The Innovation Hub
for Affordable Heating and Cooling

Technology Evaluation Report

Amaroo in-slab gas heating compared to split system air conditioning

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.

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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-19 risk minimisation. Providing these internal conditions through heating, ventilation and air-conditioning requires substantial energy, and has significant environmental implications.

Amaroo School is located in Canberra and was constructed in 2004 according to passive solar design principles including northerly aspect with solar access onto the thermally massive concrete slab. Raked ceilings with automated clerestory windows were provided for natural ventilation. Such construction is typically considered as exemplary for both thermal comfort and energy efficiency.

The current technology evaluation report presents the results of an as-built performance evaluation of the in-slab gas hydronic heating system by sub-measuring the energy used in a classroom on the 2nd storey Amaroo General Learning Area (Building 8), and comparing it with the energy used by a newly installed split system air conditioner in a thermodynamically equivalent classroom on the same floor of the building.

An additional comparison is also included in the study to quantify the energy implications for the existing gas-fuelled hydronic heating systems when windows remain open (e.g. to adhere to COVID-19 guidelines) against the energy used by the same system in a control room with windows closed.

Four classrooms were identified as equivalent by analysing the baseline data with metrics such as Mean Absolute Error (MAE) and Spearman’s coefficient. For the air-conditioner comparison tests two classrooms were used; one with the existing in-slab heating and the other with a split system air-conditioner installed and in-slab heating isolated. The tests were undertaken at the start of heating season (late April/early May) and during both occupied and unoccupied periods (weekends + public holiday). However, heat gains from occupants and equipment were accounted for by using fan heaters during unoccupied periods.

The test that compared the energy use of the hydronic heating system in two classrooms with windows open and close respectively showed that the opening of windows caused a longer operation of the heating system and a 15% increase on energy use on one sample day. Heating did not come ON in the room with closed windows for the remaining days of the test but there was additional energy use during those days for the room with open windows. In this test, the outside conditions were relatively mild, thus the recorded heating energy consumption is likely to be higher during colder winter days. In conclusion, it was verified from these results that the opening of windows to mitigate potential COVID-19 infections as per school guidelines is likely to cause higher energy use in schools and therefore lead to higher energy costs and emissions, especially during colder winter periods.

The comparison between the split AC and the existing hydronic heating system revealed significant differences in terms of energy use and hours of operation between the two systems. It was evident from the measurements that due to their operating hours, school buildings could benefit from lower thermal mass construction to better align the HVAC energy demand with solar PV energy generation. However, even in Amaroo School which is a heavyweight building, the AC split system was able to quickly increase the indoor air temperature and provide thermal comfort much faster while using less amount of energy than the existing gas-fuelled hydronic heating system. While longer side by side comparisons are needed during colder winter conditions, the electric AC split system was using energy at times of solar PV energy generation and required from 4 to 7 times less energy than the hydronic system (75-85% energy savings by replacing a gas system) based on the measurements taken during this evaluation. For both, occupied and unoccupied comparisons, the AC split system operated typically 40-50% less compared to the hydronic system, usually reaching the set point faster, which was then maintained during daytime at relatively acceptable levels due to the passive energy features of the building. However, a longer evaluation of the two systems would also be beneficial under colder conditions.

This test has shown that the transition away from gas-fuelled HVAC systems in schools towards electric systems is important not only because of the obvious greenhouse gas emissions savings and the unlocking of the full potential of renewable energy supply, but also because it provides significant opportunities to reduce energy costs while maintaining indoor thermal comfort.

2 INTRODUCTION

2.1 Background

2.1.1 ACT Government climate change and emissions policy

The education sector living labs were set in ACT where the living lab host (ACT Education Directorate) has shown great interest for the project. The ACT Government has achieved the targeted 100% procurement of renewable electricity in 2020. Their next step is emissions reduction and to this end the ACT Government has implemented a ‘social price of carbon’ at $20 per tonne. This internal costing will be used to fund emissions reduction initiatives including school heating systems that do not create any emissions.

> *“Implementing the social cost of carbon will mean paying $20 per tonne of emissions into a dedicated fund, and investing these funds in activities to reduce emissions, such as upgrading to efficient electric schools” (ACT 2021).*

Counter to this emissions reduction goal is the mounting pressure to provide active cooling for some school classrooms. This increased demand is driven by rising global temperatures and the increasing normalisation of split system air conditioners where natural ventilation and fans were previously acceptable. Air conditioners are typically already provided in ACT schools for staff areas and are specified for transportable classrooms (iHub 2021b). This increasing demand for cooling in schools could be expected to exacerbate grid peak demand events on very hot afternoons.

2.1.2 Thermal comfort impact upon learning outcomes

This increasing demand for active cooling in schools is supported by a growing body of evidence that links thermal comfort to 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.

2.1.3 Classroom thermal performance

The baseline thermal comfort data from this living laboratory, iHub (2021a), contrasts the performance of the heavyweight concrete construction of Amaroo School Building 8 against transportable classrooms of lightweight construction, particularly for winter heating (see Figure 1).

Notice how the indoor temperatures of the lightweight transportable classrooms B13 and B14 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 several hours to heat up before reaching the minimum thermal comfort threshold.

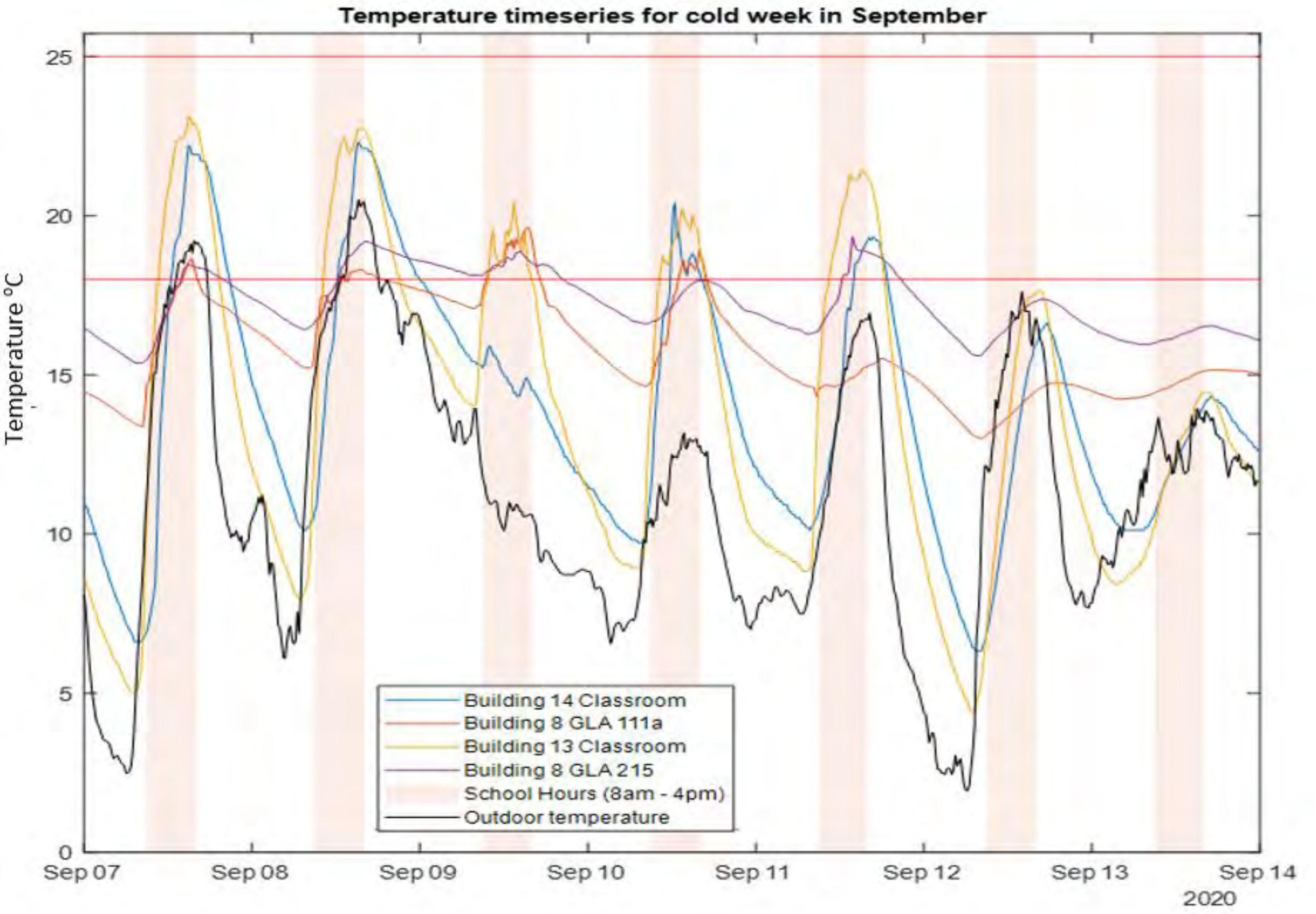

Figure 1 - Amaroo School temperature performance comparing two transportable classrooms (B13 and B14) with the Building 8 heavy weight construction during a period of active heating.

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.

2.1.4 Indoor air quality and ventilation impacts in the school learning environment

Similar to thermal comfort, indoor air quality (IAQ), and specifically ventilation rates, have been shown to impact on productivity in offices, and there is an emerging body of evidence related to student performance in schools. Carbon Dioxide (CO_2) concentration is commonly used as a proxy for ventilation and IAQ; providing adequate fresh air is essential to remove CO_2 and other pollutants in a space (NSW DG55 recommended minimum ventilations rates of 12 l/s/person).

BPIE (2018) also assessed current evidence relating ventilation rates to learning performance. The review concluded: *For every 1 litre per second per person (l/s/p) increase in the ventilation rate up to 15 l/s/p, academic performance increases by 1%.* The review also identified evidence of a relationship between CO_2 and absenteeism, concluding: *Every 100ppm decrease in CO_2 concentration is associated with a 0.5% decrease in illness-related absence from schools.* Similarly to the temperature impacts, the review was unable to assign financial value based on the current evidence, and in general, the above issues will require large scale and thoroughly developed studies to verify the conclusions drawn.

Assessing the impact of alternative upgrades on indoor air quality requires consideration of many factors. The ability of a system to deliver sufficient fresh air is vital, yet increased ventilation also increases heating/cooling energy losses in the exhaust, so the ability to match ventilation to occupancy is likely to be very beneficial.

Recent experiences have highlighted the benefits of flexible ventilation systems. During the COVID period, systems able to deliver large amounts of fresh air are seen as valuable. However, experience during the 2019/20 bushfires period, and the anticipated increase in hazard reduction burns, have highlighted the value of systems that can limit outside air to minimum requirements, and systems with high efficiency filtration, noting the associated increase in fan energy consumption. Considerations when assessing competing upgrades include the ability to supply minimum recommended fresh air (e.g. 10 to 12 l/s/person [ref]), ability to supply additional outdoor air when conditions allow (e.g. up to 15 l/s/person), filtration and smart controls (e.g. CO_2 sensing). An AIRAH guidance document for schools recommends four to six air changes per hour (4 to 6 ACH) (AIRAH 2021) and indicated that this is typically achieved with windows and/or doors opened.

The tests presented in this report were conducted whilst the ACT Government's short-term ventilation strategies for COVID-19 risk management are still in place. The guidelines (ACT Government 2021) include:

- Outdoor learning should be encouraged and assisted where possible (balanced against sun safety and temperature considerations);
- Maximise fresh (external) air and reduce air recirculation (balanced against temperature considerations);
- Use mechanical controls when possible, such as for opening windows and doors;

It should also be noted that routine use of portable HEPA filters and carbon dioxide (CO_2) monitors in ACT schools is not supported at this time.

2.1.5 Moving from gas heating systems towards electric systems: the common case for retrofitting schools with split systems AC

In-slab hydronic heating systems need to be incorporated into the building at the design stage and are not a practical retrofit option. With the explicit ACT Government targets to electrify school heating systems, gas boilers should no longer be replaced with a gas supplied boiler or retrofitted.

Hydronic heat pumps are a logical retrofit for gas boilers, however, this technology was the subject of a separate trial at another Primary School, which was unable to be completed within the timeframe of i-Hub. Direct air to air heat pumps in the form of a split system air-conditioner was chosen for this project as a convenient, well-known comparison to in-slab gas hydronic heating.

Split system AC units are a relatively low capital cost cooling solution for the mass market, and reverse cycle AC units are amongst the most energy efficient space heating technologies. However, split system AC units have no fresh air exchange. They process recirculated air in a dedicated zone. Split systems can create an unsightly and ad hoc retrofit option with substantial maintenance implications and poor BMS integration when compared to integrated and centralised commercial HVAC systems.

2.1.6 A Whole of Life approach to HVAC technology decisions

Immediately prior to the commencement of this living laboratory, a separate project was underway to roll out split system AC units in Amaroo school for Building 8 level 2 classrooms. The baseline data report discussed above confirms the relative summer discomfort for these rooms compared to downstairs rooms. Note that this pressing need for active cooling was identified for a relatively modern school with good thermal envelope, solar passive design, and automated clerestory windows for natural ventilation. Further detail on the facility is provided in Section 3.1.

It is remarkable that this i-Hub living laboratory site played out such a timely scenario of the tensions between the rising pressure to increase summer cooling against the downward pressure on emissions and costs. Quality ceiling fans were provided for the 2nd floor classrooms to alleviate the situation, however, the demand for an active cooling system was sustained even after the ceiling fans were installed. This situation calls for an evidence-based coordinated approach to guiding HVAC provision policy for school classrooms.

The *whole-of-life assessment guide for HVAC technology replacement decisions* (iHub 2021) that was developed as part of the iHUB project provides a practical framework for the selection, replacement and installation of HVAC and related technologies for the education sector. This holistic approach prompts for the best value for money for the whole service life of the system. The list of questions in this whole-of-life guide help decision makers probe for systems that are truly fit for purpose of improving learning outcomes for students, durable and are well integrated with the whole learning environment (building, HVAC, BMS and other services), with a future focus on valuable innovations as well as energy source trends and limitations for the site.

This Whole of Life Guide could be a useful framework for assessing such conflicting requirements for HVAC technology decisions such as this for Amaroo GLA Level 2 classrooms. This living laboratory technology trial evaluation has provided a timely opportunity to evaluate the energy performance of the gas-fired in-slab hydronic heating against an all-electric direct heating of the classroom air by a new split system air-conditioner.

2.2 **Problem statement**

This two-level thermally massive concrete slab and block construction building with open stairwells has issues with very slow warm up on winter mornings. Additionally, the gas-fired boiler servicing the in-slab hydronic heating circuits is not compatible under the ACT Governments electrification of school heating systems.

The Amaroo School building design is well-suited to maintaining stable indoor thermal comfort continuously throughout the heating season. However, baseline testing of the building has suggested that both thermal comfort and heating energy performance may not be optimal for the occupied hours of an Australian classroom environment. The high thermal mass design of this building results in delayed warm up times on winter mornings, so an integrated heating system that is largely decoupled from the slab’s thermal mass by directly heating the air, may improve winter morning thermal comfort of the learning environment whilst also reducing total energy consumption. The study presented in this report investigates the benefits and implications from using a common AC split air conditioning system to replace the gas-fuelled in slab hydronic heating system of the building.

3 Test description

3.1 Technology overview

A Mitsubishi Electric split AC system was installed in one of the classrooms (room 211) for the trial of this study. The selection of the system was based on typical procurement processes of ACT Schools with the i-HUB team not intervening in the selection decision. This ensured that the test was evaluating a typical new installation that represents common AC split systems installed in schools (i.e. there was not a deliberate selection of a top-performing non-conventional AC split system). Details of the split system AC unit and the in-slab hydronic heating system are provided in **Error! Reference source not found.**.

Table 1 - Specifications of the test technology and the comparison technologies.

Technology	**Split AC**	**In-slab heating**
Brand/Model	Mitsubishi Electric / PKA-M100KAL	Rheem / Raypak 1900
Heating capacity	10 kW (rated)	430 kW (serving 40 classroom equiv spaces)
Heating ACOP/efficiency	3.49	0.80 (1926 MJ/h)
BMS integration	Stand alone	Automated in Carrier BMS

The key benefits of a split system air-conditioner compared to the existing in-slab hydronic heating system include:

- Providing convective supply of heating and therefore decoupling of the indoor air temperature from the thermal mass of the slab and walls.
- Thermal comfort improvement due to shorter time to reach set temperature in the morning.
- Potentially lower total energy consumption.

A schematic of the existing in-slab system is also included in Figure 2 for information.

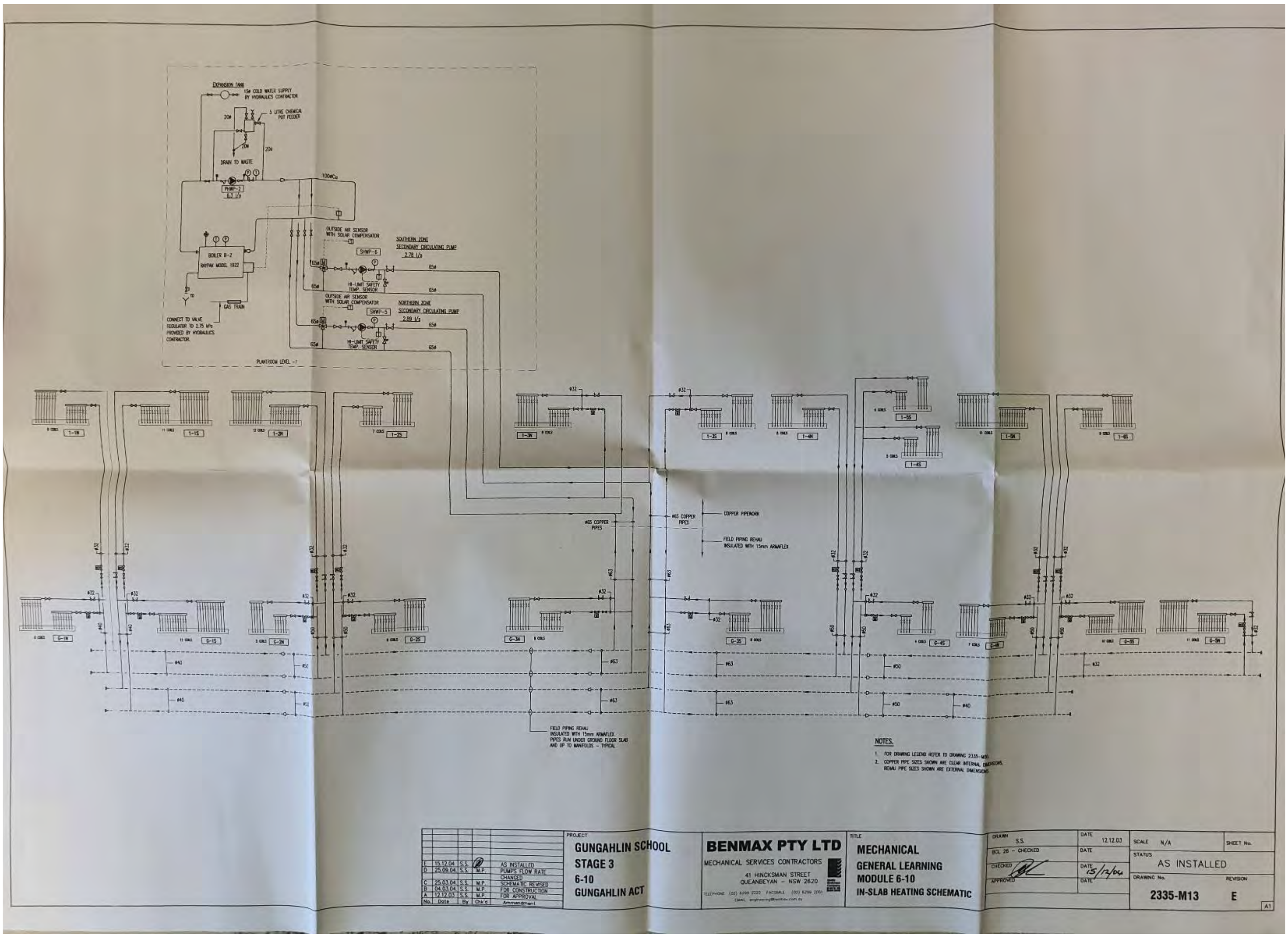

Figure 2 - Schematic of the in-slab heating system circuits

3.2 Aim of study

The main aim of this trial was to evaluate the overall energy implications from the installation of a split system air-conditioner compared to the in-slab hydronic system for classroom heating. Moreover, the existing hydronic system will be evaluated with both windows closed and windows opened to assess the differences under COVID ventilation protocols.

3.3 Site information

This technology trial was undertaken at Amaroo School GLA Building 8, Level 2. This building was designed as the General Learning Area (GLA) for year 6 to year 10 students and is now utilised for a mix of year 3 to year 10.

Figure 3 - Aerial view of GLA Building 8.

The building design is based upon solar passive and natural ventilation principles (see the sectional view in Figure 4). A direct northerly aspect with generous eaves provides good solar access in winter and complete shade of windows in summer. The natural ventilation design uses raked ceilings with automated external windows to introduce outside air and clerestory windows venting into the corridor (see Figure 4). Ceiling fans were provided in classrooms on the upper level as a recent upgrade.

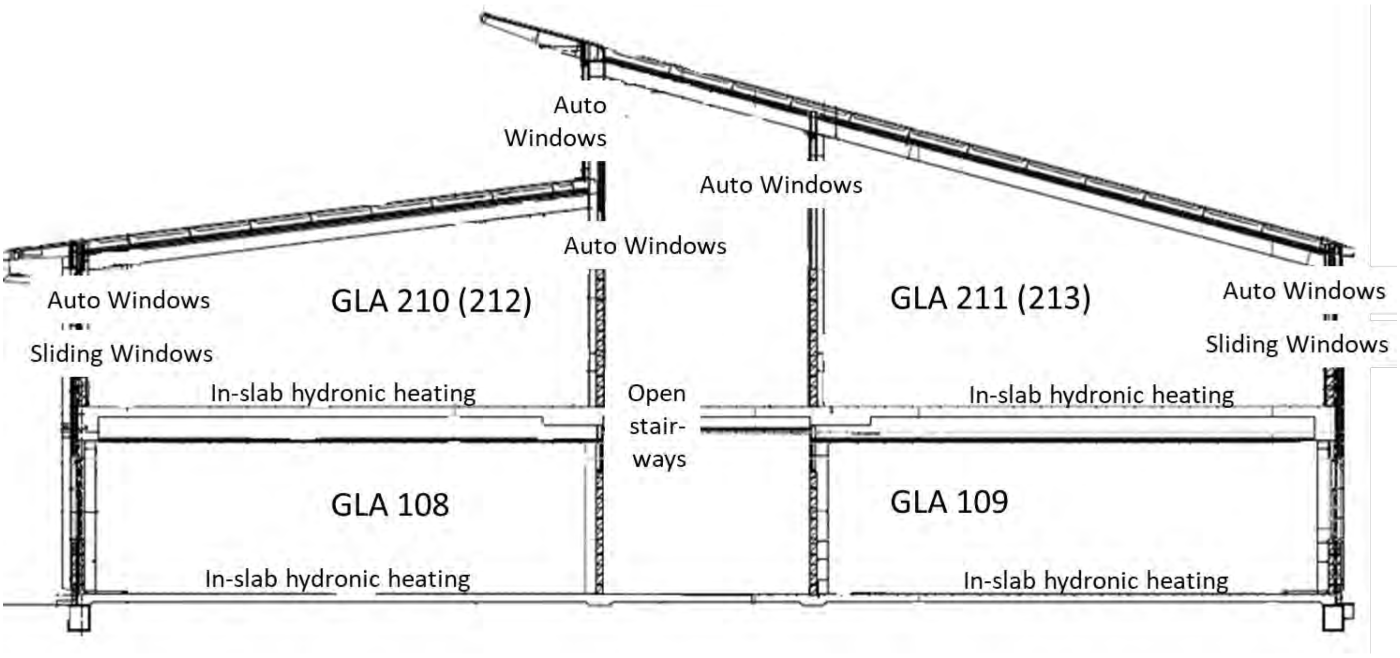

Figure 4 - Section view from the west (north to the left) showing solar passive design elements.

The two-level thermally massive concrete slab construction has walls of concrete block and stud frame. The implications of high thermal mass design with in-slab hydronic heating for schools are discussed in Section 5.1.

4 Methodology

4.1 Test Approach and Description

To compare the gas boiler in-slab hydronic heating against a split system AC, a side-by-side comparison method was used under controlled conditions during unoccupied periods. In this case, internal heat gains from occupants were artificially imposed by fan heaters.

To select classrooms for the comparison tests, the temperature records of rooms 201, 202, 210 and 211 was reviewed (Figure 5), since the ERS-CO2 sensors (temperature, humidity, CO_2) were already installed in these rooms with baseline data available. Rooms 210 and 211 were the most comparable pair of rooms, with mean absolute error (MAE) of 0.7 °C and Spearman’s coefficient of 0.95 for unoccupied hours only, although all four rooms were quite comparable (MAE < 0.8 °C and Spearman’s coefficient > 0.95). It should be reiterated that the baseline data were used for this initial analysis to find equivalent spaces for comparison by filtering out the occupied hours to exclude any impact the occupancy patterns may have on the measured temperatures. All selected four rooms have the same floor area (75 m^2).

The trial focuses on comparing the performance for room 202 (in-slab hydronic heating) against room 211 (split system AC). A preliminary test comparing rooms 201 (windows open) and 210 (windows closed) both with in-slab heating was used to assess the energy and thermal comfort impact of COVID ventilation practices when windows are operated differently. The rooms on the ground level were also monitored to ascertain any heating benefit loss downstairs when the level 2 in-slab heating is isolated.

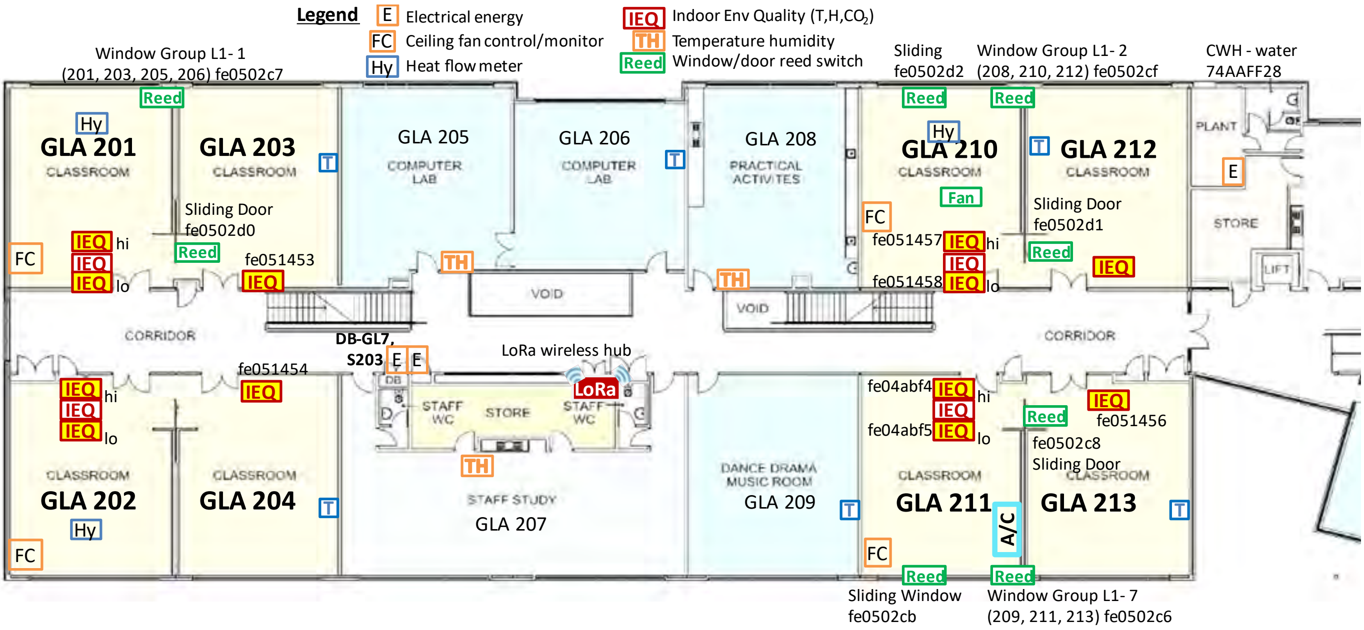

Figure 5 - GLA Building 8 Level 2 west wing ducting and monitoring layout.

4.2 Potential confounding factors

- The **selection of the comparison split system AC unit** for GLA-211 and its associated COP could have a substantial impact on the energy performance comparison results. It should be reiterated here that this AC unit was selected and installed according to standard ACT Government procurement processes without an interference from the i-HUB team specifying the performance.

- **Temperature feedback calibration offsets** and sensor locations for the in-slab heating and split system AC will result in different actual room temperature at the standard monitoring sensor height of 1.1 m. The i-HUB team put significant effort on calibrating the sensors of the study and account for any offsets in the presented results.

- **Temperature stratification** for the high raked ceilings may have a substantial impact upon temperature and energy performance. Temperature sensors were installed for this trial at the following three different heights from floor level to monitor this effect: 0.1m nominal, 1.1 m, close to the highest ceiling level.

- The **classrooms have slightly different cross section and solar gains** (north to south). The south side classrooms (202 and 211) have a higher rake angle of the ceiling and larger volume compared to the north side classrooms (201 and 210) as seen in Figure 4. Solar access into the south rooms is through the external high clerestory windows on either side of the corridor so lower solar gains are expected but this proved to be insignificant while analysing the baseline data and deriving the Mean Absolute Error and Spearman's coefficient between classrooms. To further ensure these differences have no impact on the results of the study, the comparisons of the trial were made between rooms of the same orientation, volume and rake angle of ceiling, i.e. rooms: 202 vs 211, and 201 vs 210.

- The **west end classrooms have exposed external western walls**. Classrooms 201 and 202 have an exposed external wall on the west, which is expected to affect indoor temperatures somewhat in the afternoon. On this occasion too, the errors and trends measured from the baseline data using MAE and Spearman's coefficient showed that these differences should not have a significant impact on the results, especially given that comparisons of this study took place at the start of the heating season with relatively mild outside conditions.

- **Ceiling fan** operation may impact thermal comfort and stratification in winter, so an indication of ceiling fan state, speed and direction was monitored and reported.

- The classrooms are constructed in pairs with an **interconnecting sliding door** (see Figure 6). Energy and temperature results will be mixed if these doors are opened, so the status of these doors was monitored and the results included in this report are from periods when these doors were closed.

- Winter heating performance evaluation needs to **isolate the impact of in-slab heating** for the trial classrooms. Hydronic heating zones typically have four circuits per classroom and the isolation valves have been identified for the trial classrooms.

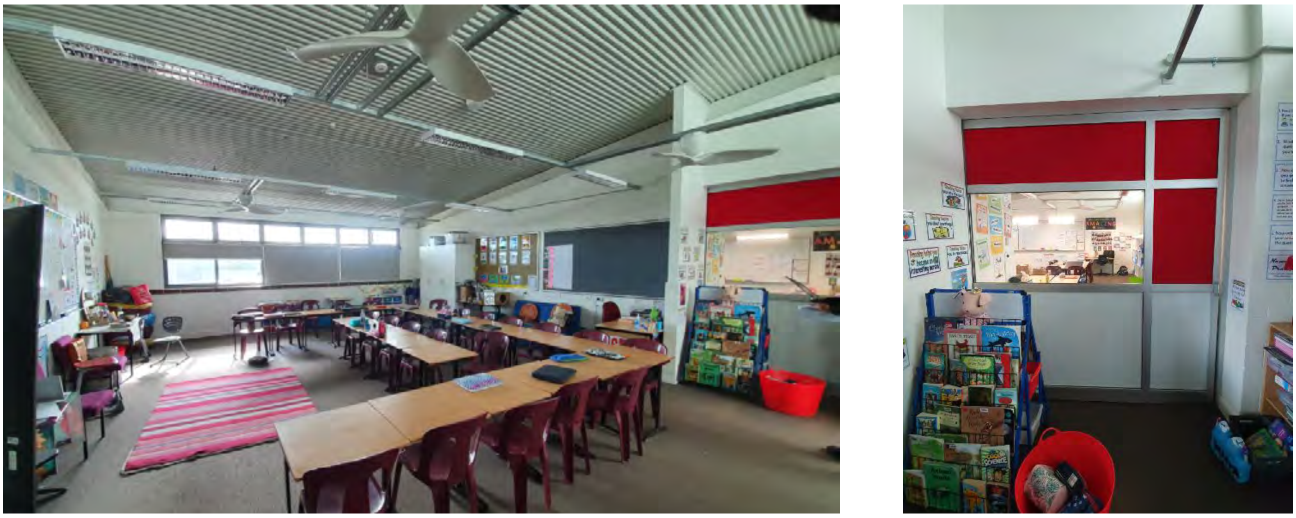

Figure 6 – Typical level 2 north side classroom layout (room 201) with the interconnecting sliding door closed.

The methodology is outlined in the series of tests below.

4.3 **General test set up**

4.3.1 Equipment set points

Heating schedules were fixed for all rooms on weekends to provide energy performance comparison results without occupancy-induced variations. Window control schedules for the test rooms were disabled during the tests after the window positions were set up as required.

- Heating temperature set point: 21.0 °C
- Heating schedule start time: 6:00 am
- Heating schedule end time: 5:00 pm

4.3.2 Including student heat gains for unoccupied tests

The unoccupied tests were designed to provide controlled conditions for side-by-side performance comparisons outside normal school hours (9am – 3pm). Occupancy loads were simulated with the following conditions to account for 25 occupants:

- Sensible heat load from 9am to 3pm:
    - Occupants: 1600 W (heat gains from children are typically lower than adults)
    - Lighting/appliances: 1400 W
    - Total: 3000 W

Electric fan heaters were used to deliver the heat load and sub-metered electrical energy was monitored to confirm constant equal loads per room.

4.4 **Hydronic heating performance test - COVID ventilation impact** *(unoccupied)*

The objective of this test was to provide a side-by-side performance comparison of a COVID ventilation requirement (windows opened) against a control room with windows closed. Rooms 201 and 210 were selected for this test.

Project schedule and other constraints left only a brief period to conduct these cooler weather tests at the start of the heating season. These tests were conducted over a 3-day period in late April of 2022 when temperatures were still relatively mild. To conduct the trial, the hydronic heating system was forced to operate over the weekends following the normal weekday schedule.

Sensible internal heat loads were added in a way that follows normal school hours: 9:00 am to 3:00 pm. Ceiling fans were only switched on during these school hours each day as noted below.

These tests will provide a comparison benchmark for both warmup time and energy performance of the in-slab gas boiler hydronic heating against the split AC system.

Table 2 includes the comparison conditions that were used in this part of the trial. Awning windows were left open for 24 hours during the periods shown in Table 2, and the opening length measured from the base was 110mm (i.e. not fully open).

Table 2: Details of test conducted in rooms 210 and 201 for quantifying the impact of ventilation/windows operation against energy use (Hydronic heating performance test - COVID ventilation impact)

Date	Windows - Room 210	Windows - Room 201	Ceiling fans
16 - 17/04/2022	Closed	Open	Off
18/04/2022	Closed	Open	Reverse (winter); Low speed

The interconnecting sliding doors to the adjacent rooms were closed.

4.5 **Heating performance comparison tests – Hydronic vs. AC split system**

The objective of this test was to provide a side-by-side performance comparison of a split system air-conditioning unit and the existing in-slab hydronic heating. This test was considered as important to inform the transformation from gas heating systems to all-electric systems in ACT schools. The following two types of periods were considered:

- A period when the classrooms were unoccupied to filter out the effect the occupants may have on the operation of the system and the classroom in general (opening doors, classroom schedule etc.). In this case, heat gains from occupants were emulated with fan heaters as described in section 4.3.2. This test was undertaken with windows closed. Ceiling fans were switched off for this test.
- A period when the classrooms were occupied to better discuss the energy of the two systems during the actual operation of the building. However, it should be noted that this comparison may include results that have been affected by differences in the operation of

classrooms. These differences are not expected to be significant, as the two classrooms are of the same size and have the windows open typically at the same time.

Table 3 describes the comparison conditions that were used for this test.

Table 3: Heating performance comparison tests – Hydronic vs. AC split system

Date	Room 211 (AC split)	Room 202 (in-slab)
23/04/2022 - 25/04/2022	Windows closed	Windows closed
02/05/2022 - 06/05/2022 & 09/05/2022 – 13/05/2022	Normal operation (system controlled by the occupants)	6am – 5pm @ 21 °C

4.6 Key performance indicators

Key performance indicators for these tests are in terms of energy use and duration of operation of the heating systems.

4.7 Instrumentation Plan

The instrumentation plan that was used in this evaluation is listed in Table 4.

Table 4: Sensor list and accuracy comparison

Measured parameter	Sensor model and specifications	Location and comments
AC Energy	Wattwatchers A6M IEC62053-21 Class 1 Instrument	Split system AC energy input.
Hydronic heat flow	Pulse output water meter with MicroEdge, plus water temperature sensors in the supply and return	Rooms 201, 202, 210.
Indoor Temperature	±0.2°C (Elsys ERS-CO2)	Three heights for stratification in rooms: 201, 202, 210, 211. Single height in additional rooms.
Door and window opening status	Elsys EMS: Reed switch.	Installed on room divider sliding doors, and windows.
Ceiling fan operation (speed) & control	Wattwatchers A6M+3SW	Monitor all fans at the wall switch (speed indication).
Fan heaters energy & control (internal hat gains)	Wattwatchers A6M+3SW	
Local weather station	Davis Pro (6328AU): Temperature and humidity in a solar-powered, 24-hour fan-aspirated radiation shield; rainfall, anemometer, solar radiation, UV.	Amaroo Preschool roof.

5 TEST RESULTS

5.1 Initial findings from baseline data

The baseline report concluded that thermally massive construction is not ideal for school operating hours, especially when trying to align with solar PV generation. For example, if the hydronic in-slab heating was converted from the gas boiler to an electric heat pump, the bulk of the energy for heating would be required in the early morning to pre-heat the heavyweight building envelope before PV energy is available. This stored thermal energy then substantially dissipates through the unoccupied hours of the late afternoon and night. Thermal mass is better suited for retaining stable temperatures through the night for 24-hour operations or residences with daytime sun-activated slabs. The present operating schedule for the hydronic gas boiler is 6:00 AM to 5:00 PM, Monday to Friday, but our baseline analysis found that on many occasions the existing system is unable to heat up the space to comfortable temperatures by the time the classes start at 9am.

It can also be seen from the earlier reported Figure 1 that the upper-level room (GLA 215) tends to remain warmer compared to the ground level room (GLA 111a) due to warmer air easily rising through open stairwells to the upper level. In winter this makes the downstairs areas more difficult to heat and in summer the upstairs rooms tend to be warmer. Although the downstairs rooms also have hydronic in-ceiling heating from in-floor heating of the upper level classrooms, the ceiling slab is enclosed by a false ceiling so it does not effectively radiate heat below.

5.2 Hydronic heating performance test results - COVID ventilation operation impact

The measurements from the first period of the analysis (16-18 April 2022) are shown in Figure 7. Both rooms reach the set point of 21°C during daytime due to the added internal heat gains from the fan heaters (emulating occupancy) and the season that the study took place. It can be seen that room 201 with the windows open was consistently cooler by 1 to 2.5°C during daytime (blue line in Figure 7), however this experiment requires colder outdoor conditions to obtain more representative data on the energy use of the heating system. The room with the windows open (room 201) had a starting disadvantage with records of cooler indoor air temperatures at the start of the test. However, despite this disadvantage, less energy is used at the start of the measurements for room 201 with the open windows than the room 210 with closed windows (see 16/4 day in Figure 7). This is due to the higher water flow rates supplied to the hydronic circuits of the room 210 with closed windows. On the other hand the temperature differences between the supply and return water temperatures are much higher for the room with open windows (~13-15 °C) compared to those for the room with closed windows (~8-9 °C), indicating that if water flow rates were similar in these rooms, the room with the windows open would consume more energy than the room with closed windows. In terms of duration of operation for the first day of the measurements, the heating system in the room with open windows operated for 5 hours while the system in the room with closed windows was only ON for approximately 2 hours and 45 mins. In total, for the first day of this test (16/4), the heating system used approximately 23.4 kWh to serve the room with open windows and 20 kWh to serve the room with closed windows. The reported values here should be further adjusted to account for the gas boiler’s nominal efficiency, which in this case is 80% according to the input/output figures provided in Rheem’s website for the Raypak B1922 model (https://rheem.com.au/rheem/products/Commercial/Commercial-Gas/Commercial-Raypak%C2%AE/RAYPAK-B1922/p/B1922NCO_ID). Adjusting the above values for 80% efficiency gives 29.3 kWh and 25 kWh for the open and closed window rooms respectively.

In regards to the 2nd and 3rd days of the test, it can be seen in Figure 7 that heating is only ON in the room with open windows, as the indoor air temperature in the room with closed windows does not drop below the set point temperature. In these two days, the heating system uses approximately 18 kWh and 12 kWh (or 22.5 kWh and 15 kWh respectively when adjusted for an 80% efficiency), respectively, noting that the indoor temperatures even in the room with open windows rarely drop below the set point. The reason for these high temperatures can be partly attributed to the 3 kW of heat gains from the fan heaters which are mostly stored in the high thermal mass envelope of this school building, the season of the study (ambient temperatures were relatively mild during daytime), the good insulation levels of the building as well as the size of window openings.

Nevertheless, it is evident that the additional ventilation through opening of windows in order to mitigate the impact of COVID-19 is likely to cause a heavy burden on the energy bills of schools, especially during the cold winter periods of the year.

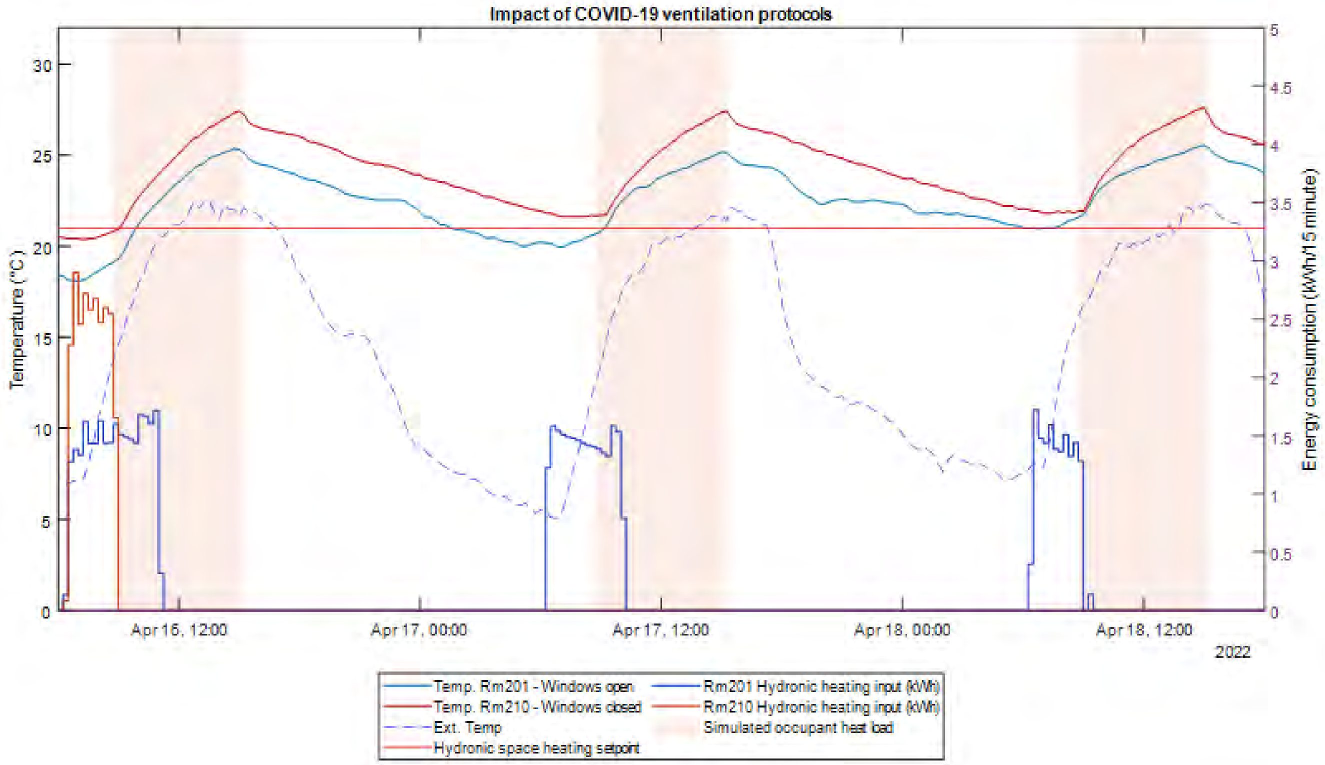

Figure 7 - Energy use and temperature comparison between a classroom with windows open (Room 201) and a classroom with windows closed (Room 210). Shaded areas represent school hours during which internal heat gains where imposed with fan heaters (unoccupied test).

5.3 Results from the unoccupied heating performance comparison tests – Hydronic vs. AC split system

For the period of this unoccupied comparison (23/4 -25/4), the windows were closed in both classrooms. Starting the test from approximately the same indoor air conditions for both rooms, it can be seen from Figure 8 that both systems maintain the temperature above the set point, but the AC split system reaches that required set point temperature much faster than the hydronic system while using a lot less energy. In the first and third days of the test, the AC split system operated for 2 hours and 30 minutes in total and the hydronic system for 6 hours and 15 minutes. It can also be seen from Figure 8 that the AC split system operated also for an additional 1 hour during the second day of the test (24/4) while the hydronic system was not required to operate at that time. This resulted in a total energy use for the 3 days of the test of 7.2 kWh for the AC split system (a minor portion of that was due to standby power) and 41.5 kWh for the hydronic system (when assuming an 80% efficiency as per boiler's specification; 33.2 kWh if the gas boiler is assumed to be 100% efficient).

A clear observation from these results should be highlighted here: the gas hydronic system operates for approximately twice as long as the AC split system and consumes 5 to 6 times more non-renewable energy. A longer evaluation of the two systems would also be beneficial under colder conditions and scenarios of less densely occupied classrooms, i.e. scenarios with lower amounts of heat gains to represent for example a classroom with 15-20 students (currently these tests account for ~25 students in these classes).

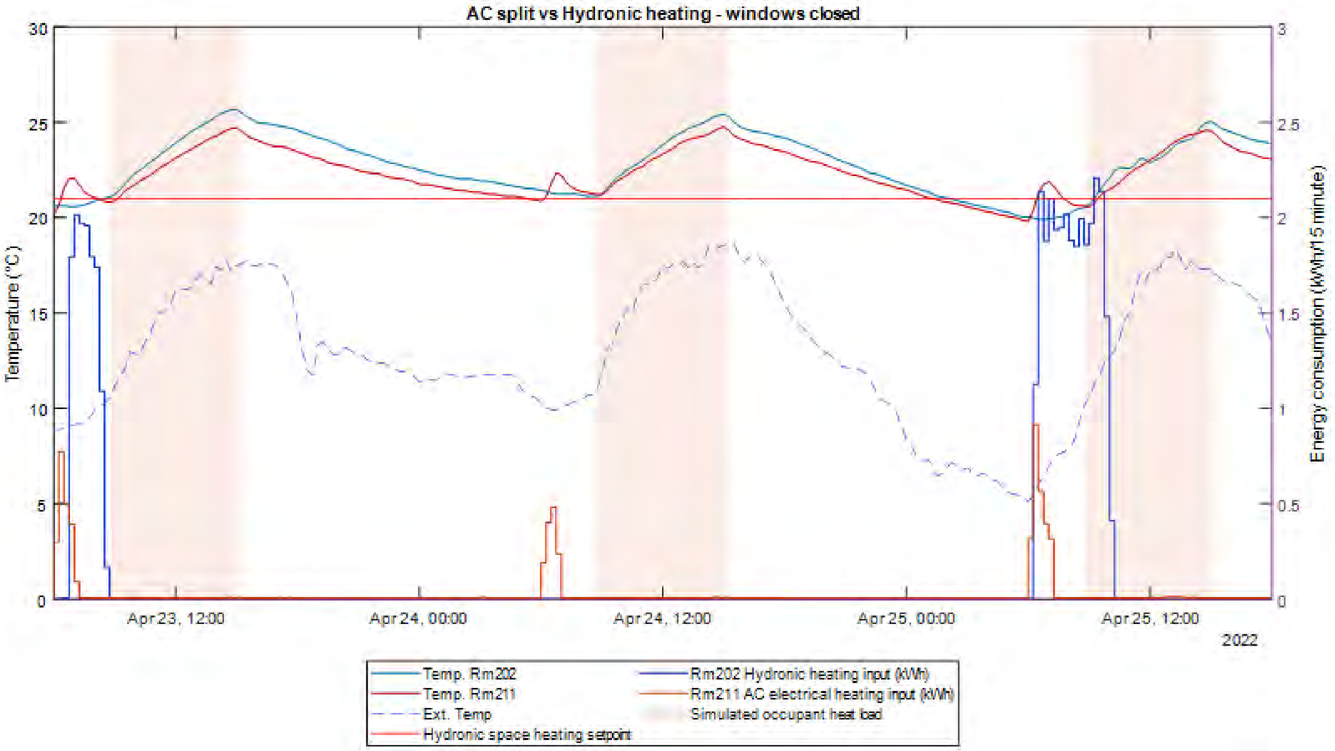

*Figure 8 - Energy use of AC split system in room 211(red line) and of hydronic heating system in room 202 (blue line). Shaded areas represent school hours during which internal heat gains where imposed with fan heaters (**unoccupied** test). Indoor and outdoor air temperatures are also plotted.*

5.4 Results from the occupied heating performance comparison tests (selected periods) – Hydronic vs. AC split system

Further side by side comparisons between the two systems were undertaken during two relatively cold weeks in May and the measured results are shown in Figure 9 and Figure 10. Moreover, the daily and total energy use and hours of operation of each system for the days of the analysis are shown in Table 5. Table 5 also includes the average daily indoor air temperature in each classroom.

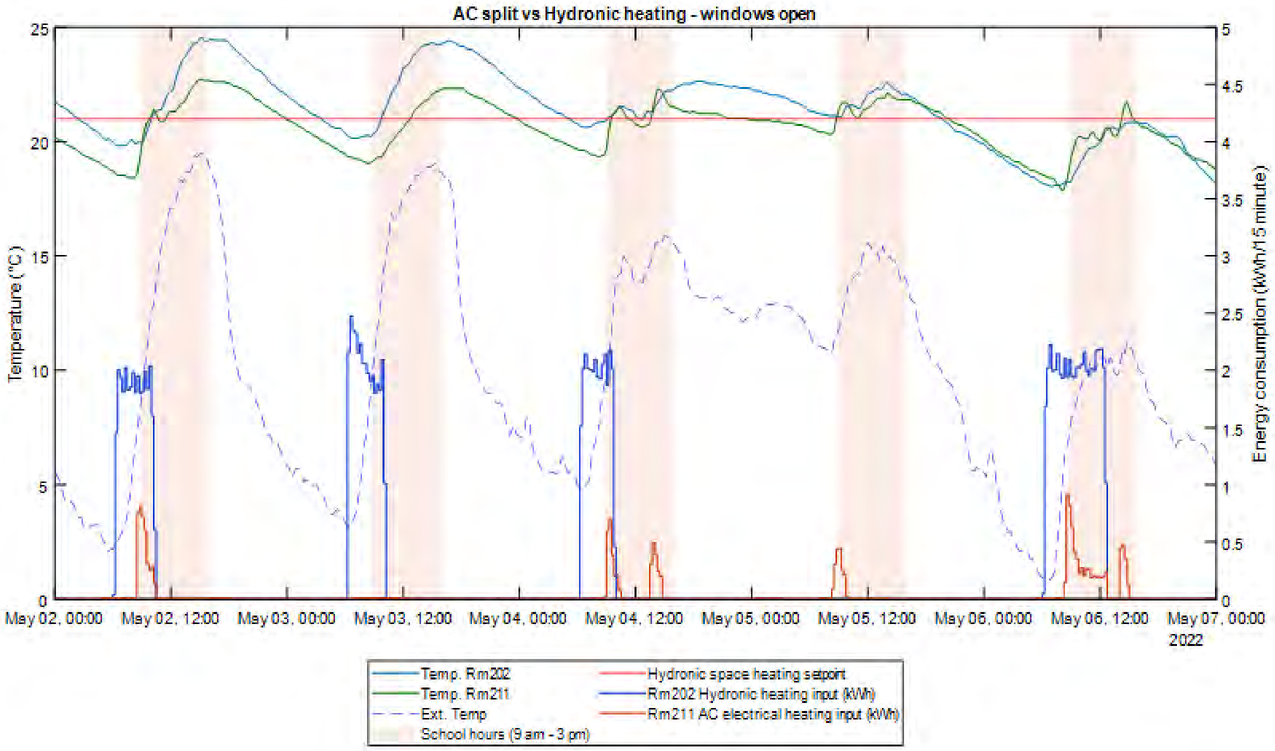

*Figure 9 - Energy use of AC split system in room 211(red line) and of hydronic heating system in room 202 (blue line). Shaded areas represent school hours (**occupied** test on weekdays from 2-6 May). Indoor and outdoor air temperatures are also plotted.*

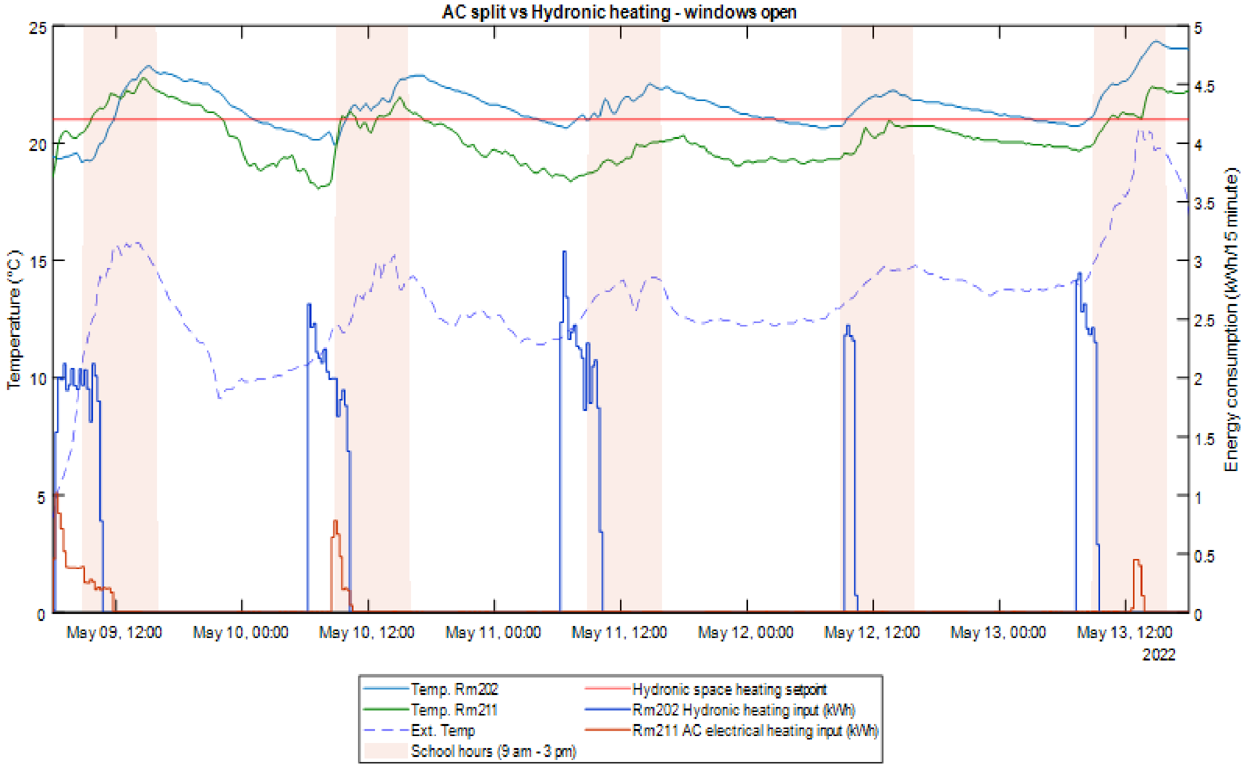

Figure 10 - Energy use of AC split system in room 211(red line) and of hydronic heating system in room 202 (blue line). Shaded areas represent school hours (occupied test on weekdays from 9-13 May). Indoor and outdoor air temperatures are also plotted.

Table 5 - Comparison between AC split system and hydronic heating system during 2 occupied weeks: daily energy use, hours of operation and average indoor air temperature.

Date	**AC Energy use; Duration heating was ON & Average Indoor Air Temperature from 9am-3pm (Room 211)**	**Hydronic heating system energy use; Duration heating was ON & Average Indoor Air Temperature from 9am-3pm (Room 202)**	**Comments**
2-May	4.4 kWh – 2 hrs – 21.4 °C	30.4 kWh – 4½ hrs – 23 °C	
3-May	0.6 kWh – 0 hrs – 20.6 °C	32.3 kWh – 4 hrs – 23.6 °C	AC system not used in the class. Only standby power is reported.
4-May	4.2 kWh – 3¼ hrs – 21.2 °C	28.4 kWh – 3¾ hrs – 21.2 °C	Comparable day. Significant difference in energy use.
5-May	2.2 kWh – 1¾ hrs – 21.6 °C	0 kWh – 0 hrs – 22 °C	AC split system not used – relatively warm indoor conditions. Early start of hydronic system by default leads to energy use.
6-May	7.6 kWh – 5½ hrs – 20.4 °C	51.8 kWh – 6¾ hrs – 20.1 °C	AC system was ON the whole day, except during lunch time. Hydronic system ON 6am until lunch time.
9-May	9 kWh – 5¾ hrs – 21.8 °C	33.7 kWh – 4¾ hrs – 21.9 °C	Both system ON 6am (Monday). Comparable day in terms of operation and indoor conditions.
10-May	3.7 kWh – 1¾ hrs – 21.1 °C	32.8 kWh – 4 hrs – 21.8 °C	Energy use for hydronic system higher due to operation from 6am (slower thermal inertia).
11-May	0.5 kWh - 0 hrs – 19.4 °C	34.6 kWh - 4 hrs – 21.7 °C	AC system not used in the class. Only standby power is reported.
12-May	0.5 kWh - 0 hrs – 20.3 °C	9.6 kWh – 1¼ hrs– 21.9 °C	AC system not used in the class. Only standby power is reported.
13-May	2 kWh - 2¼ hrs –21.2 °C	21 kWh – 2¼ hrs – 23.4 °C	Warm indoor conditions after noon.
Total:	**34.7 kWh – 22¼ hrs**	**274.6 kWh – 35¼ hrs**	

It is clear from these results that even during occupied periods, the occupant-controlled AC split system is used a lot less without this having a noticeable impact on thermal comfort. When both systems were used for lengthy periods (4, 6 and 9 of May in Table 5), the AC split system uses approximately from 4 to 7 times less energy than the gas hydronic system. Over the two weeks of the analysis, the AC split system operated for approximately 40% less hours and consumed ~8 times less energy. It must be emphasised though here that the occupied tests ignore any differences between the classrooms in terms of occupancy and opening of windows/doors.

As it can also be seen from the graphs, the outdoor conditions for the occupied tests are more representative of winter conditions when compared to those during the weekends of the unoccupied tests, thus energy use of both systems appears higher for some days than the energy use during the unoccupied tests.

6 SUMMARY FINDINGS AND CONCLUSIONS

Two types of comparisons were described in this evaluation: i) a comparison of the energy used by the existing gas-fuelled hydronic heating systems when windows remain open (e.g. to adhere to COVID-19 guidelines) against the energy used by the same system in a control room with windows closed; and ii) a comparison of the energy used by an electric AC split heating system in relation to the energy used by the existing hydronic heating system under equivalent unoccupied periods (with heat gains from occupants artificially imposed in the classrooms) and under typical occupied periods in the early winter season.

The baseline data were analysed to determine the rooms that were most suitable (equivalent) for a side by side comparison of the two heating systems.

The following observations can be made from the evaluation results:

- Opening the windows while the hydronic heating system was ON led to using 15% more energy on one sample day. In addition, the heating system operated only in the room with open windows two other days during which the indoor temperature in the room with closed windows never dropped below the set point temperatures. It can be concluded from these results that the additional ventilation through opening of windows in order to comply with COVID-19 guidelines is likely to lead to higher energy use and higher energy bills in schools, especially during the cold winter periods of the year.

- With regard to the comparison between split AC and the existing hydronic heating system the results illustrate significant differences in energy use and hours of operation between the two systems. It was evident from the measurements that school buildings could benefit from lower thermal mass construction to better align the HVAC energy demand during school operating hours with solar PV energy generation. Nevertheless, in this heavyweight building (Amaroo school), the AC split system was able to quickly increase the indoor air temperature and provide thermal comfort much faster while using less energy than the existing gas-fuelled hydronic heating system. While longer side by side comparisons are needed during colder winter conditions, the electric AC split system was using energy at times of solar PV energy generation and required from 4 to 7 times less energy (75-85% energy savings) based on the measurements taken during this evaluation. A longer evaluation of the two systems would also be beneficial under colder conditions and scenarios of less densely occupied classrooms, i.e. scenarios with lower amounts of heat gains to represent for example a classroom with 15-20 students.

This test evaluated the feasibility and the benefits from using an electric Air Conditioning system as opposed to the existing gas hydronic system. The analysis highlights that, apart from the obvious greenhouse gas emission reductions, an electric AC split system that can be potentially powered by renewable energy consumes significantly less energy and maintains thermal comfort in the classroom of the trial. On the other hand, neither of the heating systems of this trial provides fresh air in these typically densely occupied classrooms. Comparisons with alternative systems that provide also fresh air would be highly beneficial and the i-HUB living labs have the existing infrastructure for commissioning such comparisons.

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