions, except that the AC units were all switched off.

4.3.4 Free running test

This test may be used to compare the thermal performance of the building envelopes without any active heating.

This test was conducted as a continuation of the heating failure response test without interruption or change of conditions. The test was conducted with blinds closed for five days, then repeated with all internal blinds opened for a further five days.

4.4 Instrumentation Plan

Table 2: Sensor list and accuracy comparison

Criteria	Amaroo/Fadden	Majura/Hivve
Electrical Energy Sensor	**Wattwatchers A6M:** True RMS, kWh/5min IEC62053-21 Class 1	**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	**Nube iO droplet** ±1°C **Elsys ERS-CO2** ±0.2°C	**Carlo Gavazzi SHSUCOTHL** ±0.5° (0.1 resolution)
Outdoor Temperature Sensor	**Davis Instruments Vantage Pro weather station** 0.3°C	**Carlo Gavazzi BSI-TEMANA-U** 0.5°C
Indoor Humidity Sensor	±0.3 (ERS) Resolution 0.008	**Carlo Gavazzi SHSUCOTHL** ±5% (0.1% resolution)
CO2 Sensor	0-2000 ppm ±50 ppm (±3% of value); manual Calibration every 2-3 years	**Carlo Gavazzi SHSUCOTHL** 0-2000 ppm ±50 ppm (±2% of value) Non-dispersive infrared; 2 ppm CO2/°C, 20 ppm/year drift
Door opening	Installed on select doors/windows	None
Local weather station	Davis Pro at each site	Amaroo site weather station used.

4.5 Excluded Items

There are no items to be specifically excluded items. CO_2 levels were monitored and differences noted, but ventilation and CO_2 levels are the subject of separate ongoing work and were not a feature of this evaluation.

5 TEST RESULTS

5.1 External conditions

Davis Pro weather stations were installed in both Fadden and Amaroo during the establishment of these living laboratories. As Majura was not originally conceived as a living laboratory, it did not have existing instrumentation, and there was insufficient budget to install an additional weather station. External conditions were being recorded by sensors installed on the exterior of the Hivve transportable, however there were concerns regarding the reliability of these sensors, with respect to micro-climatic conditions.

To assess the most appropriate data to use for representing conditions at Majura, Figure 10 shows data collected during the first week of testing. It can be seen that the Majura sensors consistently record higher temperatures than the weather stations, and that there is little difference between temperature as recorded at Amaroo and Fadden. The Hivve outdoor air temperature measurements appears to be influenced by either internal or micro-climatic conditions or possibly both. Comparing overnight outdoor temperatures during the heating and free running periods shown in Figure 11, it can be seen that the Hivve sensors are clearly showing relatively warmer conditions during the period of the heating tests. They are also showing substantially warmer daytime temperatures, which may indicate impacts of solar gains on a local micro-climate around the sensor. This suggests these sensors are not appropriately located to represent ambient conditions. Given the relatively small observed difference between conditions at Amaroo and Fadden (approximately 30 km distance), it is considered acceptable to use weather data from Amaroo to represent conditions at Majura (approximately 8.5 km).

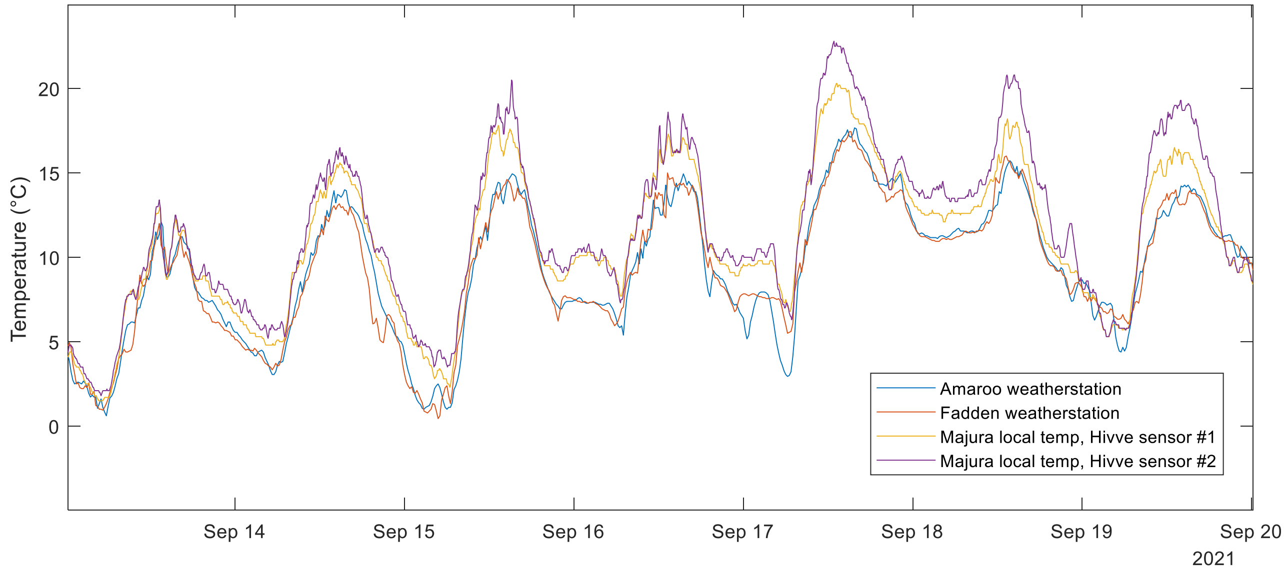

Figure 10. External temperature for the first week of testing as recorded at Amaroo and Fadden weather stations, and as recorded by low cost sensors installed on the Hivve Transportable.

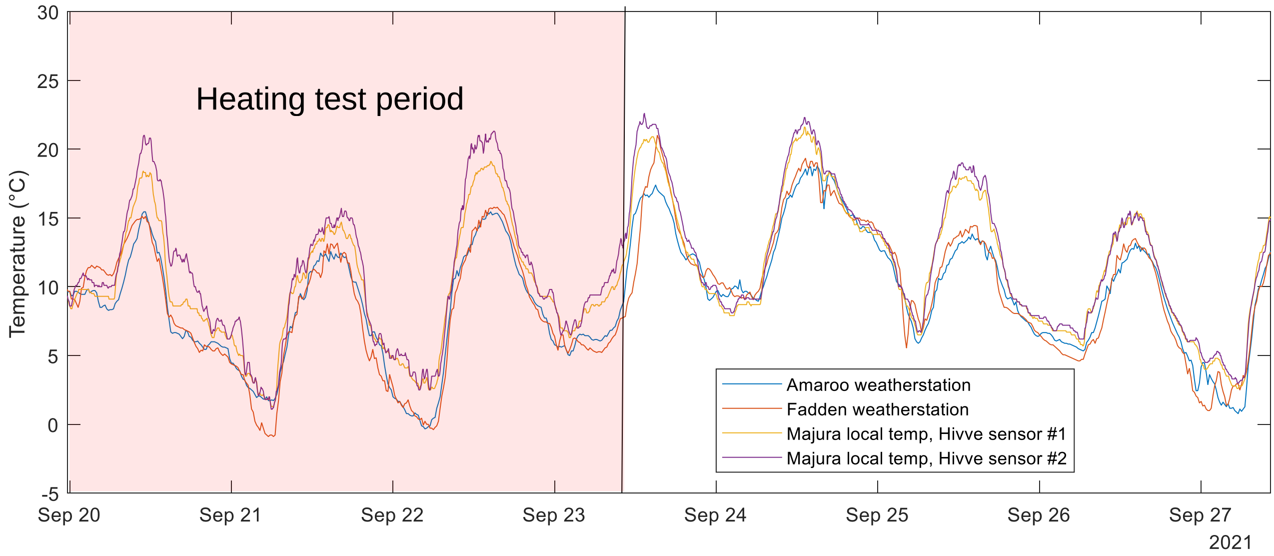

Figure 11. External temperature during heating and free-running test periods.

5.2 Heating start up

The heating start-up test involved two phases. First, an initial 3 hour normalisation period with all windows and doors open and AC off. After the 3 hour normalisation period, the heating test was then commenced with the following settings:

- All external windows and doors were closed, and all internal doors were left open.
- All internal blinds are to be closed.
- The main classroom AC split systems were switched on to heating mode with the temperature set-point at 25 °C, with the fans speed at maximum and with oscillation.
- Heating was commenced at 12:00pm on the 13th September.

Several items can be observed from the heating start up period measurements shown in Figure 12:

- All air-conditioners were controlled to a set point of 25 °C. Allowing for a tolerance of ±1.5 °C, **only three of the tested transportable were able to achieve the target temperature in each classroom on the day of the start-up test**. A summary of the duration to warm the room from ambient to various intermediate temperatures towards the target temperature is shown in Table 3.
- A substantial variation was observed in the temperature profiles following the test inception, and it can be seen that two of the tested transportables (Amaroo B13 and Fadden Nam Classroom 2) did not reach the target temperature. Each room in the Hivve transportables achieved 24.5 within 24 hours. Notice that the two Majura RLU-B classroom temperatures were slower to rise when compared to RLU-A classrooms. This is likely to be due to RLU-A classrooms having greater solar gains in the afternoon. The two classrooms in each buildings were opened to each other via the open breakout area.

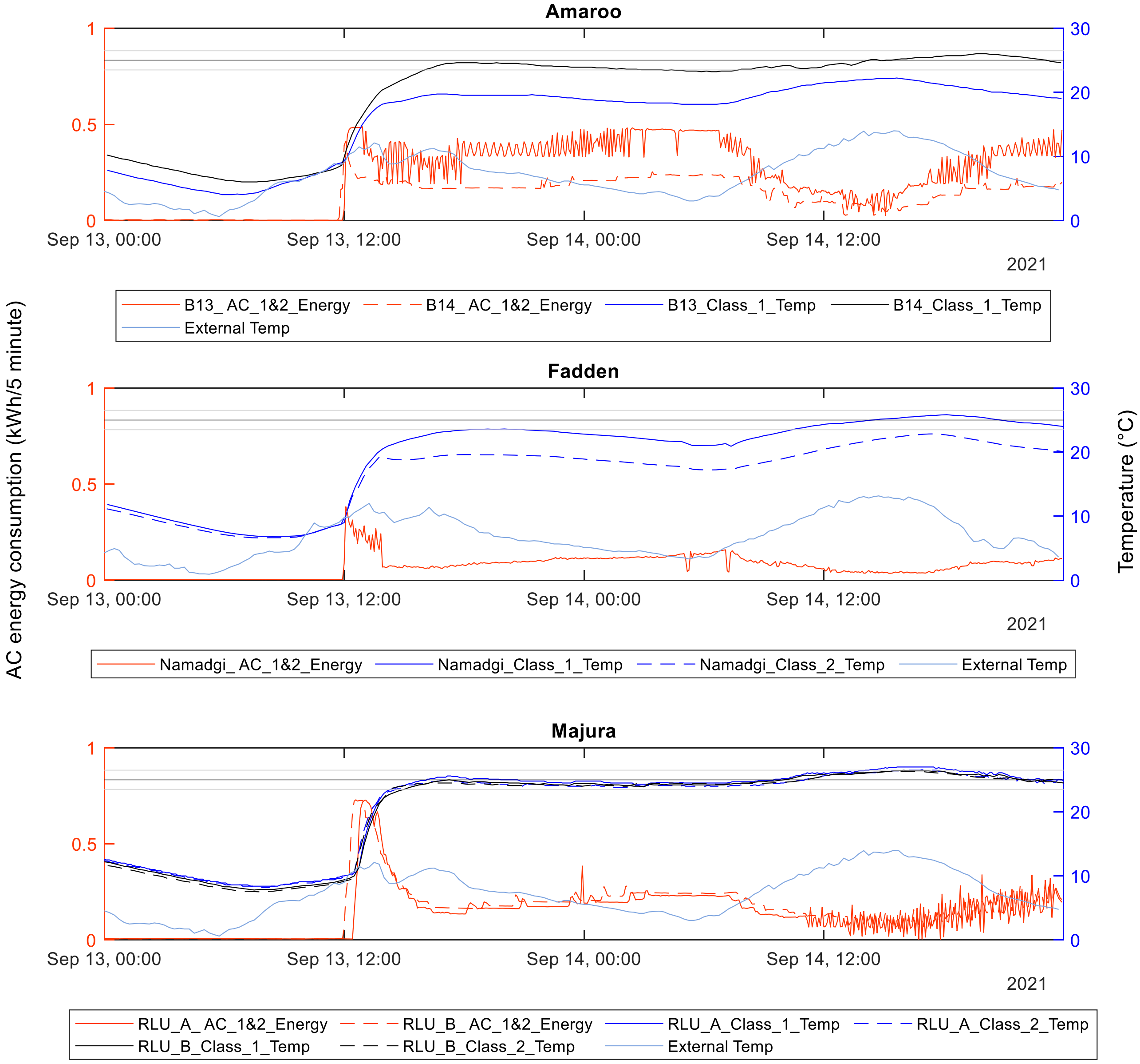

Figure 12. Start up period of heating test, showing results for two transportable at Amaroo (B13 and B14), one transportable at Fadden (Namadgi), and two Hivve transportables at Majura (RLU_A and RLU_B).

Table 3. Time to reach target temperatures for various classrooms. Calculation is based on actual heating start time, allowing for slight (~15 min) differences is start time across the various buildings.

Location	Time to reach 20 °C (hours:min)	Time to reach 23.5 °C (hours:min)	Time to reach 24.5 °C (hours:min)	Time to reach 25 °C (hours:min)
Amaroo B13	21:23	Not achieved	Not achieved	Not achieved
Amaroo B14	02:07	04:22	05:22	26:37
Fadden Nam C1	01:55	06:21	25:10	26:33
Fadden Nam C2	23:39	Not achieved	Not achieved	Not achieved
Majura RLU A - Turnip	01:00	1:55	03:00	03:40
Majura RLU A - Orange	00:50	2:10	03:40	22:35
Majura RLU B - Dragon	1:45	3:15	04:30	22:14
Majura RLU B - Pumpkin	1:25	2:25	21:54	23:54

A fault was identified in the AC unit serving classroom 2 in the Fadden Namadgi transportable. It can be seen in Figure 13 that the AC energy for classroom 2 drops to zero approximately 1 hour after start up. This AC unit was reset a number of times through this test, but kept tripping out on an intermittent fault. A number of site visits were required to progressively identify the root cause as a faulty control board on the outdoor unit. The fault was not rectified during the heating test period, therefore the results from the Fadden transportable were not able to be included in this analysis. Since these Fadden classrooms were openly connected to each other during these tests, the classroom 1 AC unit performance was also substantially compromised. This explains the inability of the Fadden transportable to achieve the target temperature during the start-up period. A fault was also identified in Amaroo B13, which is explored further in the next section.

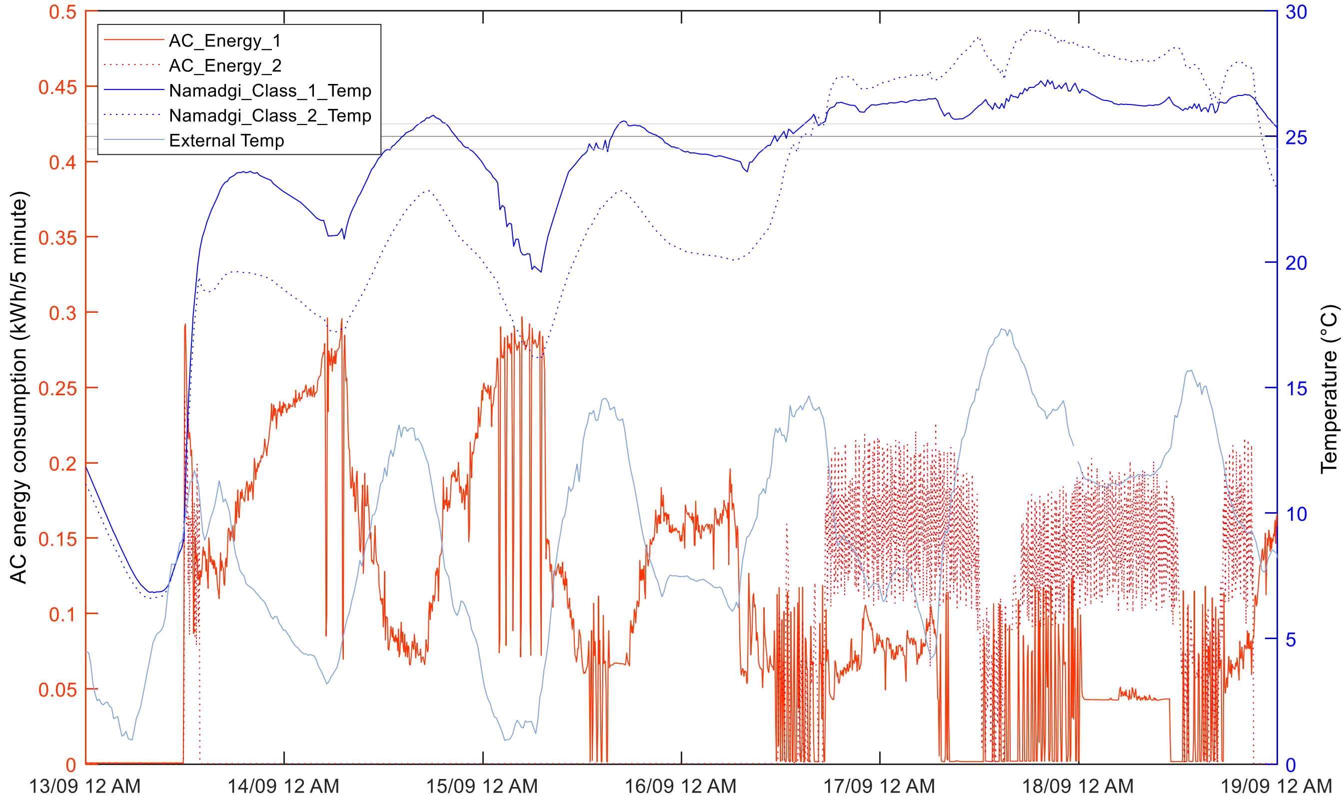

Figure 13. Energy consumption and temperature for Fadden transportable, showing fault with AC unit serving classroom 2.

5.3 Active stable heating energy test

The stable heating test was considered to have commenced 24 hours after the start-up period, that is at 12:00pm on the 14th September, and was continued until 12:00pm on the 23rd September, resulting in 9 days of steady state heating. The energy use, internal and external temperatures for the Amaroo and Majura transportables are shown in Figure 14, including the start- up period.

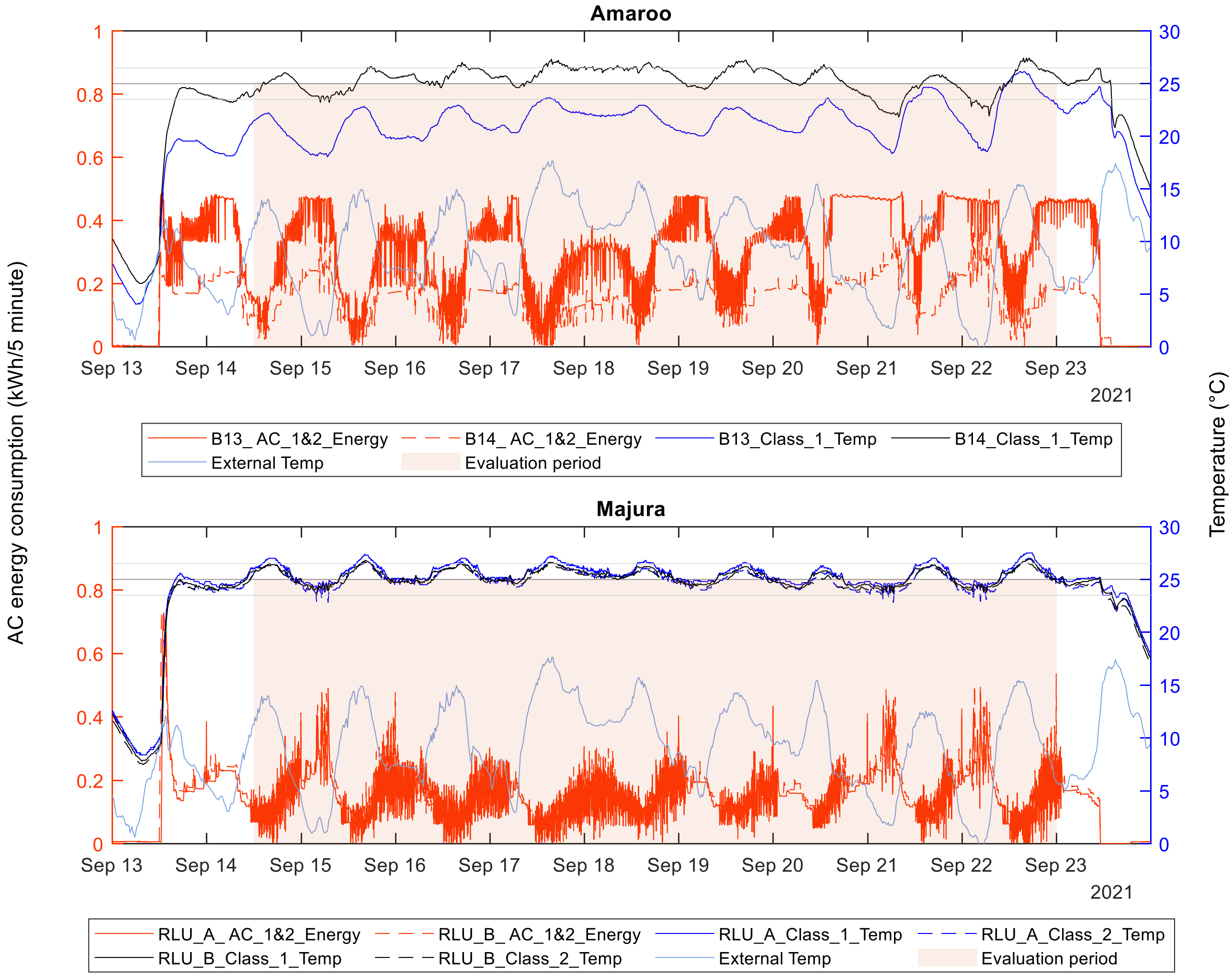

Figure 14. Energy use, internal and external temperatures for the Amaroo and Majura (Hivve) transportables during the Active stable heating test period.

As noted in the test plan, there was anticipated to be some variation in the achieved temperatures across transportables due the limited accuracy of AC thermostats. This is evident in the achieved temperatures of Figure 14.

In Amaroo B13, despite substantial energy input, the target temperature was not reliably achieved. Analysis of the time series data indicated an issue with the thermostat, which appeared to be controlling to approximately 22 °C. This AC unit was reset multiple times to ensure the set-up was correct, with no influence. The system is 17 years old and it appears that the thermostat sensor has drifted over time and no longer accurately reporting temperatures to the unit. However this does not explain the high energy consumption and it was further suspected that the unit may have had an incorrect refrigerant charge or similar issue impacting performance. An HVAC technician checked the pair of AC units and found that the refrigerant charge, compressor current draw and outdoor fan unit were all within specifications. Substantial differences in the as-built construction of B13, for example poor insulation installation or air-tightness, could explain this result; COVID19 restrictions during the testing period precluded the further investigation of this difference that would have typically occurred (i.e. blower door testing and thermal camera survey). The results from Amaroo B13 were excluded from consideration during the active stable heating test due to it being unable to reach the specified temperatures.

A summary of the key statistics regarding the energy use and achieved temperatures are provided in Table 4, with a boxplot of the achieved temperatures in

Figure 15. As noted, Fadden and B13 were not considered valid in this test. It can be seen that all of the other classrooms achieve an average temperature of at least 25.0 °C. The rooms were often above this temperature, as the AC was in heating only mode, so solar gains during the day would often lead to higher temperatures. The amount of over-heating above the set point in each classroom, calculated as the number of degree hours above 25 over the stable heating period was similar, with a slightly higher value for Hivve RLUA compared to Amaroo B14 and Hivve RLUB.

Table 4. Summary statistics for transportables for which valid active stable heating energy tests (9 days heating with a set-point of 25) were completed.

Transportable	Average temperature	Degree hours above 25	Standard Deviation	Total Energy consumption (kWh)	Peak demand (kWh/hour)	Area based Energy intensity (kWh/m^2)	Volumetric Energy intensity (kWh/m^3)
Fadden	*23.3*	*-365*	*3.4*	*182*	*1.3*	*1.3*	0.49
Amaroo B13	*21.7*	*-714*	*1.7*	*832*	*2.9*	*5.3*	1.99
Amaroo B14	25.2	49	1.2	402	4.15	2.58	0.96
Hivve RLU A	25.3	72	0.9	384	3.95	2.26	0.81
Hivve RLU B	25.2	46	0.7	430	4.30	2.52	0.91

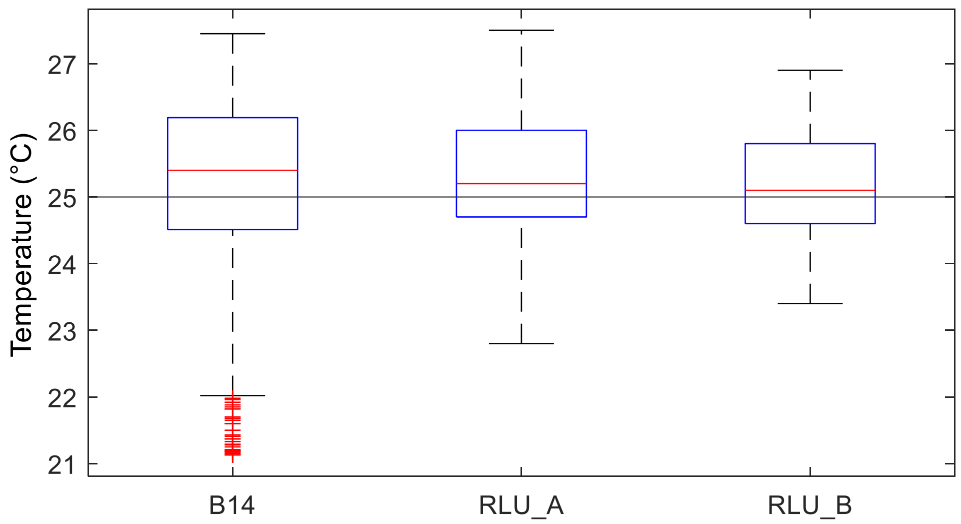

Figure 15. Achieved temperature for Amaroo B14 and the two Hivve transportable during the active stable heating test with a set point of 25

Total energy consumption over the period ranged from 384 kWh for Majura RLU A to 429 kWh for Majura RLU B; Amaroo B14 consumed 401 kWh over this period. The Majura transportables had a slightly larger floor area, as well as a slightly higher ceiling. Hivve transportables reported lower energy intensity considering both area and volume. When normalised by floor area, Amaroo B14 had an energy intensity of 2.6 kWh/m^2; RLU A and B reported energy intensity of 2.3 (13% lower) and 2.5 kWh/m^2 (2% lower) respectively. When normalised by volume, Amaroo B14 had an energy intensity of 1.0 kWh/m^3; RLU A and B reported energy intensity of 0.8 kWh/m^3 (15% lower - see exact values in Table 4) and 0.9 kWh/m^3 (5% lower) respectively This result is reflective that:

1. Amaroo B14 is a relatively new transportable relative to the ACT schools portfolio and is expected to have insulation to meet NCC requirements.

2. The Hivve transportables building fabric is slightly more thermally efficient than NCC requirements. The building ceiling and floor insulation is constructed to NCC minimum standards. The walls are slightly more insulated, and the windows are double glazed.

3. Both the split-system installed in Amaroo B14 and the Hivve transportables are modern, relatively efficient units with comparable name plate COPs (Hivve 3.36 & 3.42 vs B14 3.31).

It would have been expected that the thermal envelope of Fadden, an older transportable, would have performed relatively poorly, although the recently replaced AC units have a significantly higher name plate COP compared to both Hivve and Amaroo B14.

It is remarkable that the two Amaroo transportables that appear identical from the outside yielded such different energy performance results. B13 is reportedly approximately four to five years older and has a less efficient AC unit and no sub-floor insulation. Wall and ceiling insulation cannot be inspected and specifications for these buildings could not be obtained. As noted, COVID19 travel restrictions during the evaluation period precluded further on-site investigation of these differences.

5.4 Free running test

Following the active stable heating test, a heating failure response test was planned. Due to an unplanned absence of one of the building service officers the heating failure test was not able to be commence as planned (simultaneous test across all sites at 8:00 am and the living lab team could not access the sites due to COVID19 restrictions), but was initiated at 11 am. This resulted in different temperature starting points, and limited time before the normalisation for the free running test had to be commenced. Consequently, the heating failure test did not return a valid result for comparison across the sites.

The normalisation period prior to the free running test commenced at 2pm on the 23rd of sept, with all windows and doors left open until the end of the school day. The free running evaluation period was commenced at 9 am the following morning. At this point there were slight temperature differences; the starting temperatures are noted in Table 5. Whilst there are some differences between the various classrooms (maximum temperature was 14.5 °C in RLU B, minimum temperature was 12.1 °C in Amaroo B13), this was considered acceptable. This is because the classroom temperatures after 24 hours of free-running had a greater range (10.4 – 13.6 °C), suggesting that the differences in starting temperatures were due to the thermal envelope and microclimate differences in the transportables, rather than unequal starting positions.

Table 5. Temperatures in each transportable at the start of the free-running test, and after the first 24 hours.

Transportable	Starting temperature (9am 24rd Sep) (°C)	Temp after 24 hours (9am 25th Sept) (°C)
Fadden	13.7	12.7
Amaroo B13	12.1	10.4
Amaroo B14	12.3	10.5
Hivve RLU A	14.5	13.6
Hivve RLU B	13.9	13.0

The time series temperature and energy consumption for the free running period are shown in Figure 16 and Figure 17; Figure 17 shows mean classroom temperatures for each transportable, and Figure 16 shows result for each classroom with a sensor. As designed, there was no energy consumption by the AC units during the free running tests. This means that the transportables with faulty AC units (Fadden and Amaroo B13) are able to be included in the free-running evaluation.

Several observations can be made from the time series data:

- During the free running test period, all transportables were below 18 °C for the vast majority of the day, indicating that despite being late September, this was still clearly during the heating season.
- All transportables have large diurnal temperature ranges when operating in free-running mode, indicative of their lightweight construction and minimal thermal mass.
- Typically, the transportables experience a minimum internal temperatures between 6 am and 8am, and a max internal temperature between 3pm and 6 pm.
- Amaroo B13 was notable in having the largest diurnal range, the lowest mean and minimum temperatures, and the earliest afternoon peaks temperatures.
- Hivve RLU A was notable as the warmest transportable, with the least diurnal variation. A possible explanation for the observed difference between RLUA and RLUB is slight differences in solar gains; the solar generation data for the period of the free running test indicated that RLUA generated 16% more electricity from an identical array, suggesting higher solar gains (See Table 8).
- It can be seen from the time series data that the Hivve transportables typically achieved higher maximum daily temperatures, higher minimum overnight temperatures and would generally be at a warmer temperature at the start of the school day.

The individual room temperature, mean transportable temperature and average daily profile during the free running evaluations are provided in Figure 16 and Figure 17 and Figure 18.

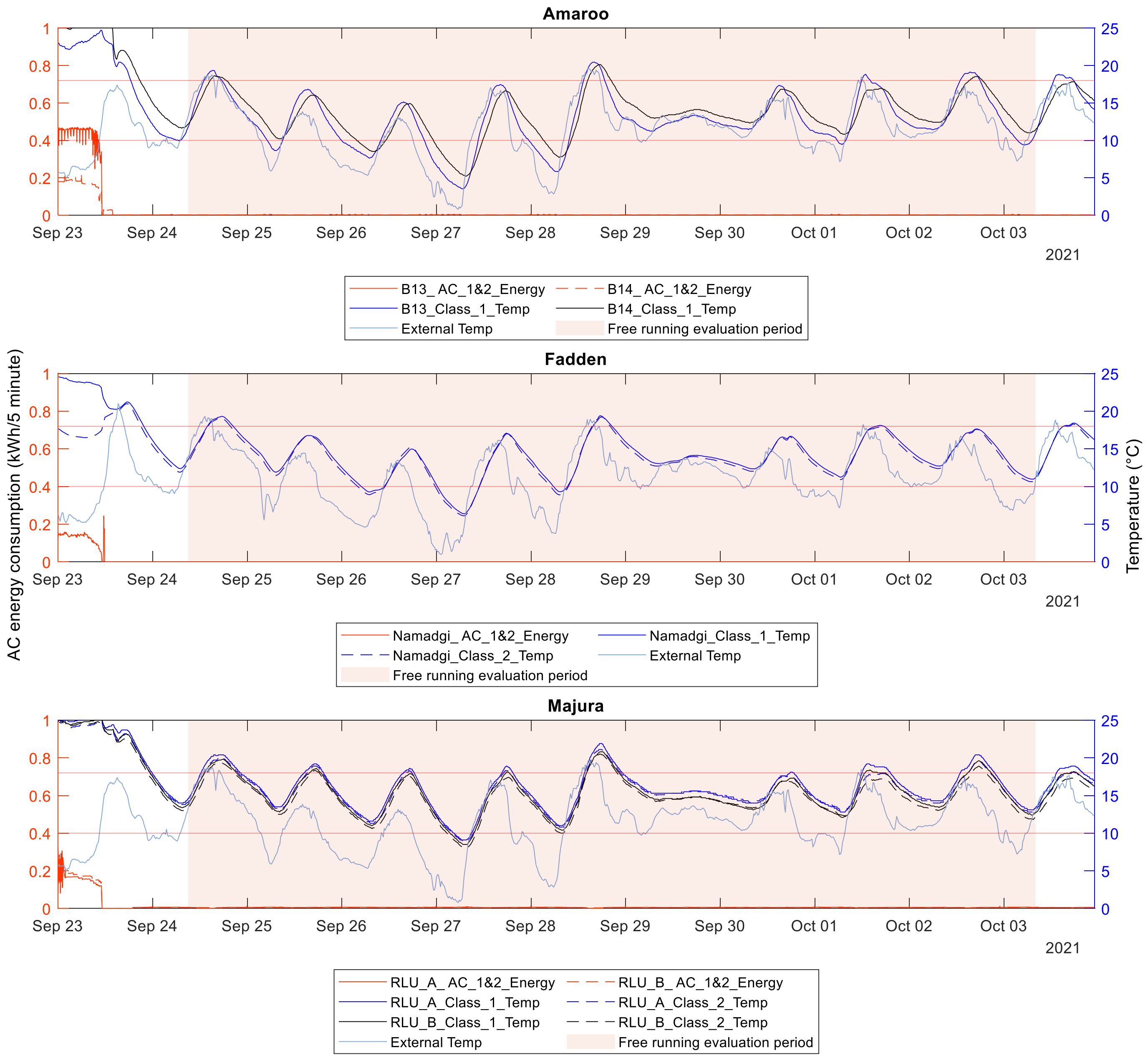

Figure 16. Time series energy and temperature showing the end of the stable heating period (Sep 23, 11am), a normalisation period, and the start and end of the free running test period (Sep 24, 9 am – Oct 3 9am). Recorded temperatures are shown for each individual sensor in the transportable classrooms.

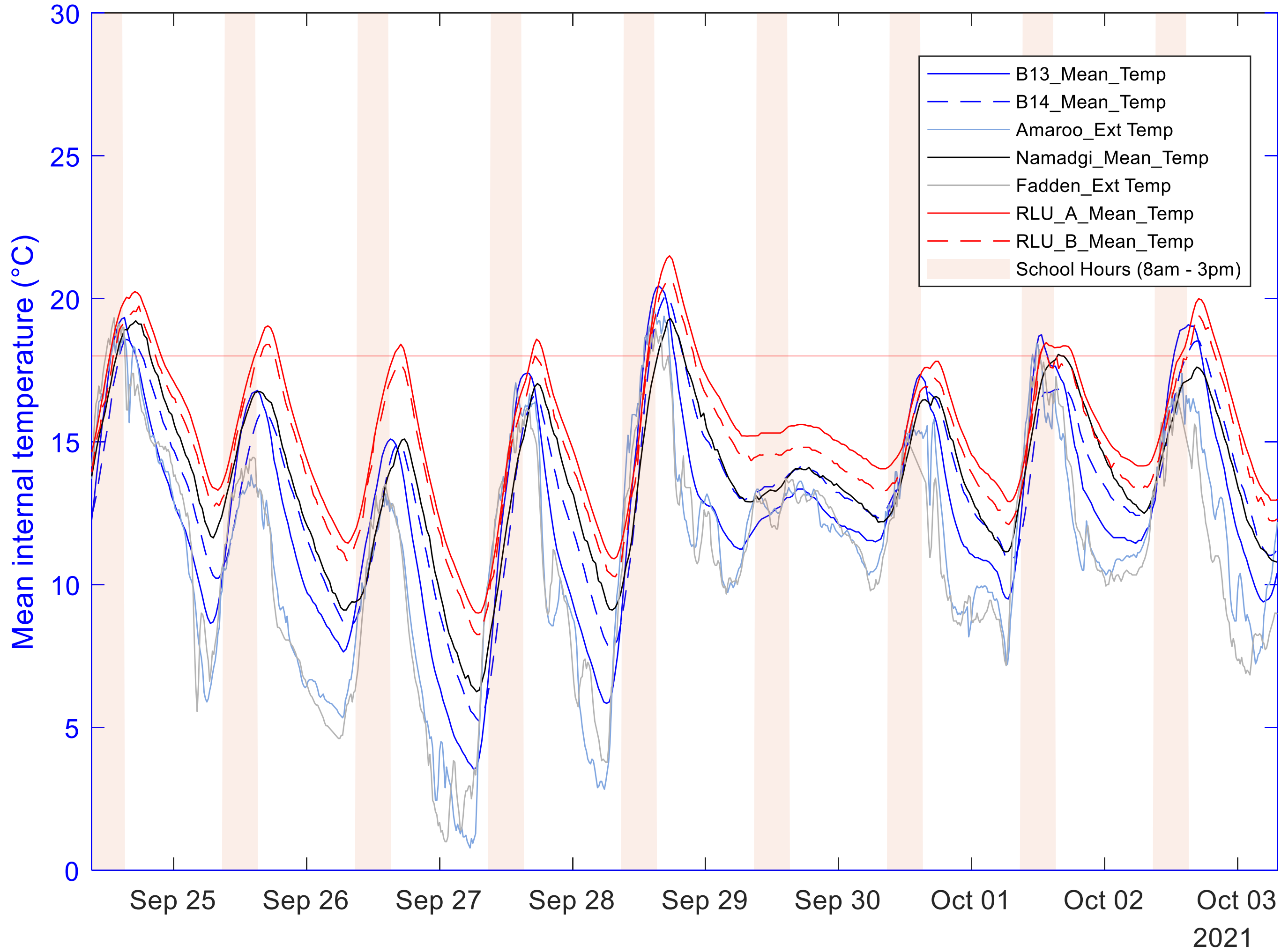

Figure 17. Time series energy and temperature showing free running evaluation period (Sep 24, 9 am – Oct 3 9am). Mean classroom temperatures are shown for each transportable. The red bands indicate school hours (8am – 3pm).

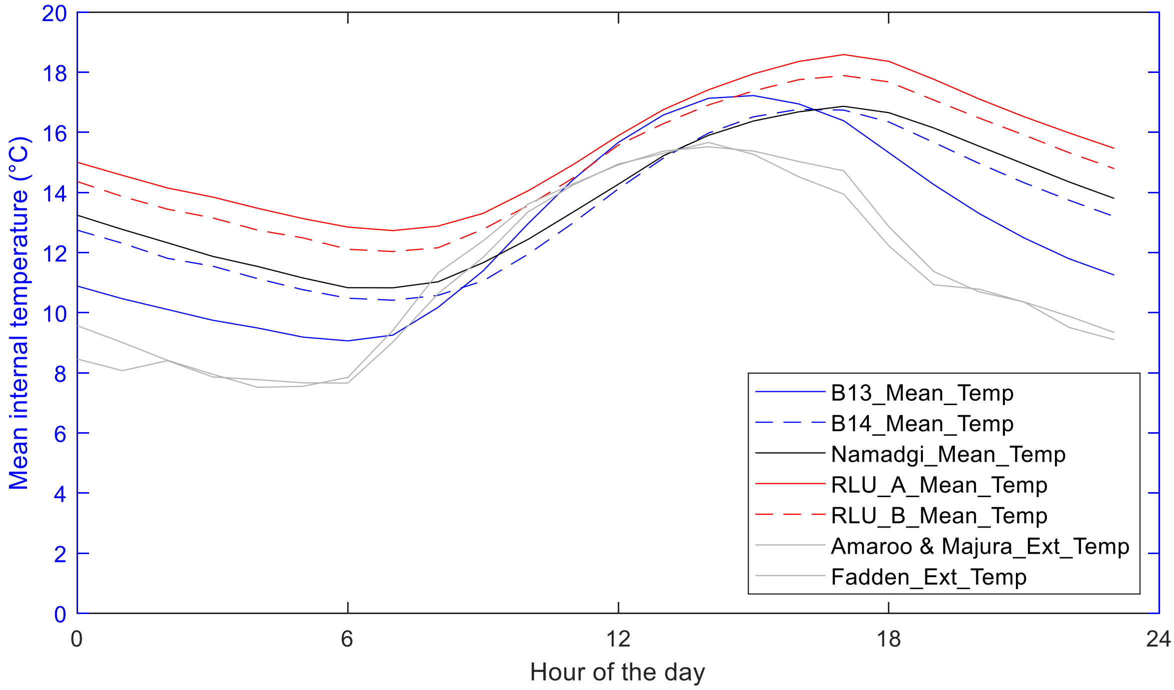

Figure 18. Average daily internal and external temperatures profiles for the free running evaluation period.

A quantitative summary of the transportable performance during the free running test is provided in Table 6. The two Hivve transportables had the warmest mean, minimum and maximum temperature, and the most stable temperatures. The heating degree hours (HDH) below 18 °C were also calculated for the evaluation period, considering both the 24-hour period, and just the school day (8am – 3pm). The Hivve transportables had the lowest HDH considering all periods. Amaroo B13 had the highest HDH considering all periods, although HDH was relatively low considering just the school hours period. This is due to the more pronounced diurnal profile (see Figure 18), including a rapid heating up and early peak temperatures relative to the other classrooms (meaning that more warm hours were during school periods of this transportable).

Table 6. Summary temperature statistics for the free running test

Transportable	Mean temperature (°C)	Mean T_{in} - T_{out} (°C)	Minimum temperature (°C)	Maximum temperature (°C)	Std Dev (°C)	HDH below 18 °C (degree-hours)	HDH during school hours (8 am – 3pm) (degree-hours)
Fadden	13.8	2.6	6.1	19.4	2.7	906	283
Amaroo B13	12.7	1.2	3.5	20.4	3.6	1133	261
Amaroo B14	13.4	2.0	5.2	20.1	3.0	1000	316
Hivve RLU A	15.6	4.1	8.9	21.9	2.5	567	186
Hivve RLU B	14.9	3.6	8.0	20.8	2.5	677	206

Table 7. Diurnal range for outdoor temperature and indoor air temperature for each transportable, calulcated from mean buidling temperature in buildings with multiple classrooms.

	Diurnal range (max daily temp – min daily temp) in °C						
	Amaroo External	Fadden External	Fadden	Amaroo B13	Amaroo B14	Hivve RLUA	Hivve RLUB
Day 1	7.4	7.8	5.0	8.2	5.8	5.8	5.7
Day 2	10.7	11.9	6.0	8.5	6.4	7.0	6.8
Day 3	16.3	15.2	10.8	13.9	11.4	9.6	9.6
Day 4	16.8	15.2	10.2	14.6	12.4	10.6	10.4
Day 5	3.9	4.1	2.6	2.1	2.1	2.3	2.5
Day 6	7.6	6.6	4.5	6.3	4.5	3.8	3.9
Day 7	11.3	11.1	7.0	9.3	6.1	5.6	6.0
Day 8	8.7	9.3	5.0	7.7	6.1	5.9	6.1
Day 9	10.4	12.0	7.5	9.4	6.8	5.5	5.7
Mean	10.4	10.3	6.5	8.9	6.8	6.2	6.3

Clear differences can be seen between Amaroo B13 and Amaroo B14 transportables. Inspection revealed B13 had no sub-floor insulation, while B14, with a later manufacture date, had sub-floor insulation installed. This is expected to explain much of the difference between these buildings. It is likely that some of the performance difference can be attributed to micro-climatic differences between the buildings, which cannot be accounted for in the current evaluation method. Considering the aerial view of B13 and B14 in Section 3.1 (Figure 5), it can be seen that the north façade of B14 is protected by shipping containers slightly offset form the building, and the western façade is protected by an adjacent un-monitored transportable. By contrast, B13 is exposed to ambient conditions on all sides, albeit with shading to the east and west. The north façade is unshaded. These additional solar gains for B13 may help explain the faster warm-up during the day, and the unmonitored transportable next to B14 would be expected to reduce heat loss overnight.

The complexities of local contextual features are common confounding factors of in-situ evaluation of the energy performance of buildings and become important when comparing buildings that have similar performance, however some clear conclusions were drawn from the evaluation of this study.

5.5 Renewable energy systems performance

Although not part of the current evaluation, due to the unrealistic energy usage profiles during the various unoccupied tests, the renewable energy generation of these transportables is of great interest. The energy generation, consumption from grid, consumption from battery and export to grid form the two Hivve transportables are summarised in Table 8. It can be seen that even during the active heating tests, the Hivve transportables were close to net-zero operation over the course of the evaluation. The transportables could meet the much of their energy needs during this energy intensive test from direct solar generation or drawing from the batteries, with 29% (RLUA) and 50% (RLUB) of energy coming from the grid. This was close to being offset by grid exports from RLUA.

Table 8. Summary of the average energy consumption and generation for the two Hivve transportables during the testing period, supplied by Hivve.

	RLU A		**RLU B**	
	Active stable heating	**Free Running**	**Active stable heating**	**Free Running**
Average Energy Consumption (kWh/day)	48.3	6.7	49.8	3.7
Average solar generation (kWh/day)	48.5	46.8	40.3	40.3
Average energy from battery (kWh/day)	22.2	3.7	12	1.9
Average energy from Grid (kWh/day)	14	0.3	24.8	0.1
Average export to grid (kWh/day)	-10.9	-39.3	-13.8	-36.1
Net average consumption from grid (kWh/day)	3.1	-39	11	-36

6 SUMMARY FINDINGS AND CONCLUSIONS

6.1 Overall Technology Assessment

The Hivve transportable buildings used substantially less energy for the steady state heating test on a heated volume basis. During the free-running (unheated) tests the Hivve transportable buildings maintained the warmest and most stable temperatures compared to the other transportables.

6.2 Barriers and Enablers to Adoption

The Hivve iQ smart monitoring and control system includes temperature, humidity and CO_2 sensors for IEQ monitoring and control, as well as energy monitoring. This provides useful flexibility for COVID-related ventilation improvements, monitoring and control.

The PV and battery storage system included in Hivve transportables has been used by a number of schools to enable school enrolment expansion without an otherwise essential upgrade to the local substation and main switch board to increase electricity supply capacity.

A future evaluation is proposed to explore the nexus between the PV and Battery energy system and HVAC control (including improved ventilation) within these transportables.

6.3 Recommendations

This evaluation has found that Hivve transportables use less energy during heating than typical transportable buildings on a floor area and volumetric basis. This was primarily attributed to the improved thermal envelope of the Hivve building that was observed during the free running test. The results of this testing has several implication for both the technology provider and school.

- Of the six non-Hivve air-conditioning units involved in our test, one clear fault was diagnosed, and poor energy performance and an inability to achieve set-point temperatures was identified in another unit (which may be due to an AC fault or poor thermal envelope). The performance issues with these units are unlikely to have been identified during typical maintenance inspections, but were identified through detailed comparative analysis of similar units in similar operating modes. The prevalence of AC split systems in the education sector, and the high proportion of AC split system units presenting with functional and efficiency issues in our small sample, suggests the potential for significant energy wastage. The value of detailed sub-metering and ongoing monitoring of energy performance in identifying and rectifying this energy wastage is clear and should be a point of consideration for schools infrastructure departments. This is an additional benefit of the Hivve transportables, in that they have sub-monitoring integrated in their HivveIQ controls system, which could be used for fault detection.

- Increasing insulation values above the minimum NCC requirement could be a cost-effective upgrade for the Hivve transportables, especially in the ceiling and sub-floor. Additionally, a review of the detail of the window specification may be justified, noting that the insulation benefits of double-glazed window performance may be compromised by thermal bridging through the aluminium-framing. The energy efficiency impact of insulation of transportables is highlighted by the different energy performance between the two Amaroo transportables that appear identical until much closer inspection.

- AC split system performance is continually improving and model selection should be regularly revised to maintain higher performance results. The most –efficient unit based on nameplate COP was not the Hivve unit, but rather the recently installed system at Fadden.
- The current evaluation has considered the energy performance of the thermal envelope and AC units, none of which included capacity for the provision of outdoor air. Effective ventilation is emerging as a critical issue for school classrooms, and further development and evaluation of transportables to include advanced ventilation systems (i.e. Energy Recovery Ventilation) is warranted. Consideration of the integration of this additional ventilation with existing HVAC, solar and battery systems is a promising development for this broader technology package.

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