The Innovation Hub

for Affordable Heating and Cooling

Report

Technical Report: ACT Education Living Laboratory Monitoring and Baseline Data Analysis

21 May 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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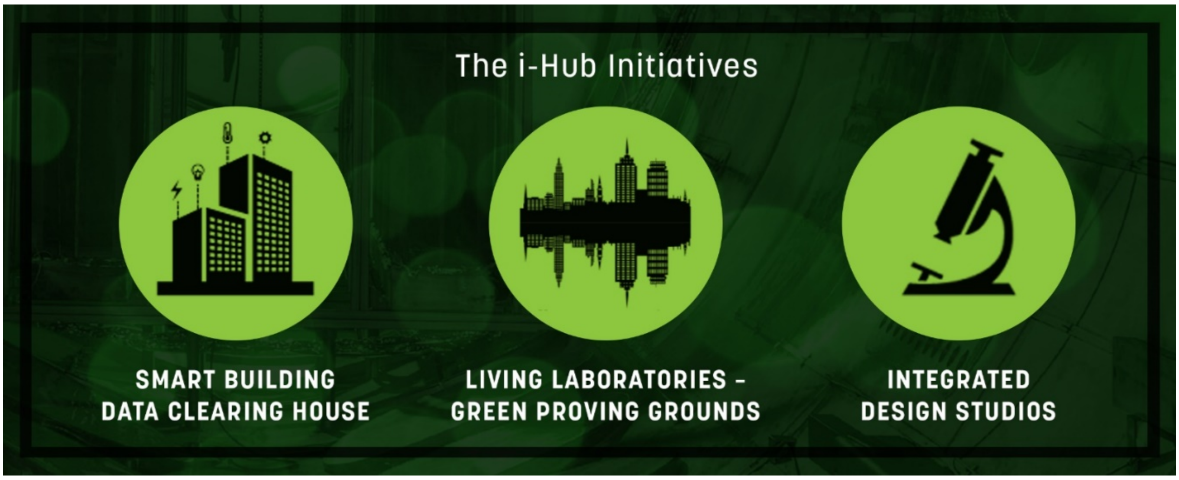

[Technical Report: ACT Education Living Laboratory Monitoring and Initial Baseline Data Analysis]

This Technical Report: ACT Education Living Laboratory Monitoring and Initial Baseline Data Analysis details the as-installed monitoring and evaluation capabilities implemented in the ACT Education living laboratory facilities to meet the requirements of the i-Hub Education Renewable Energy and Enabling Technology and Services Evaluation Framework, as well as an initial baseline data analysis, to demonstrate available data sources and analysis techniques.

Lead organisation

University of Wollongong (UOW)

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1.0	23/10/2020	Released for comment by AIRAH and ARENA	D Daly	C McDowell
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Please note, this a living document that will be iteratively updated during the establishment and operation of the foundation living laboratories. The above table only tracks major published updates. Please download the latest version from Note: Insert Public Link After Major Feedback from AIRAH and ARENA Implemented.

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1 Introduction

1.1 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.

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1.2 ACT Education Living Laboratories

A 'Living laboratory' is a user-centred open-innovation, ecosystem within collaborative partnerships. Living Laboratories benefit both technology providers and technology users, addressing barriers to the uptake of innovation, such as lack of familiarity, risk aversion and distrust in supplier claims. The i-Hub Living Laboratories are flexible spaces where product suppliers can bring their technology for validation. Many technologies can be tested over time.

The i-Hub ACT Education living laboratory establishes research-quality measurement and verification systems within existing school buildings in order to observe and evaluate technology upgrades within the context of the daily life of these school ecosystems. The technology upgrades trialled in this living laboratory will be selected from promising electric heating and cooling strategies that increase the energy flexibility of ACT Education facilities, and deliver increased value for renewable energy, at the site and grid level.

The ACT Education living laboratories are:

- **Amaroo**: Opened in 2004 with a gross floor area of 16,832 m^2 and over 1,800 students. Renewable generation includes a 600kW array of solar panels and a wind turbine. Heating includes in-slab hydronic heating supplied by gas boiler, ducted gas heating, and split system reverse cycle air conditioning units. The main building is fitted with actuator operated windows and integrated building management system (BMS).
- **Fadden**: Opened in 1984 with a gross floor area of 3,283 m^2 and over 250 students currently enrolled. Renewable generation consists of a 10kW array of solar panels. Heating is supplied by the original central gas boiler hydronically distributed to air handling units (AHU's) in each building/block. This system has had minimal capital expenditure and poses a high operational security risk to the school. There was no provision for mechanical cooling in the original construction, but the last decade has seen the progressive rollout of

evaporative coolers in learning areas, and split system reverse cycle air conditioning units in staff rooms and special learning areas.

The i-Hub living laboratories activity stream has the objective to quantify (i.e. analyse measurable data) and qualify (i.e. develop insights into reasons, motivations and opinions) the potential for innovative technologies and the integration of technologies in educational settings to add value to renewable energy, enabling schools to transition to a net-zero energy/demand future while simultaneously contributing to occupant wellbeing, comfort and health. A nominal target of a 25% increase in the value of renewable energy for education, relative to business-as-usual (BAU), was hypothesised.

HVAC is the electricity end-use application with by far the greatest potential for increasing the value of renewables in this way. HVAC&R accounts for approximately 22% of all electricity consumed in Australia and around 50% of peak electricity demand. HVAC is already reasonably well correlated with solar generation in large commercial and institutional buildings, thus creating the opportunity that relatively minor adjustments of HVAC load timing can significantly increase the value of on-site generation by:

1. Deferring HVAC load during short-term solar generation variabilities, thereby enhancing the peak demand benefits of the on-site renewable generation.
2. Utilising HVAC as a ‘productive source of demand’ during periods of local or grid level solar generation excess (and subsequently reducing demand and electricity import at other periods).
3. Enabling the combination of HVAC control and on-site renewable generation to provide the potential to respond to mechanisms that enhance grid stability and robustness, currently characterised by mechanisms such as the Reliability and Emergency Reserve Trader (RERT) and Frequency Control Ancillary Services (FCAS).

In all cases, these need to be achieved without causing loss of comfort for occupants, and have to be based on efficient use of energy at the site level. These objectives may be achieved, for example, via a combination of load management, efficiency, renewable generation and short term and long-term storage.

1.3 **About this report**

This report provides a baseline analysis of the ACT Education living laboratories. The purpose is to evaluate the data collected to this point against the KPIs defined in the Renewable Energy and Enabling Technology and Services Evaluation Framework (REETSEF).

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

2 Venue 1 — Amaroo School

2.1 Monitoring details

The schematics and lists, as presented in the figures in this section comprise the primary documentation for the real time monitoring system, with explanatory notes included below.

2.1.1 Site energy utility metering

Smart electricity meters monitor consumption in 15-minute intervals with data remotely accessed from the ACT Government Enterprise Sustainability dashboard, managed by Envizi. The locations of the energy utility meters for the site are indicated in Figure 2-4 with a single line diagram provided in Figure 2-1.

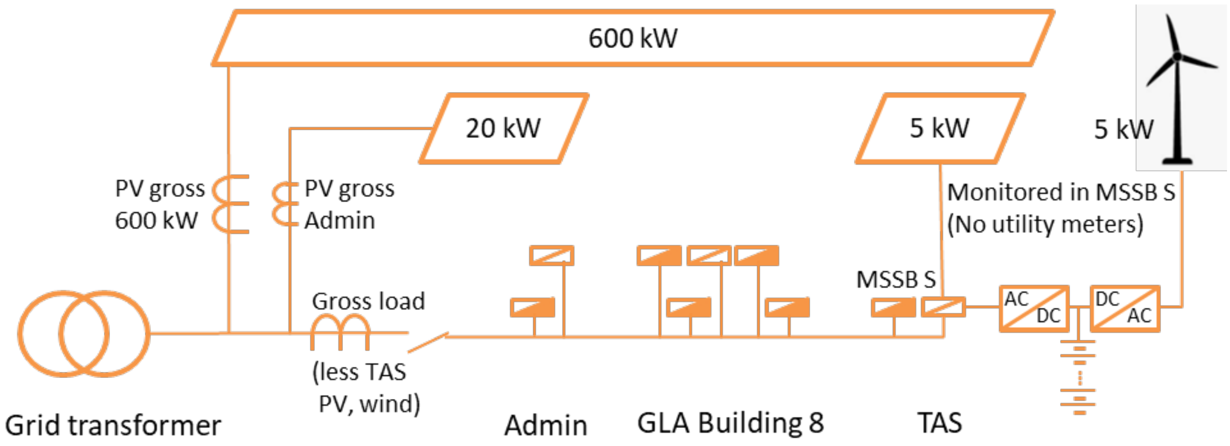


Figure 2-1. Electricity metering single line diagram

Metering of the site renewable generation is as follows. The 600kWp rooftop PV array at the school is owned by a joint venture and is gross metered. The PV system on the administration building (20kWp array) is gross metered at the site main switchboard. The PV system (5kWp small array) and wind turbine connected into the TAS building distribution board are not metered at the utility level. Thus, their energy generation directly offsets the main site load “gross” meter. Electricity generation from these two TAS building renewable energy systems have been separately monitored as part of this project.

The preschool part of the school has independent metering for both electricity and gas. There is currently no renewable generation on the preschool circuits.

The utility gas meters are fitted with pulse outputs. Obsolete 2G transmitters were removed and replaced with project specific Nube iO MicroEdge data loggers, using the existing intrinsically safe cabling. This provides 15-minute interval gas consumption data.

2.1.2 Measurement Boundaries and monitoring device layouts

The Amaroo School site is too large to be managed in a single living laboratory for this project, so two distinct areas have been selected as focus areas for the living laboratory, as outlined in Figure

2-4. Each area was selected for the unique offering it brings to the overall i-Hub living laboratories project:

2.1.2.1 General Learning Area (GLA - Building 8)

- The site's renewable generation network consists of a 600 kWp PV rooftop array, a wind turbine and two smaller independent rooftop PV arrays.
- Passive heating with north facing solar activated slab and in-slab hydronic active heating.
- Passive cooling with ongoing issues, recent fan and AC installation as correction measures.
- Incorporates some split system AC with active plans to improve summer comfort. This living laboratory provides an opportunity for data-driven innovative and appropriate solutions to be trialled.

2.1.2.2 Preschool

- Ducted gas furnace.
- Two identical transportable classrooms for side-by-side testing of room-scale technologies. Transportable classrooms are commonly utilised throughout Australian schools and are typically poorly insulated and fitted with standalone AC as the primary source of HVAC.

The measurement boundary for this site may be further sub-divided, to facilitate a range of potential technology upgrade evaluations, and may be usefully considered as five levels of monitoring, as below.

2.1.2.3 Site monitoring

Site monitoring is an essential requirement in order to evaluate the impact of HVAC technology upgrades upon the renewable generation at the site level. Site metering and monitoring layout is provided in *Figure 2-4*. Energy consumption (electricity and gas) and generation are measured at the utility meters, as detailed above, and external weather conditions are measured on site.

2.1.2.4 Building monitoring

The measurement boundaries for the Amaroo venue of this living laboratory are a selection of independent buildings, which represent clear HVAC zone boundaries. Building monitoring layouts are provided in Figure 2-5 through Figure 2-9.

2.1.2.5 HVAC appliance monitoring

Separately monitoring the energy input to each HVAC appliance is essential in order to evaluate the impact of an upgrade on any single HVAC unit, and in order to aggregate the total HVAC energy load for the site.

Heating gas consumption is monitored at the GLA plant room boiler and, for the preschool, at the gas utility meter, with no other downstream gas appliances.

All electrical HVAC loads are individually monitored wherever it is practical to do so, including water pumps, AHU fans, supplementary AC units, wall mounted electric heaters and exhaust ventilation fans. These individual loads may then be aggregated to a room-level, building-level or site-level as required.

2.1.2.6 Room monitoring

Indoor temperature is monitored for most conditioned spaces for this living laboratory. This is to ensure that indoor temperature service quality remains comparable between the technology evaluation and baseline period, and that any differences in service quality may be compensated for in the model.

IEQ sensors are located at a height of nominally 1.1m above floor level in a location that does not receive direct sunlight at any time of the day in any season, not immediately adjacent to any glazing or heating/cooling outlets, and not on an external wall.

Similar to the building-level monitoring, some HVAC systems service individual rooms; for example: supplementary AC units and wall-mounted heaters. Where these are the only HVAC service for a room (that is, there is no hydronic heating service), then HVAC upgrades may be evaluated at a room-level.

BMS system data is available from the Carrier BMS system for the GLA building.

2.1.2.7 Case study opportunities

The GLA building provides several opportunities for a closer comparison of technologies where pairs of rooms may be closely compared north to south, Level 1 to Level 2, and adjacent similar rooms.

The matched pair of preschool transportable buildings also provide a useful opportunity for technologies that may have potential to rollout across school transportable buildings.

2.1.3 Monitoring equipment details

The monitoring system design provides for remote automated access for regular (typically daily) downloads of data from each data cloud source for the purposes of fault checking, data continuity and progressive data analysis.

An indicative sensor network diagram with physical device photos is presented Figure 2-3. Table 2.1 provides more specific technical details for each device with reference back to the monitoring equipment layout legend symbols.

Further details of each type of monitoring device are included below.

2.1.3.1 Electricity consumption

Wattwatchers Auditor-6M metering-grade electrical energy monitoring devices were installed to measure real power, power factor, and cumulative energy consumption logged at 5-minute intervals. Each device has six channels, which may be configured variously to monitor:

- phase gross consumption + 3 phase gross PV generation

- phase load + 3 off single phase loads in a switchboard
- off single phase loads

These Auditor 6M devices have 3G SIM cards installed with a monthly subscription fee for this service per device.

2.1.3.2 Gas consumption

Site gas consumption is measured from the ACTEWAGL pulse output meters at both the main school site and the preschool. Nube iO MicroEdge pulse input loggers connect to the LoRa network.

Gas consumption at the GLA plant room boiler is monitored using an EDMI U8 gas consumption meter with a pulse output being read into a Nube iO MicroEdge logger on the LoRa network.

2.1.3.3 LoRa IEQ sensor

A combination of Nube iO Droplet DL-TH (temperature and humidity) and Elsys ERS CO_2 (temperature, humidity, CO_2, occupancy and light level) sensors are installed in most conditioned spaces within the living laboratory. These sensors communicate over the LoRa wireless IoT network designed for very low power, long battery life with reasonably long range wireless transmission.

The Nube iO sensors employ a private LoRaRAW embedded in the proprietary LoRa controller gateway. The Elsys sensors use the public LoRaWAN network and protocol and communicate to the LoRaRAW gateway via a LoRaWAN adapter.

Elsys EMS sensors (magnetic reed switch, temperature, relative humidity and 3-axis accelerometer) are installed on the classroom doors of each of the preschool transportables to monitor natural ventilation conditions. The reed switch is employed to monitor window open/closed status and window opening counts during each sample period. The EMS sensors are mounted directly on the fixed frame with the magnet mounted onto the moving door or window. As such, the temperature and humidity readings of these sensors will be affected by outside air when the door is opened and by solar radiant heat and external wall heat flux while the door is closed.

Each installed temperature and humidity sensor was calibrated in the laboratory against a certified temperature and humidity sensor.

2.1.3.4 BMS data

A Carrier brand central BMS serves the whole original school site with comprehensive monitoring and control implemented. Data available from this system includes the boiler gas flow and controls, hydronic hot water pumps control status, automated window control status, and room temperature set points and feedback in a sample of rooms serviced by the central heating system. The calibrated LoRa IEQ Droplet and ERS CO_2 sensors may provide an indicative calibration offset for these uncalibrated sensors.

2.1.3.5 Weather station

A Davis Instruments wireless integrated sensor suite plus with fan-aspirated radiation shield (model number 6328AU) weather station and data logger are installed on site (see Figure 2-4 for locations) to collect localised weather data for the living laboratory. The features include a rain collector, temperature and humidity sensors, anemometer, solar radiation sensor, UV sensor, sensor mounting shelf, and solar panel. For improved accuracy, temperature and humidity sensors are housed inside a solar-powered, 24-hour fan-aspirated radiation shield. The shield protects against solar radiation and other sources of radiated and reflected heat.

Figure 2-2. Davis Pro weather station.

2.1.4 Static data collection

The list of static data parameters required to determine the KPIs are listed in Table 2.3. This static data record is collected during the initial site audit with some fields updated periodically during site visits as appropriate.

2.1.5 Monitoring equipment layouts and lists

The following pages constitute the package of schematics and tabled lists of monitoring systems, including:

- Monitoring system network diagram (Figure 2-3)
- Monitoring device specifications and legend (Table 2.1)
- Device location plans (see Figure 2-4 to Figure 2-9)
- Monitoring parameter list (Table 2.2)
- Static data collection list (Table 2.3)

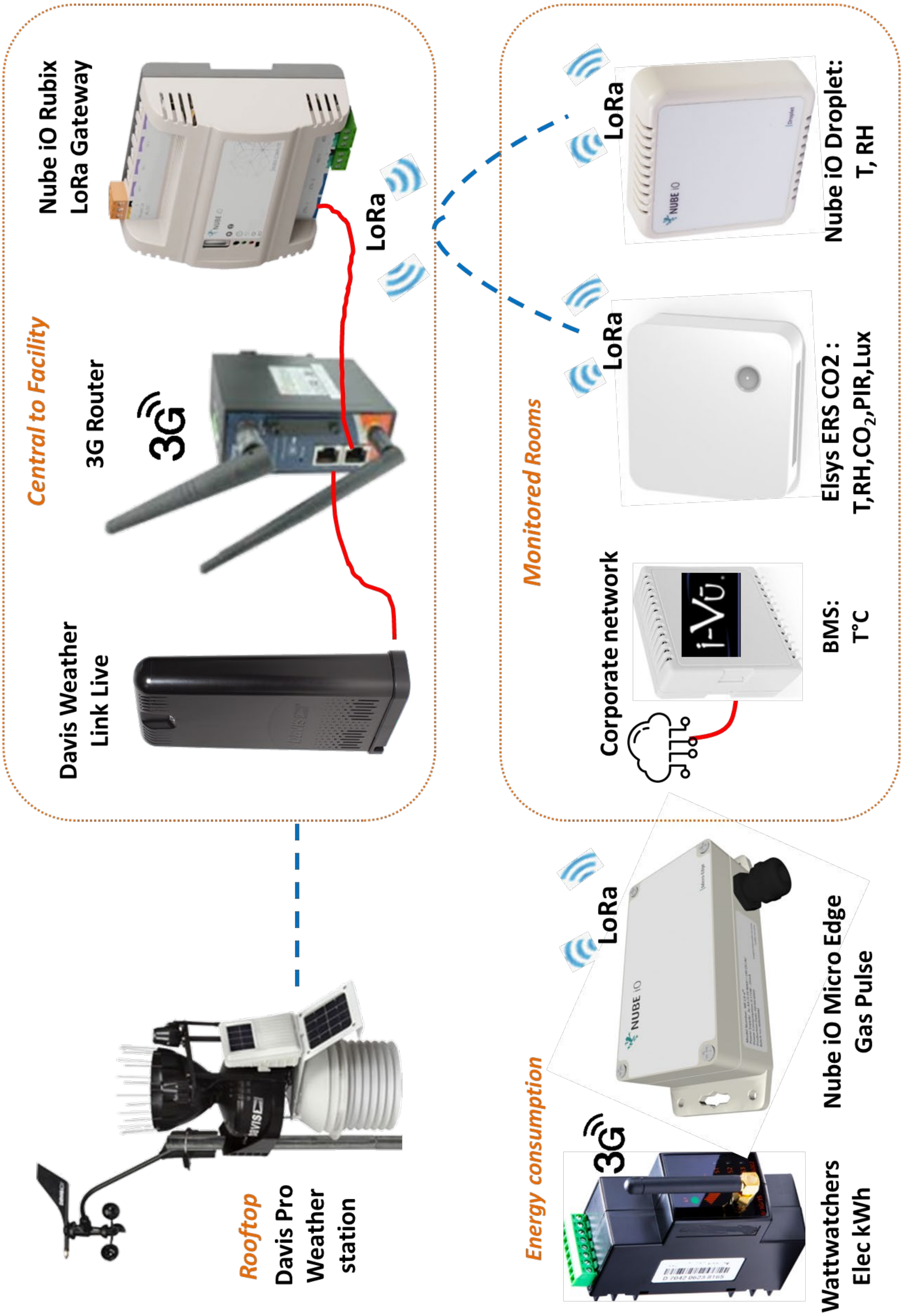


Figure 2-3. Monitoring system network diagram – Fadden and Amaroo.

Table 2-1. Monitoring device specifications and legend – Fadden and Amaroo.

Symbol	Device	Brand/Model	Photo	Parameters measured	Comms	Wireless range	Connection limits	Sample period	Battery life or power	Comments, accessories required
E	Electricity consumption	Wattwatchers / Auditor 6M		$E_{elec\ gross}$ (kWh - also V, A, kVA, PF, and more)	3G - Wattwatchers cloud - API	3G network coverage	Unlimited devices	5 min	Hard wired	External antenna available
G	Gas consumption	Nube IO / MicroEdge		E gas site	LoRa private network - API	70 x 70 m x 3 storey		15 min	5+ year battery	Rubix LoRa Gateway; Gas meter with pulse output
Hy	Hydronic sub-sys energy	Nube IO / MicroEdge		$Q_{hyd\ A}$ $T_{hyd\ sup\ A}$ $T_{hyd\ ret\ A}$	LoRa private network - API	70 x 70 m x 3 storey		15 min	5+ year battery	Rubix LoRa Gateway; water meter with pulse output
TH	IEQ basic	Nube IO/ Droplet DL-TH		$T_{A,B}$ $RH_{A,B}$	LoRa private network - API	70 x 70 m x 3 storey		15 min	5+ year battery	Rubix LoRa Gateway
IEQ	IEQ detailed	Elsys / ERS CO2		$T_{A,B}$ $RH_{A,B}$ $CO_{2\ A,B}$, Motion, Light	LoRaWAN network - API	70 x 70 m x 3 storey		15 min	5+ year battery	Rubix LoRa Gateway with LoRaWAN chipset
RATH	Window opening	Elsys / EMS		Open/closed Count $T_{A,B}$ $RH_{A,B}$ $Accel_{x,y,z}$	LoRaWAN network - API	70 x 70 m x 3 storey		15 min	5+ year battery	Rubix LoRa Gateway with LoRaWAN chipset
T	Temperature - existing BMS			$T_{A,B}$		Hard-wired				
	Weather station	Davis Vantage Pro 2Plus (6328AU)		T_{out} RH_{out} GHI V_{wind} Dir_{wind} Rain		350 m		15 min		
LoRa	Comms accessories	Nube iO Rubix: LoRa Gateway					100 devices			

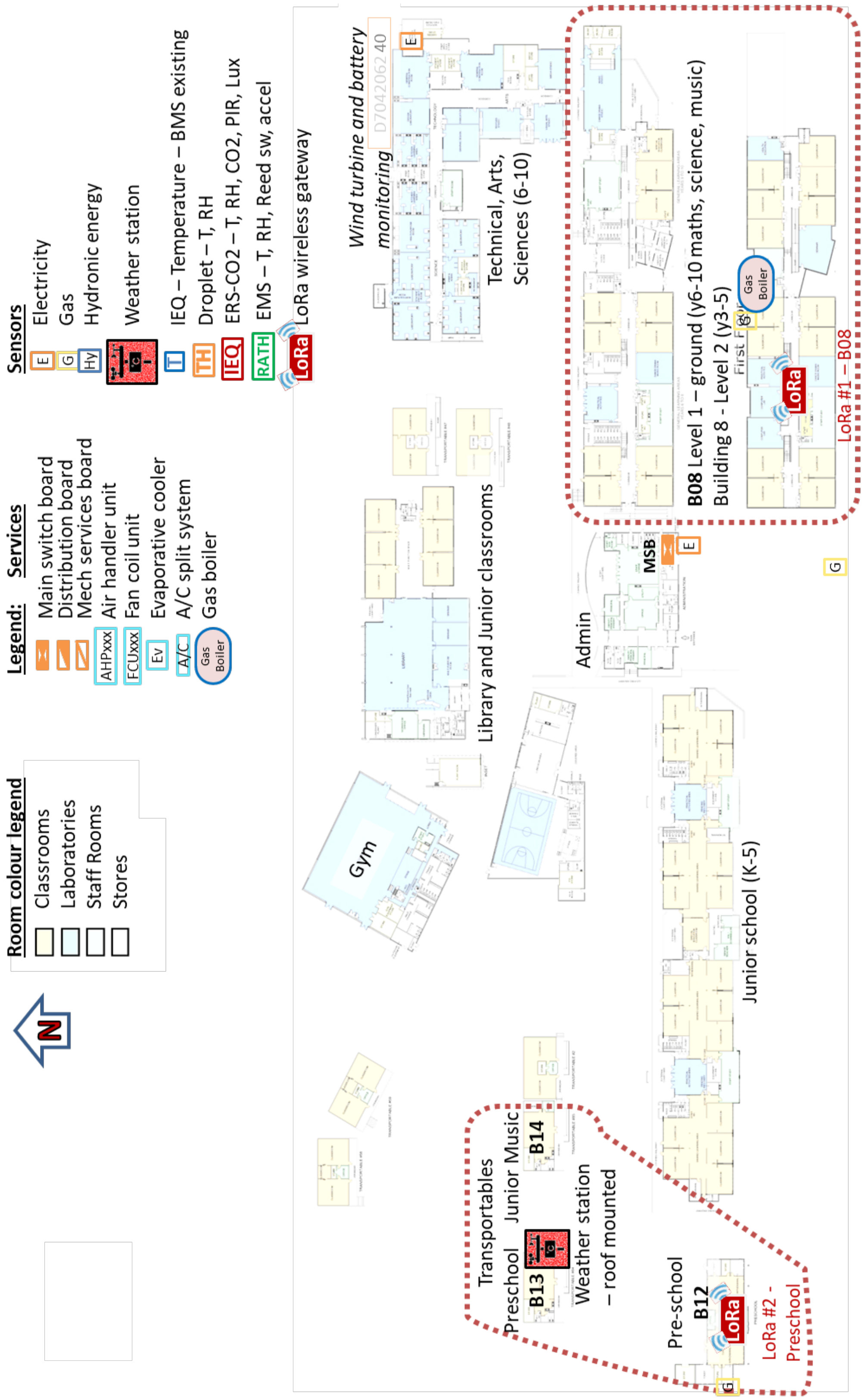


Figure 2-4. Amaroo site metering and monitoring layout.

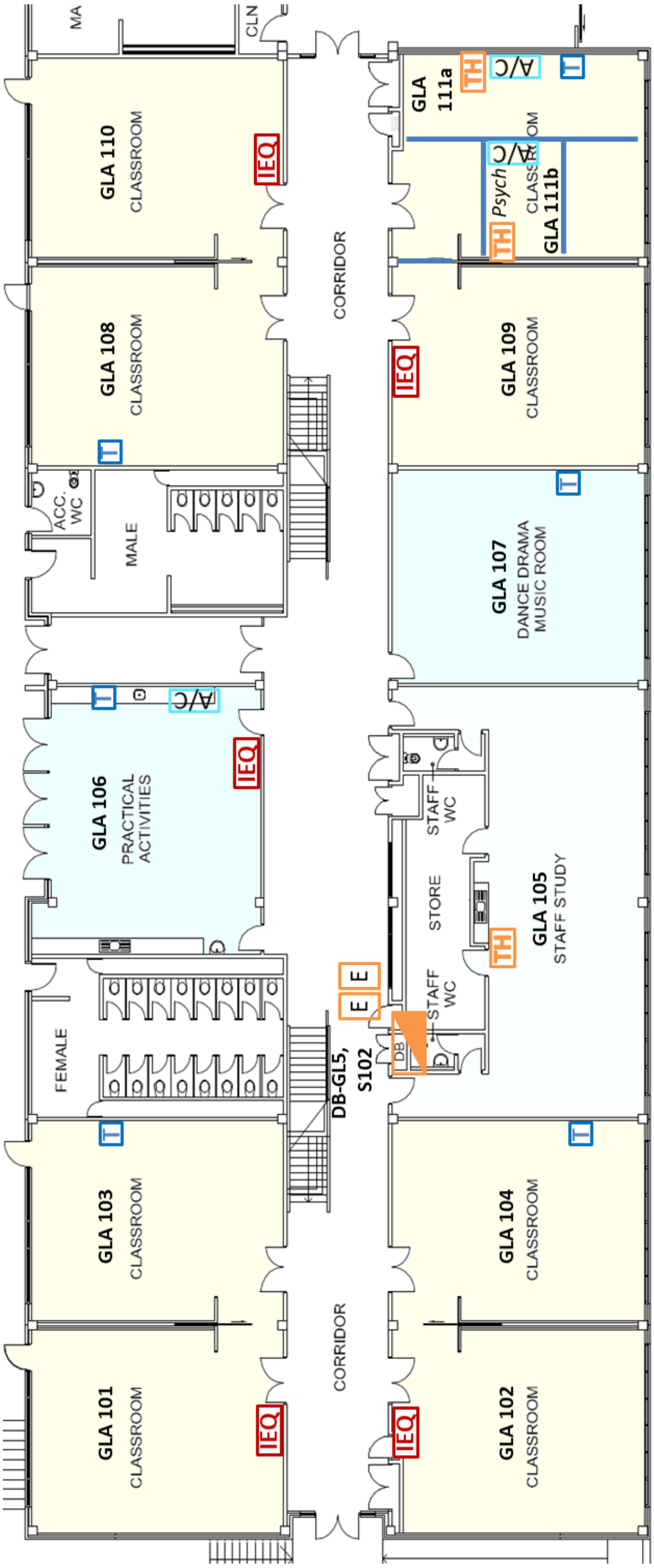


Figure 2-5. Amaroo monitoring device layout - General Learning Area (Building 8), Level 1 (ground floor) west.

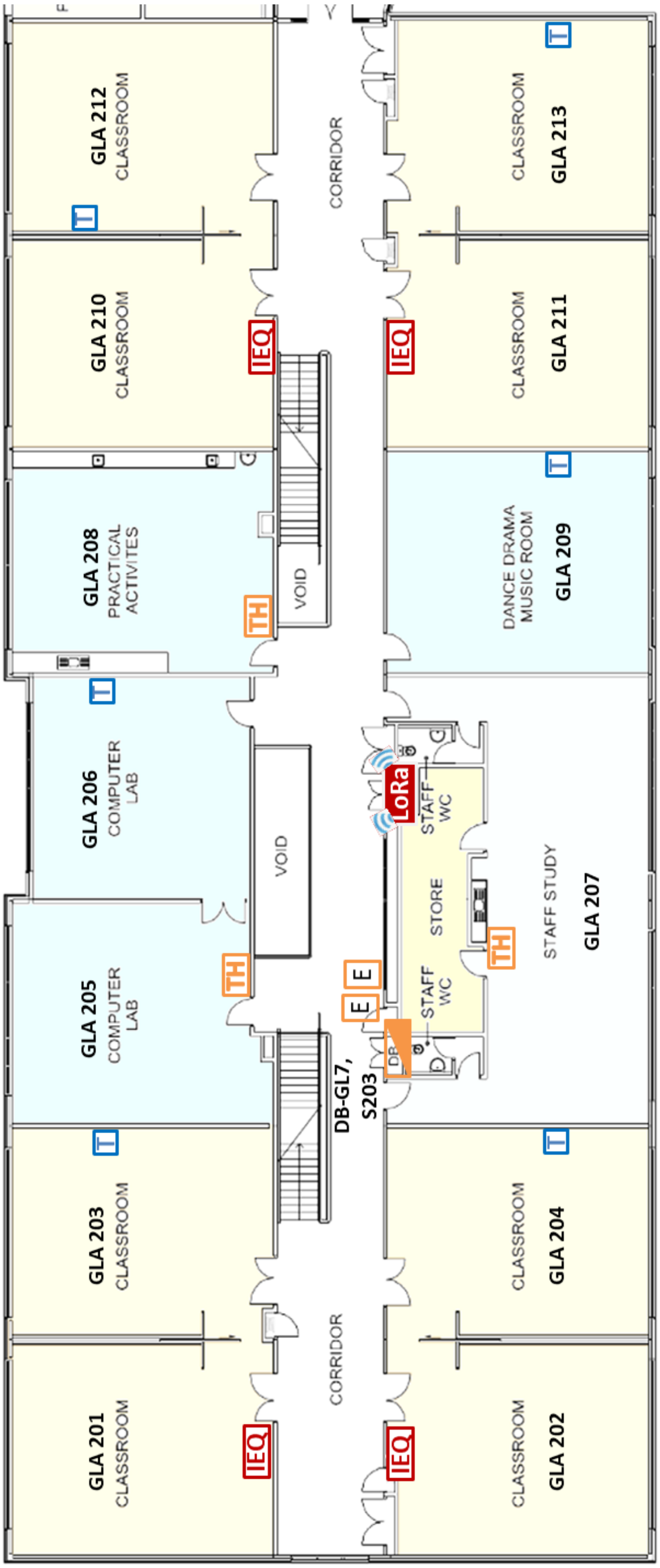


Figure 2-6. Amaroo monitoring device layout - General Learning Area (Building 8), Level 2 west.

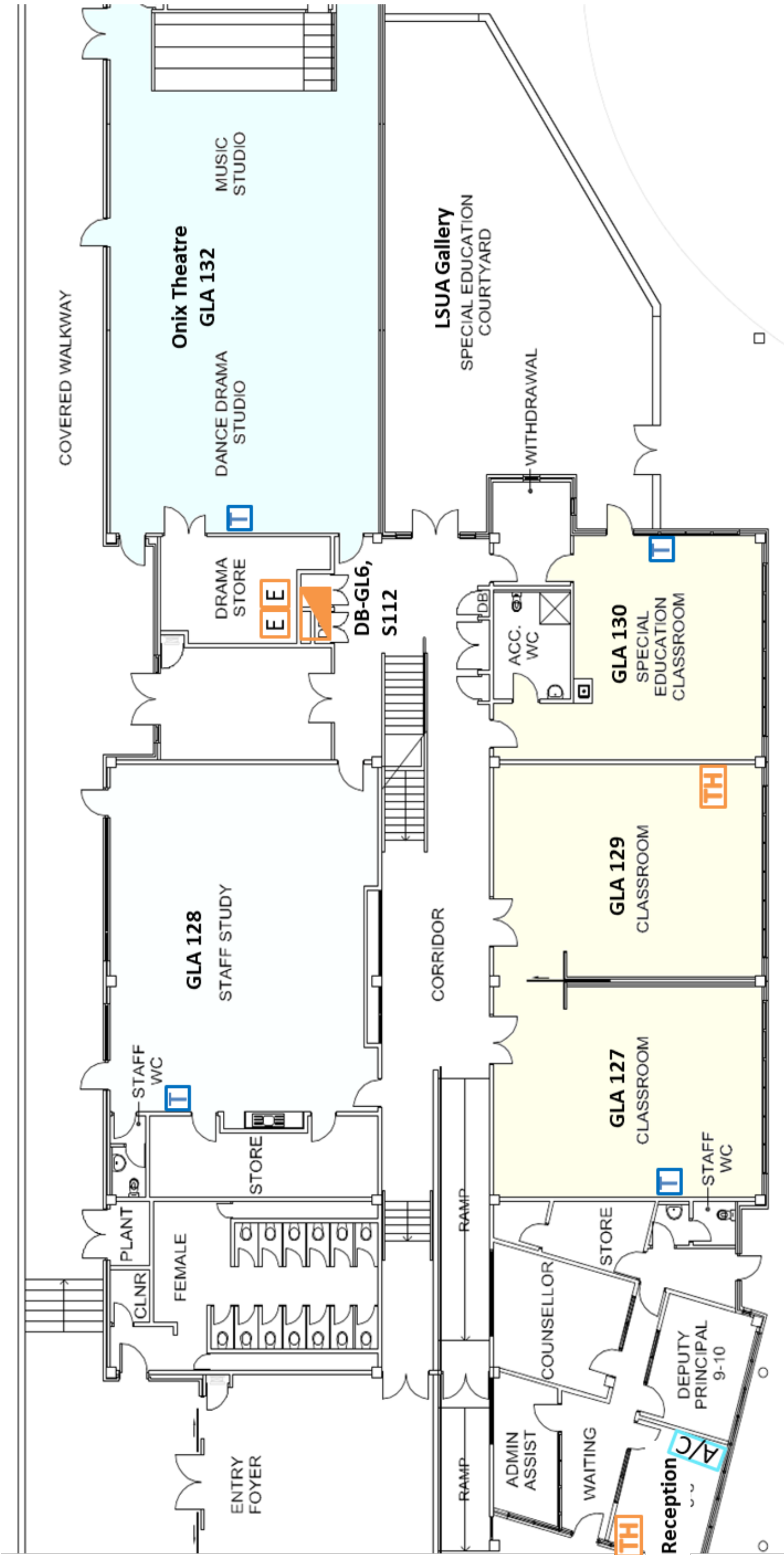


Figure 2-7. Amaroo monitoring device layout - General Learning Area (Building 8), Level 1 (ground floor) east.

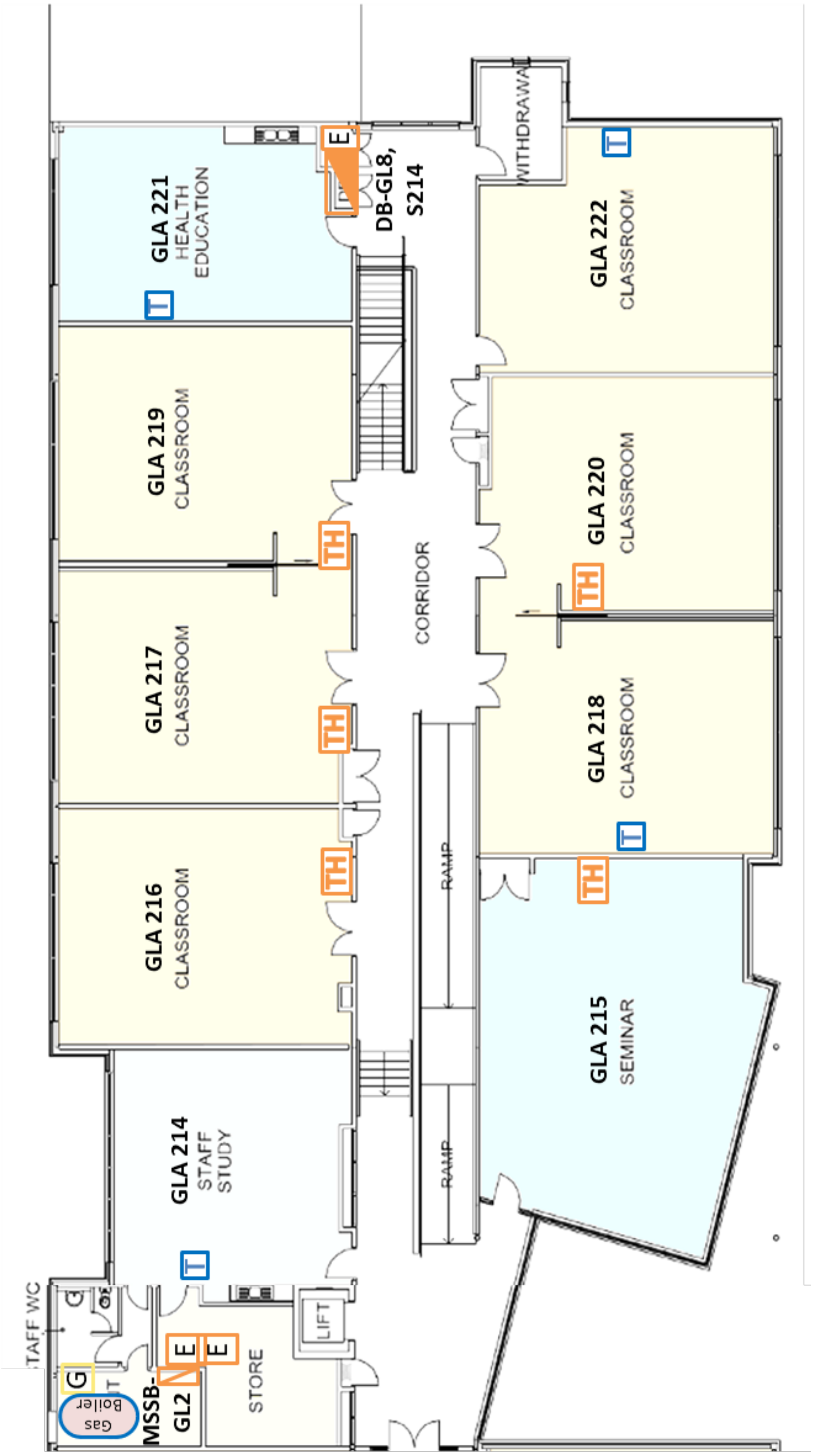


Figure 2-8. Amaroo monitoring device layout - General Learning Area (Building 8), Level 2 east.

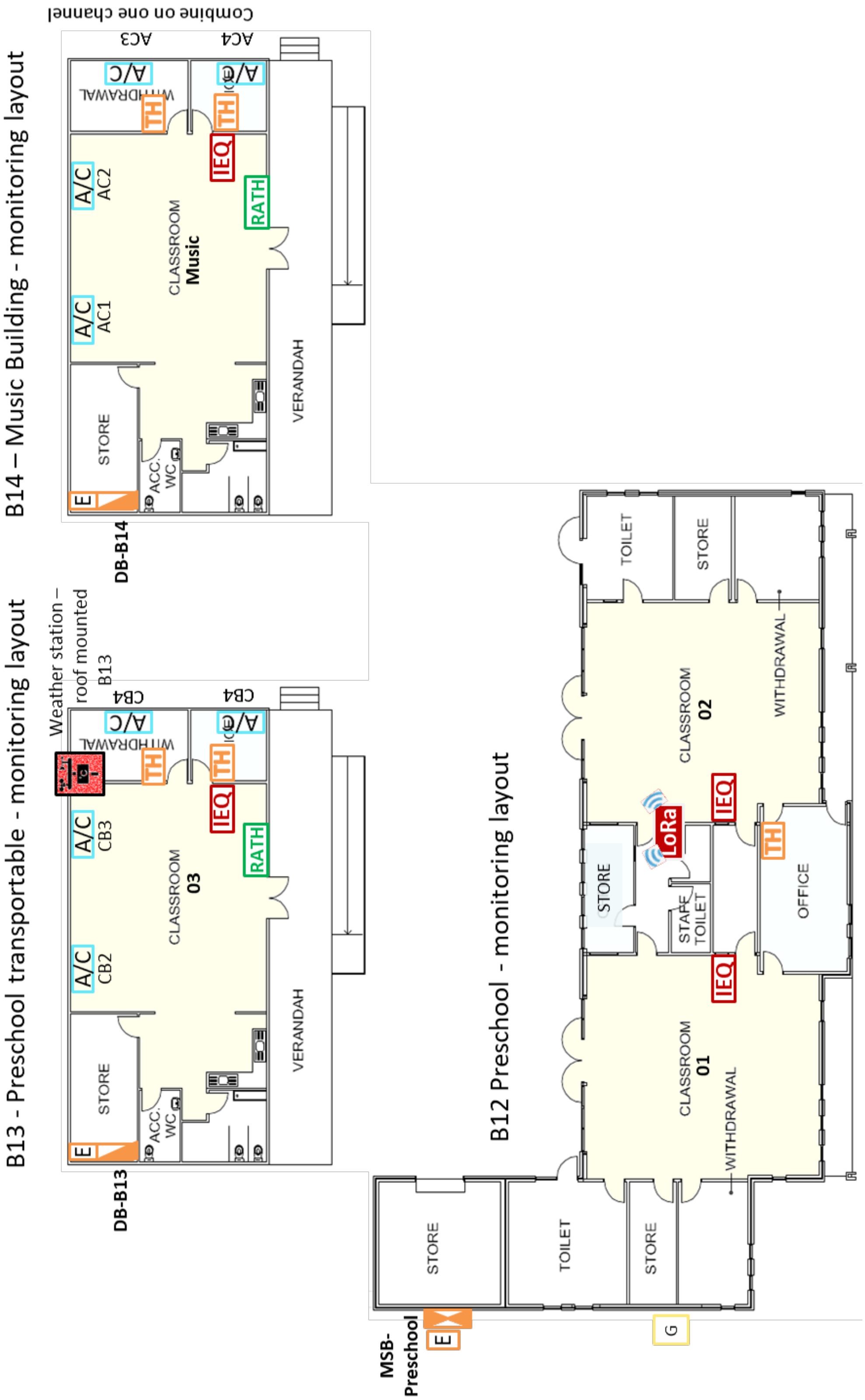


Figure 2-9. Amaroo monitoring device layout - preschool.

Table 2-2. Amaroo monitoring list – by data parameter.

Symbol	Description	Units	Qty	Location	Sample period
	Site monitoring - Main school				
$E_{gas\ site}$	Gas consumption - main school site	*MJ*	1	Utility gas meter	15 min LoRa
$E_{elec\ gross}$	Electricity gross meter - main school site	*kWh*	1	MSB	15 min smart meter
$E_{PV\ gross}$	PV gross generation	*kWh*	1	MSB	15 min smart meter
$E_{PV\ gross,\ admin}$	PV gross generation - Admin rooftop (separate, 10kW)	*kWh*	1	MSB	15 min smart meter
$E_{Wind\ gross}$	Wind turbine gross generation	*kWh*	1	MSB	15 min smart meter
	Site monitoring - Preschool				
$E_{gas\ preschool}$	Gas consumption - preschool (space heating only)	*MJ*	1	Utility gas meter	15 min LoRa
$E_{elec\ preschool}$	Electricity smart meter - preschool site (separate meter)	*kWh*	1	MSB	15 min smart meter
T_{out}	Temperature outdoors	*°C*	1	Weather station	15 min weather WiFi
RH_{out}	Relative humidity outdoors	*%RH*	1	Weather station	15 min weather WiFi
GHI	Global Horizontal Irradiance	W/m^2	1	Weather station	15 min weather WiFi
V_{wind}	Wind speed	*m/s*	1	Weather station	15 min weather WiFi
Dir_{wind}	Wind direction	*Deg*	1	Weather station	15 min weather WiFi
Rain	Rainfall	*mm*	1	Weather station	15 min weather WiFi
	Building monitoring - Main school GLA (Building 8)				
$E_{gas\ boiler\ A}$	Gas consumption for boiler 'A'	*MJ*	1	Plant room	15 min LoRa
$E_{Building\ A}$	Building-level (GLA): DB-GL5, GL6, GL7, GL8; MSSB-GL2	*kWh*	5	DB	15 min LoRa
$E_{AC\ A,B}$	AC split systems (GLA)	*kWh*	*5*	DB	15 min LoRa
E_{HVAC}	HVAC equipment - controls for windows and boiler	*kWh*	9	DB	15 min LoRa
$E_{FCU\ A,B}$	Fan coil unit fan status			Plant room	BMS data
$E_{EXH\ A,B}$	Exhaust fan status			Plant room	BMS data
	Building monitoring - Preschool (B12, B13, B14)				
$E_{Building\ A}$	Building-level (Preschool): MSB, DB-B13, DB-B14	*kWh*	3	MSB, DB-B13,14	5 min 3G
$E_{AC\ A,B}$	AC split systems (Preschool: B13, B14)	*kWh*	*8*	DB-B13, DB-B14	5 min 3G
E_{HVAC}	HVAC equipment - windows, ceiling fans, furnace fans	*kWh*	3	MSB	5 min 3G
	Room-indoor monitoring				
$T_{A,B}$	Temperature indoors for building 'A', room 'B'	*°C*	31		15 min LoRa
$RH_{A,B}$	Relative humidity indoors, building 'A', room 'B'	*%RH*	31		15 min LoRa
$CO_{2\ A,B}$	Carbon dioxide concentration indoors	*ppm*	13		15 min LoRa
$Occ_{A,B}$	Occupancy sensor		13		15 min LoRa
Lux	Lighting level	*Lux*	13		15 min LoRa
$F_{open\ A,B}$	Fenestration opening (transportables - front door)	*Status*	2	Preschool	15 min LoRa
$F_{open\ A,B}$	Fenestration opening (GLA auto windows)	*Status*	4	GLA (Building 8)	BMS data

Table 2-3. Static data parameter list – Amaroo and Fadden.

Parameter description	Category	Site	Building	HVAC system	Room - standard	Room - intensive	Data collection frequency
Air speed - indoor - spot meas't	IEQ					x	Spot meas
Floor area - gross - total site	Normalising parameters	x					Static
Floor area - gross - total site - conditioned	Normalising parameters	x					Static
Floor area - gross - per meas't boundary	Normalising parameters			x			Static
Floor area - gross - per meas't boundary - conditioned	Normalising parameters			x			Static
Total occupancy (census date) - by year	Normalising parameters	x					Static
Facility event calendar - by year	Occupancy	x					Survey
Facility weekly schedule - by year	Occupancy	x					Survey
Facility daily schedule - by year	Occupancy	x					Survey
Occupancy survey	Occupancy					x	Survey
POE	Occupancy				x	x	Survey
Extreme weather events: Bushfire, storm - potential impact on PV and occupancy	Occupancy	x					Survey
Building and equipment changes: Shading, insulation, draught sealing, fenstration, lighting	Static factors		x			x	Survey
HVAC equipment maintenance and fault logs	Static factors			x			Survey
HVAC equipment list for demand response potential	Static factors	x					Survey
Energy tariff information	Static factors	x					Survey

2.2 **Baseline living laboratory performance characterisation**

2.2.1 Summary Energy Data Analysis

The following section presents a site level summary of energy consumption at Amaroo School in the period Jan 2015 – Dec 2019, calculated based on historical meter data assembled in the ACT utility management system.

The main energy end-use for Amaroo is Gas to supply heating during the winter months. In total 65% of the energy consumption is for gas, with gas being the largest energy source from March to October, see Figure 2-10 and Figure 2-11. Amaroo generates a modest amount of electricity via a 20 kWp PV system; a large PV system (600kWp) is also installed on the Amaroo rooftop, however, this array is owned by a third party. Whilst this larger system will act physically the same regardless of ownership, the commercial arrangement means that despite the best efforts of the research team, it has not yet been possible to access generation data from the system owners. Additionally a 5 kWp PV system and wind turbine power system is connected directly into the TAS building, however, these were unable to be metered for this baseline analysis but will be included in future evaluations.

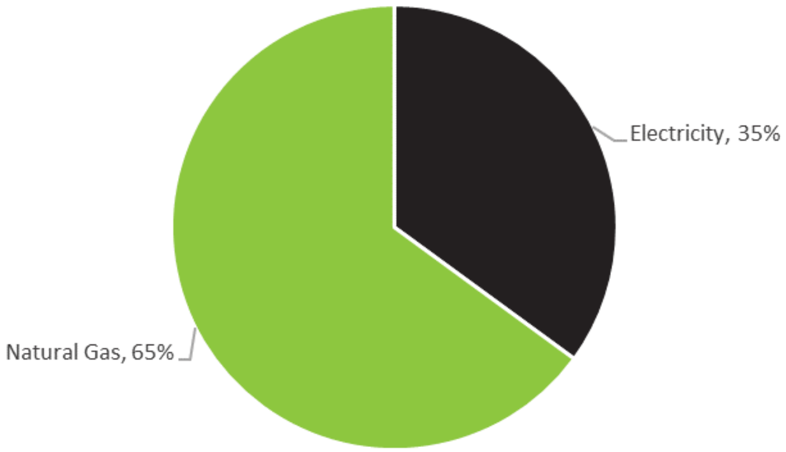


Figure 2-10. Summary of energy sources for Amaroo Primary School, 2015 – 2019

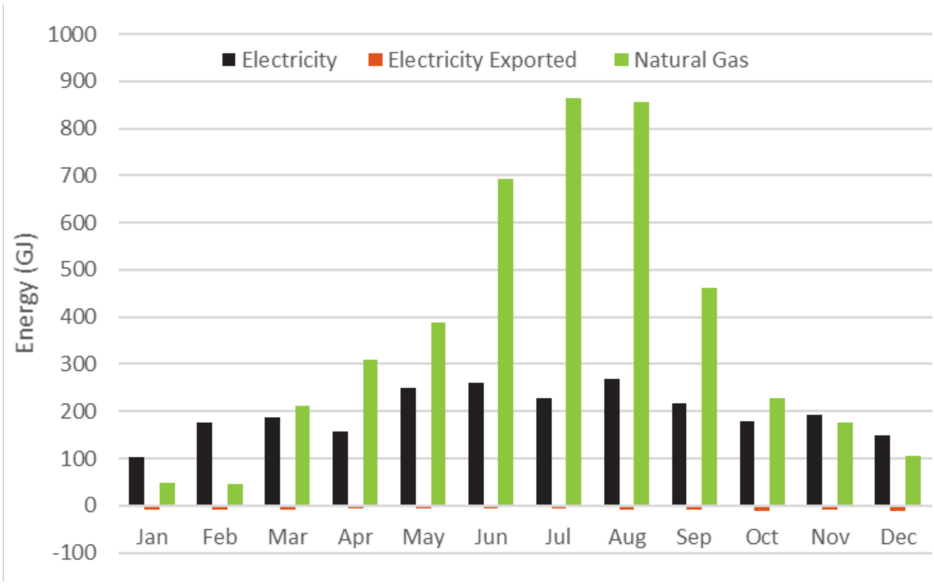


Figure 2-11. Monthly energy consumption summary for Amaroo Primary School for 2015 - 2019

2.2.2 Baseline REETSEF Data Analysis

The following baseline data is drawn from a number of sources. The most comprehensive energy data available for the baseline analysis was 15 minute interval smart meter utility billing data collected from the ACT government account management tool. 5 minute interval data collected through installed Wattwatchers monitoring devices was also available, however, given the short duration of baseline monitoring available, and the overlap with utility data, the 5-min data were only used to verify the existing utility data and will instead be employed for analysis for the trial technology evaluations. The internal and external temperature and weather information was downloaded from the installed monitoring equipment on site and Tuggeranong BOM weather station.

REETSEF KPI 1. Avoided GHG emission (tCO_2-e and $).

CO_2-e is the sum of GHG emission for all fuel sources in use at the site, and was calculated as per the National Greenhouse Accounts Factor method for fuel combustion (gas) or scope 2 emissions electricity. The Amaroo site uses both gas and electricity: scope 2 emissions from electricity were calculated using the emissions factor of 0.81 kg CO_2-e/kWh; combustion emissions from gas were calculated using the emissions factor of 51.53 kg CO_2-e/GJ.

Baseline CO_2-e emissions have been calculated using historic billing data, available for full years 2016, 2017, 2018 and 2019.

Table 2-4. Amaroo KPI 1 - GHG emission.

Year	2016	2017	2018	2019	Average
GHG emissions (t CO_2-e)	696.1	727.4	833.8	834.0	772.8
GHG emissions intensity (kg CO_2-e/enrolment)	444	424	453	450	443
GHG emissions intensity (kg CO_2-e/m^2)	41	43	50	50	45.9
Social cost of GHG emissions[1]	$33,864	$35,390	$40,563	$40,575	$37,598

REETSEF KPI 2. Avoided air pollution

The social benefit due to avoided air pollution puts a cost value to air pollution (PM_{10}, NO_x, and SO_2) impacting populations close to power station. The calculation applies a damage benefit to each MWh[2] of energy saved of $13.8/MWh for electricity, and $0.74/MWh for Gas[3].

Baseline cost of air pollution for this site is therefore:

Table 2-5. Amaroo KPI 2 –Air pollution.

Year	2016	2017	2018	2019	Average
Electricity consumption (GJ)	2149	2212	2595	2655	2402.71
Gas consumption (GJ)	4124	4460	4850	4592	4506.56
Cost of air pollution	$ 9,085.54	$ 9,396.11	$ 10,944.44	$ 11,121.41	$10,136.74

REETSEF KPI 3. Peak 30 minute electricity demand.

Peak demand was calculated as the highest 30 min electricity demand. Peak demand is reported monthly and annually (i.e. highest 30 min consumption per month and year). It can be seen that peak electrical demand typically occurs after lunch during summer months, and early in the morning during winter months.

Table 2-6. Amaroo KPI 3 – Annual Peak 30 minute electricity demand.

Year	Peak 30 minute demand (kWh)	Occurrence
2016	143.52	27/07/2016 9:45 AM
2017	148.96	5/09/2017 10:45 AM
2018	191.04	2/07/2018 9:15 AM
2019	188.48	1/07/2019 9:15 AM
2020	181.6	11/08/2020 9:45 AM

[1] Conversion from emission (tCO_2-e) to societal benefit ($) uses an estimated social cost of carbon of AUD$48.60/$tCO_2$ as a conversion factor from http://www.climateinstitute.org.au/verve/_resources/TCI_SocialCostOfCarbon_PolicyBrief_September2014.pdf. This is slightly higher than the current price of carbon with the EU ETS (AUD $41.8)

[2] https://apo.org.au/sites/default/files/resource-files/2009/03/apo-nid4196-1189331.pdf

[3] https://www.atse.org.au/wp-content/uploads/2019/01/the-hidden-costs-of-electricity.pdf

Table 2-7. Amaroo KPI 3 – Monthly Peak 30 minute electricity demand.

Month	Maximum monthly peak 2016-2020 (kWh/30 min)	Mean monthly peak 2016-2020 (kWh/30 min)	Minimum monthly peak 2016-2020 (kWh/30 min)	Occurrence of maximum peak demand
January	121.92	102.32	89.6	31/01/2020 14:15
February	137.12	124.416	108.16	18/02/2019 13:15
March	145.6	119.84	101.92	27/03/2018 8:15
April	133.76	114.84	86.52	30/04/2018 9:15
May	164.64	153.52	142.72	17/05/2018 9:15
June	189.92	162.24	142.72	26/06/2018 9:15
July	191.04	166.16	141.6	2/07/2018 9:15
August	185.6	156.032	131.68	14/08/2019 9:15
September	167.84	145.504	129.12	17/09/2019 9:15
October	123.04	110.688	94.4	14/10/2019 8:45
November	142.72	119.2	101.28	21/11/2019 12:15
December	129.28	106.72	92.48	10/12/2019 13:45

REETSEF KPI 4. Peak 30 minute electricity export.

As for KPI 3, peak export was calculated as the highest 30 min electricity export. For this gross metered site, this “export” is really gross electrical generation. Peak export is reported monthly, and annually (i.e. highest 30 min export per month and year). It is important to note that export data only includes generation from the utility metered 20 kWp PV system on the administration building. It does not include generation from the unmetered 5 kWp PV system and 5 kW wind turbine systems at the TAS building, nor the 600kWp system for which data was not able to be obtained.

Table 2-8. Amaroo KPI 4 - Peak 30 minute electricity export.

Year	Peak 30 minute export (kWh)	Occurrence
2016	9.484	13/11/2016 11:15:00 AM
2017	9.001	20/02/2017 12:15:00 PM
2018	8.381	2/09/2018 12:15:00 PM
2019	9.353	26/10/2019 11:15:00 AM
2020	9.469	1/04/2020 1:15:00 PM

Table 2-9. Amaroo Peak monthly electricity export.

Month	Maximum monthly peak export 2016-2020 (kWh/30 min)	Mean monthly peak export 2016-2020 (kWh/30 min)	Minimum monthly peak export 2016-2020 (kWh/30 min)	Occurrence of maximum peak export
January	8.8	8.2	7.4	14/01/2017 12:15:00 PM
February	9.0	8.3	7.5	20/02/2017 12:15:00 PM
March	8.5	7.9	7.1	07/03/2017 12:15:00 PM
April	9.5	7.5	6.6	01/04/2020 01:15:00 PM
May	7.3	6.6	6.1	03/05/2020 11:45:00 AM
June	6.8	6.2	5.6	23/06/2020 12:15:00 PM
July	7.4	6.9	6.0	08/07/2018 12:15:00 PM
August	8.3	7.7	6.6	22/08/2020 11:15:00 AM
September	8.9	8.4	7.6	19/09/2016 12:15:00 PM
October	9.5	8.5	7.4	31/10/2016 11:45:00 AM
November	9.5	8.6	7.4	13/11/2016 11:15:00 AM
December	9.4	8.7	7.6	06/12/2020 10:45:00 AM

REETSEF KPI 5. Wholesale cost of peak 30 minute electricity demand.

To determine whether the facility peak demand was co-incident with periods of energy market peak demand, the wholesale cost of peak demand at the time of occurrence was calculated using historic co-incidental wholesale spot prices from AEMO[4].

Table 2-10. Amaroo KPI 5 - Wholesale cost of peak 30 minute electricity demand.

Year	Peak 30 minute demand (kWh)	Occurrence	Co-incident wholesale price (c)	Percentile of monthly wholesale cost rank
2015*	141.76	12/08/2015 11:45	35.15	44%
2016	143.52	27/07/2016 9:45	37.23	38%
2017	148.96	5/09/2017 10:45	96.03	78%
2018	191.04	2/07/2018 9:15	101.14	87%
2019	188.48	1/07/2019 9:15	79.86	72%
2020	181.6	11/08/2020 9:45	54.04	77%

4 https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/data-nem/aggregated-data

REETSEF KPI 6. Total self-consumption rate (0-1).

The self-consumption rate of renewable generation (SC) is the proportion of on-site renewable generation that is consumed on-site by the facility. For the 20 kWp metered array at Amaroo, the historic self-consumption rate, calculated at each time step from interval data from 2015 – 2020, was 98.6%. Monthly self-consumption rates for the living laboratory sections of the school are provided below in Table 2-11.

Table 2-11. Amaroo KPI 7 – Total self-consumption rate

Month	Self consumption rate
September 2020	94%
October 2020	93%
November 2020	92%
December 2020	94%
January 2021	96%
February 2021	96%
March 2021	98%
April 2021	96%

The average daily consumption profile for the showing the average daily consumption and generation for entire Amaroo School, can be seen in Figure 2-12.

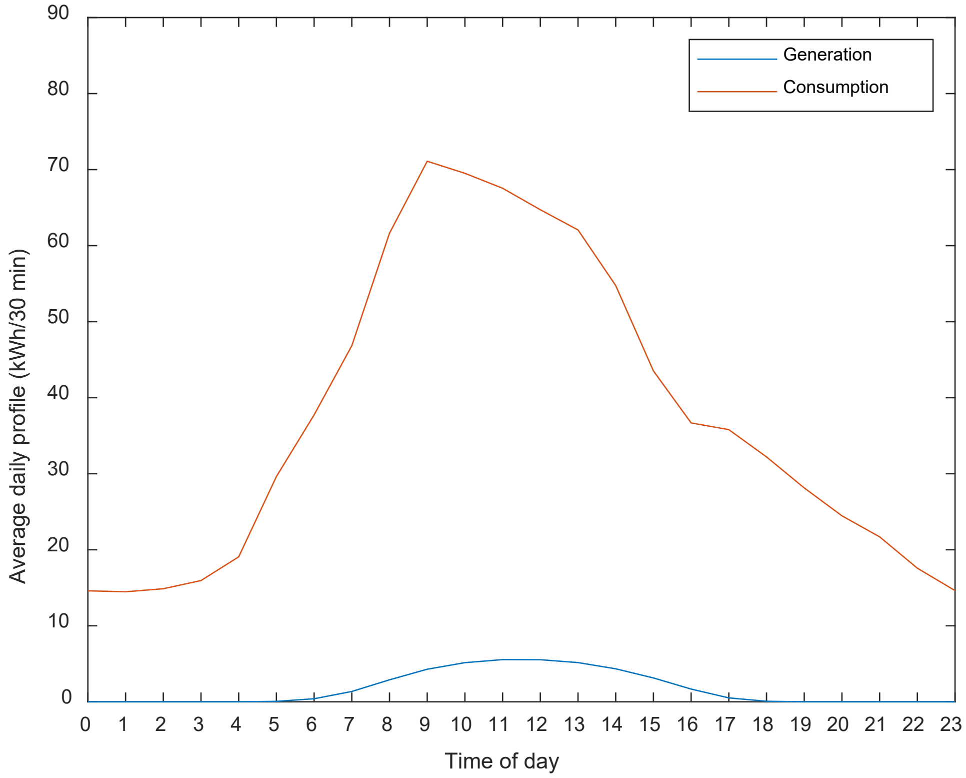


Figure 2-12. Amaroo average daily electrical energy consumption and generation profiles.

The daily total electrical energy consumption profile at Amaroo School is well matched in shape to the PV generation profile for the Administration Building PV system. It can be seen that a PV system of around ten times greater would be well-suited to this site's load profile. The electrical energy consumption daily profile rises more steeply and peaks earlier at 9:00 AM when compared to the PV generation profile. The consumption profile also drops away more steeply at 3:00 PM when compared to the PV profile. This suggests as load shifting from 9:00 AM to after 3:00 PM would capture better value from a larger PV generation system on this site.

This is of particular relevance given the large 600kW array on this site, for which generation data was not available. It is anticipated that the generation profile would closely match the smaller monitored system, given the similar orientations of the two arrays.

REETSEF KPI 7. HVAC self-consumption rate (0-1).

Considering only the electricity consumed for HVAC operation in the living laboratory section of the facility, the self-consumption rate of renewable energy from the 20 kWp gross metered system for the period from Sept 2020 to 24 April 2021 was 53.1%, i.e. on average 53.1% of energy generated was used onsite by co-incident HVAC operation.

Monthly self-consumption rates are provided below in Table 2.11.

Table 2-12. Amaroo KPI 7 – HVAC self-consumption rate

Month	Self-consumption rate
September 2020	52%
October 2020	40%
November 2020	36%
December 2020	48%
January 2021	61%
February 2021	58%
March 2021	63%
April 2021	65%

Amaroo site heating is predominately supplied by a gas boiler, which is not captured in the above KPI. Changing to electric heating would be expected to substantially increase the HVAC self-consumption rate and therefore potential for exploitation of renewable energy.

REETSEF KPI 8. Total renewable energy fraction

Renewable Energy Fraction (REF) is the proportion of energy use for a facility ($E_{elec,gross,i}$) that is generated by on-site renewable generation ($E_{PV,gross,i}$). For the historic data available, the overall REF is 5.25%.

REETSEF KPI 9. HVAC renewable energy fraction

Considering only the electricity consumed for HVAC operation in the living laboratory section of the facility, and the gross metered 20 kWp PV system, the Renewable Energy Fraction for the period from Sept 2020 to 24 April 2021 was 49%, i.e. on average 49% of electricity used for HVAC was co-incident with renewable energy generation (on a 30-minute interval basis). Monthly renewable energy fractions are provided in Table 2.12.

Table 2-13. Amaroo KPI 8 – HVAC renewable energy fraction

Month	Renewable energy fraction
September 2020	41%
October 2020	47%
November 2020	53%
December 2020	55%
January 2021	53%
February 2021	53%
March 2021	47%
April 2021	46%

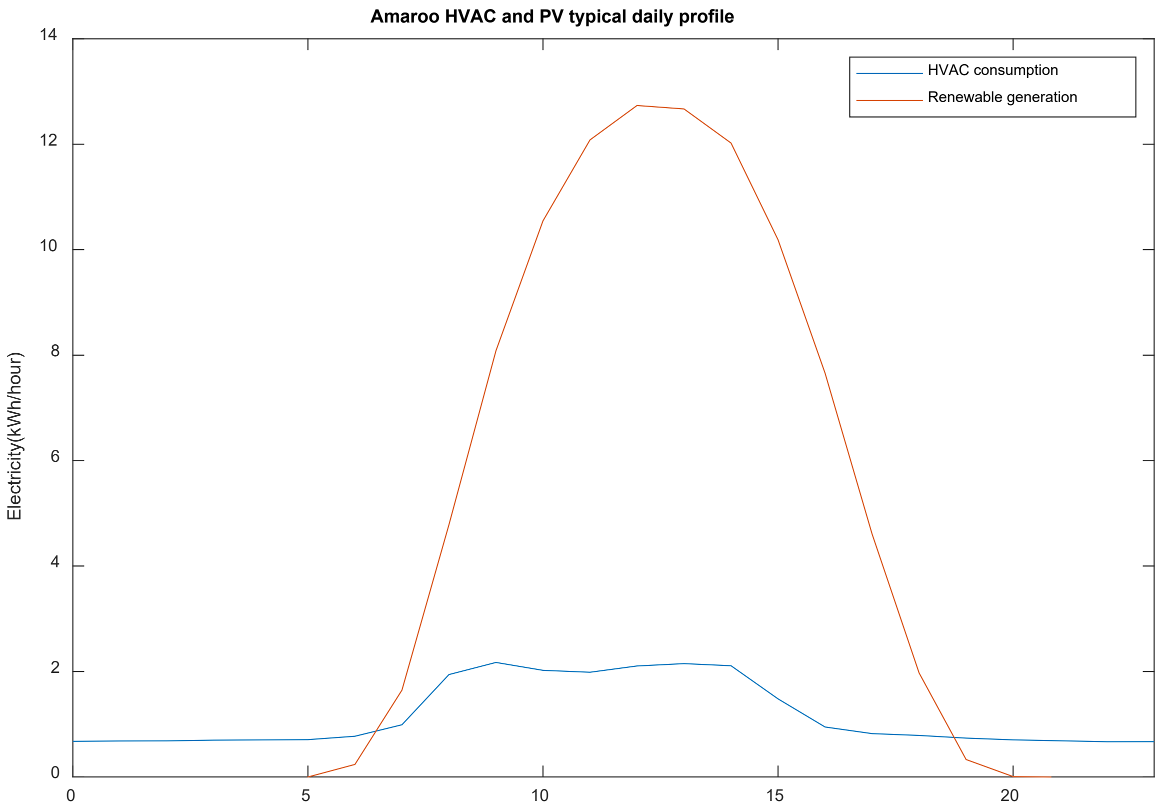


Figure 2-13. Average daily HVAC and PV electricity profile for Amaroo..

REETSEF KPI 10. Net Facility Load Factor

Net Facility Load Factor (NFLF) is the average load divided by the peak load during a specified time period, and is a measure of how 'peaky' an energy use profile is. This is calculated based on 24 hour data, and does not exclude holiday and after hour data.

For Amaroo, the NFLF calculated based on average and peak load from 2016 -2020 historic data is 0.20. Monthly and annual NFLF are given in the tables below.

Table 2-14. Amaroo KPI 10 – Net Facility Load Factor.

Year	Net Facility Load Factor
2016	0.21
2017	0.24
2018	0.22
2019	0.22
2020	0.21

Monthly NFLF:

Table 2-15. Amaroo Monthly Net Facility Load Factor.

	2016	2017	2018	2019	2020	Average
January	NaN	0.20	0.21	0.22	0.21	0.21
February	0.29	0.29	0.29	0.30	0.30	0.29
March	0.22	0.32	0.25	0.29	0.31	0.28
April	0.27	0.22	0.23	0.27	0.27	0.29
May	0.27	0.30	0.31	0.33	0.31	0.30
June	0.32	0.33	0.30	0.32	0.31	0.32
July	0.25	0.28	0.25	0.27	0.25	0.26
August	0.24	0.33	0.33	0.30	0.30	0.30
September	0.29	0.26	0.31	0.29	0.30	0.29
October	0.27	0.30	0.30	0.30	0.26	0.30
November	0.31	0.29	0.33	0.28	0.29	0.31
December	0.24	0.26	0.28	0.25	0.23	0.25

The Net Facility Load Factor for Amaroo is in line with the daily generation profile presented in Figure [KPI6] with relatively low and stable consumption during non-school hours and a substantial peak at the start of the school day tapering off as the buildings warm up. As noted above, the timing of the peak load for Amaroo is well suited to PV generation and does not tend to coincide with NEM peak event times.

REETSEF KPI 11. Demand response capacity

While there is currently no demand response capacity at Amaroo, there is potential to utilise the thermal inertia of the buildings, as well as the existing in-slab heating systems, to ameliorate facility peaks. However, this will require new technology and further analysis to assess.

And further, since peak demand for this site is on winter mornings and the grid peak demand events are summer afternoons after school hours, the potential to impact grid-level peak demand events with site HVAC demand response control is limited.

REETSEF KPI 12. Energy cost

Energy cost was calculated from historic billing data for each full year for which data was available. The annual energy usage and cost from billing data is shown in the table below.

Table 2-16. Amaroo KPI 12 – Energy cost.

		2016	2017	2018	2019	2020
Electricity Import	Usage (kWh)	596,970	614,345	720,834	737,525	678,424
	Cost ($/kWh)	$96,827	$103,193	$123,177	$190,713	$157,706
	Unit cost	$0.16	$0.17	$0.17	$0.26	$0.23
Electricity Export	Usage (kWh)	-26,359	-29,773	-28,108	-31,435	-29,657
	Cost ($/kWh)	-$13,251	-$14,967	-$14,130	-$15,802	-$14,909
	Unit cost	$0.50	$0.50	$0.50	$0.50	$0.50
Natural Gas	Usage (MJ)	4,136,527	4,432,178	4,783,068	4,587,323	3,444,434
	Cost	$87,812	$101,059	$116,401	$115,240	$87,228
	Unit cost ($/MJ)	$0.02	$0.02	$0.02	$0.03	$0.03
Total Net Energy	Usage (MJ)	6,190,727	6,536,638	7,276,880	7,129,246	5,779,996
	Cost	$171,388	$189,284	$225,447	$290,150	$230,025
	Unit cost ($/MJ)	0.03	0.03	0.03	0.04	0.04

REETSEF KPI 13. Energy Use Intensity / Productivity

Energy use intensity is a measure of how much energy is used in a facility normalised for comparison with relative benchmarks. Current school sector EUI KPIs are typically based on kWh/m^2 or kWh/enrolment.

Table 2-17. Amaroo KPI 13 – Energy Use Intensity / Productivity

Year	2016	2017	2018	2019	Average
Electricity consumption (GJ)	2149	2212	2595	2655	2402.71
Gas consumption (GJ)	4124	4460	4850	4592	4506.56
Total Energy Consumption (GJ)	6274	6672	7445	7247	6909.27
Electricity intensity (GJ/m^2)	0.13	0.13	0.15	0.16	0.14
Gas intensity (GJ/m^2)	0.25	0.26	0.29	0.27	0.27
Total energy intensity (GJ/m^2)	0.37	0.40	0.44	0.43	0.41

Electricity intensity (GJ/enrolment)	1.16	1.19	1.40	1.43	1.30
Gas intensity (GJ/enrolment)	2.23	2.41	2.62	2.48	2.43
Total energy intensity (GJ/enrolment)	3.39	3.60	4.02	3.91	3.73

2.2.3 Baseline IEQ

Baseline temperature

Data in the following sections has been analysed to determine hours above and below certain threshold temperatures. Appropriate threshold temperatures could be selected from a range of sources. There are relevant emerging bodies of research applying the adaptive thermal comfort standards to the education sector (e.g. (de Dear et al., 2015)), as well as studies exploring the impact of thermal discomfort on cognition and student learning performance (e.g. (Brink et al., 2021; Haverinen-Shaughnessy & Shaughnessy, 2015)). However, as the body of evidence is still emerging, it is not yet clear what the appropriate standard is for use in mixed-mode buildings (e.g. the living laboratory locations) ((Ledo Gomis et al., 2021) and as such is not appropriate for the simple benchmarking required for the current report. Specification JVb in Volume 1 of The National Construction Code defines appropriate temperatures for the assessment of code compliance as 18°C to 25°C for conditioned spaces with transitory occupancy; and 21°C to 24°C in all other conditioned spaces. Performance of the spaces has been reported against these wide (18°C to 25°C) and tight (21°C to 24°C) temperature bands. More nuanced assessment of the thermal comfort performance of these spaces may be required for the trial technology assessments.

For this baseline report, temperature data has been collected from 4th September 2020 to 20 April 2021. Summary statistics and a range of visualisation of the monitored temperature data are provided below. The data shown is only for school hours (defined as 8am – 4pm) and holiday, weekend and after-hours data have been excluded. It is important to note that the baseline sample period does not include any winter data. As such, further analysis of the short period of cold weather data is provided to estimate the building performance during the colder periods.

Table 2-18. Summary temperature statistics for Amaroo school (8am -4pm school days only from 4 September 2020 to 20 April 2021).

Room ID	Mean temp (°C)	Min temp (°C)	Max temp (°C)	%<18°C	%<21°C	%>24°C	%>25°C	Within threshold of 21< % <24°C	Within threshold of 18 < % < 25°C
B12 Eas	21.8	17.2	26.1	0%	25%	7%	2%	68%	**97%**
B12 Off	21.5	14.7	26.2	2%	33%	3%	1%	65%	**97%**
B12 Wes	20.8	16.5	24.7	4%	51%	1%	0%	47%	**96%**
B13 Cla	21	13.2	26.4	13%	44%	10%	3%	46%	*85%*
B13 Off	21	11.8	28.7	17%	45%	17%	8%	38%	*74%*
B13 Wit	21.6	12.9	28.5	13%	39%	26%	15%	36%	*73%*
B14 Cla	20.1	7.6	27.6	26%	57%	13%	6%	31%	*68%*
B14 Off	19.2	7	27.7	35%	66%	9%	4%	24%	*61%*
B14 Wit	19.2	7.1	27.8	36%	67%	10%	4%	23%	*60%*
G1E Sec	20.1	14.6	24.2	8%	73%	0%	0%	26%	92%
G1E 129	20	15.3	24.5	10%	70%	1%	0%	29%	90%
G1W 105	21.4	18	25	1%	43%	5%	0%	51%	**99%**
G1W 110	21.1	17.6	24.8	1%	44%	4%	0%	52%	**99%**
G1W 101	21.1	16.4	24.9	4%	48%	3%	0%	50%	**96%**
G1W 102	21	16.7	24.9	5%	51%	3%	0%	46%	**95%**
G1W 111	20.8	16.6	27	5%	51%	1%	0%	48%	**95%**
G1W 109	20.5	14	23.5	6%	61%	0%	0%	39%	**94%**
G1W 106	20.1	15.6	23.3	7%	78%	0%	0%	22%	**93%**
G1W 111	19.6	14.6	23.3	17%	77%	0%	0%	23%	*83%*
G2E 219	21.7	16.4	28	2%	39%	15%	7%	46%	91%
G2E 217	21.6	16.1	28.7	4%	41%	14%	6%	45%	90%
G2E 220	21.5	15	27.2	5%	43%	14%	7%	43%	*88%*
G2E 216	21.3	15.4	28.5	6%	48%	12%	6%	40%	*88%*
G2E 215	20.1	15.1	25.9	16%	68%	4%	1%	28%	*84%*
G2W 205	20.8	14.9	25.1	7%	53%	2%	0%	45%	**93%**
G2W 207	21.5	16.8	27.4	3%	44%	13%	6%	43%	91%
G2W 208	21.5	16	27.7	4%	39%	12%	6%	49%	91%
G2W 210	22.2	17.5	29.4	1%	30%	19%	9%	51%	90%
G2W 211	21.4	13.4	27.4	6%	41%	12%	6%	47%	89%
G2W 201	22.1	17	27.2	2%	34%	19%	9%	46%	89%
G2W 202	21.7	16.2	27.7	4%	41%	17%	8%	42%	*88%*
Mean	**20.9**	**14.7**	**26.4**	**9%**	**50%**	**9%**	**4%**	**42%**	**88%**

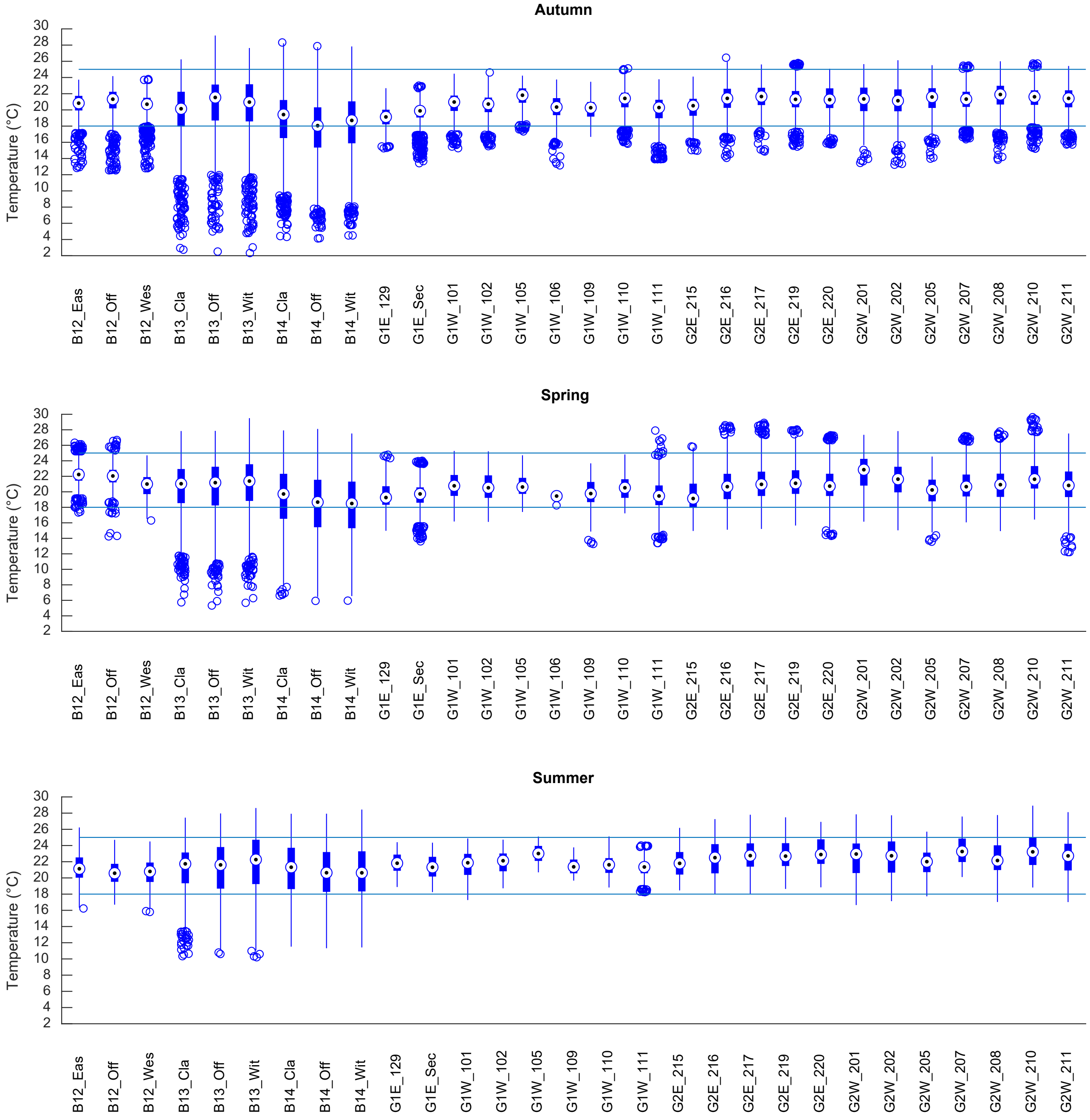


Figure 2-14. Boxplot displaying seasonal temperature variations over monitored period for each monitored room for Amaroo.

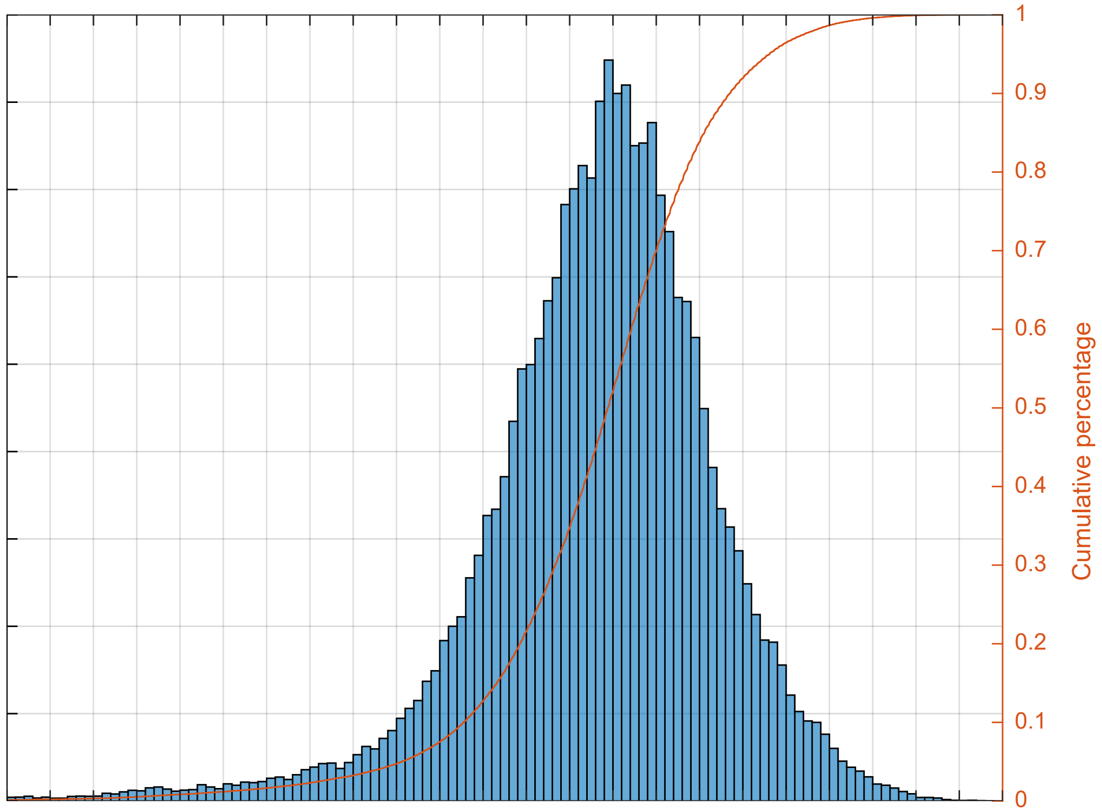
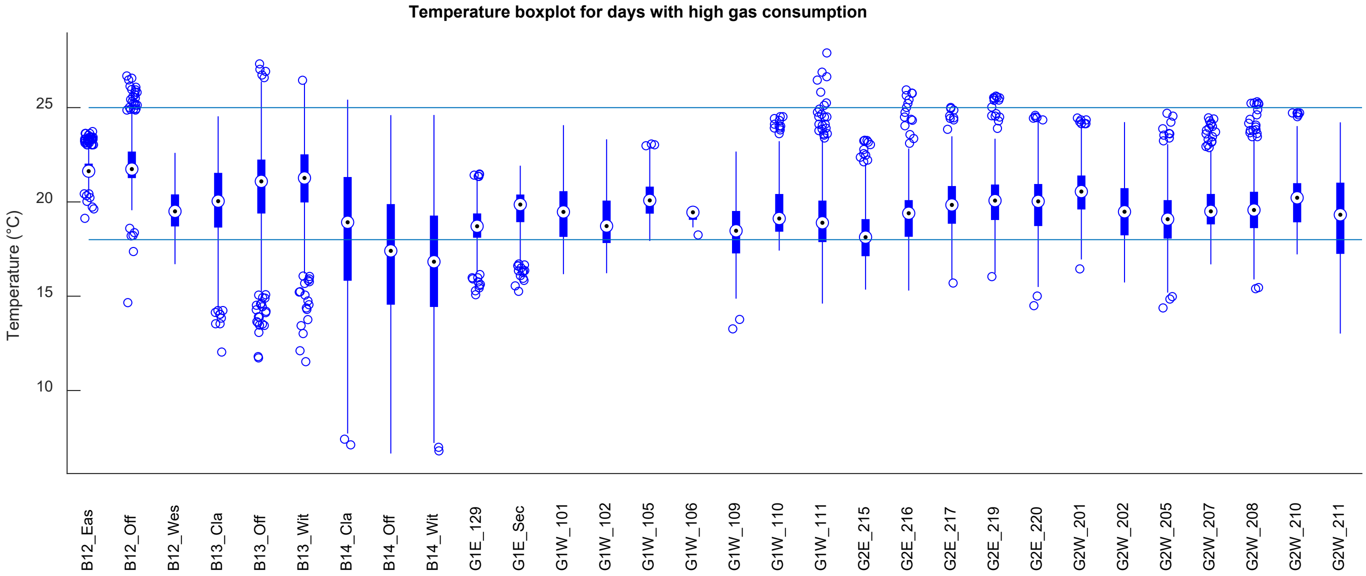


Figure 2-15. Temperature histogram and cumulative distribution for all internal temperature sensors for Amaroo (blue bars define the number of occurrences within a specific temperature bin and the red line is the cumulative percentage of occurrences as compared to the total number of occurrences).

The summary data presented in Figure 2-15, Figure 2-16 and Table 2-17 suggests, in the baseline condition there are some issues with thermal comfort, in particular winter underheating, within the facility. During school hours, the recorded temperatures were within the wider temperature band (18 – 25 °C) for much of the monitored period (mean = 88%, range 60 – 99%), however, on average conditions were only within the more stringent comfort band (21 – 24 °C) for less than half the time (mean = 45%, range 23 – 68%).

Given there was no winter data available for the current baseline, further investigation was undertaken to understand if issues of underheating may be expected to be prevalent during cold periods. Firstly, data was split into days with high (n = 45 days) and low gas consumption (n=76 days); a threshold was selected based on visual examination of the time-series data to distinguish between likely gas usage for heating and for other purposes. A summary of the recorded temperature for each zone is provided in Figure 2-16 and Table 2-18. Obviously, it would be expected that days in which there was no heater usage will have a higher external temperature, and therefore higher internal temperatures. However, it can be clearly seen that, for many rooms, when the heating system is in use it is not providing temperatures within both the wide and narrow comfort bands for substantial periods of time. On average, spaces were below 21°C for 75% of the time that the heater was in use, compared with 45% of time during which the heater was not in use. Note: the baseline period is predominately over the warmer months.

It can also be seen that, on days when the heater was in use many rooms have a significant portion of time below 18°C, particularly in the transportables (Building 13 and Building 14). A time series plot, showing the coldest rooms in each block for a cold week in September, is provided as an example in Figure 2-17. This figure shows periods during the mornings, in some cases for many hours, where rooms are not recording temperatures within the desired range.



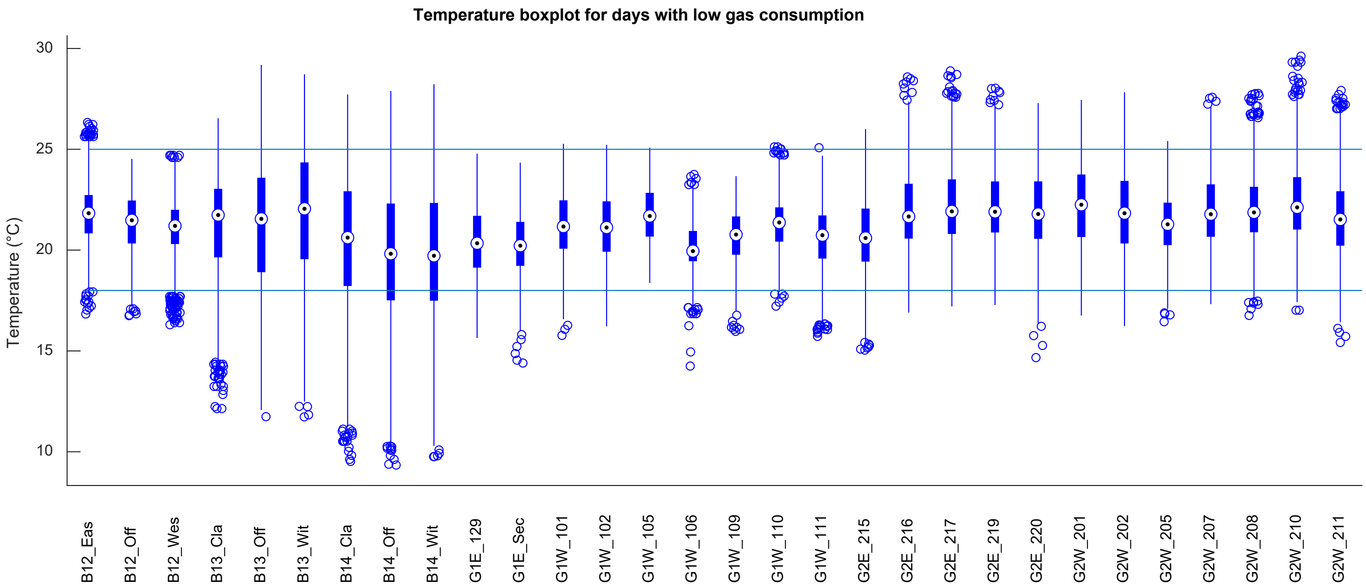


Figure 2-16. Boxplot displaying temperature variations over monitored period for each monitored room for Amaroo. Subplots show data from periods in which there was high gas consumption (plot 1) and low gas consumption, suggesting little heating use (plot 2).

Table 2-19. Summary temperature statistics for Amaroo School showing temperatures for days when heating was in use and days without.

	Days with high gas consumption			Days with low gas consumption		
Room ID	**Mean temp (°C)**	**%<18 °C**	**%<21 °C**	**Mean temp (°C)**	**%<18 °C**	**%<21 °C**
B12 Wes	19.6	9%	87%	21.0	4%	44%
B12 Off	22.0	1%	15%	21.3	2%	37%
B12 Eas	21.8	0%	5%	21.8	1%	29%
B13 Cla	20.0	16%	67%	21.2	12%	39%
B13 Cla	14.7	50%	67%	18.7	29%	52%
B13 Off	20.6	17%	52%	21.1	18%	44%
B13 Wit	21.0	10%	43%	21.8	13%	38%
B14 Wit	16.7	64%	88%	19.7	30%	62%
B14 Off	16.9	53%	86%	19.7	30%	62%
B14 Cla	18.5	40%	71%	20.4	23%	54%
B14 Cla	15.7	43%	57%	17.8	36%	60%
G1E 129	18.9	19%	96%	20.4	8%	62%
G1E Sec	19.6	12%	93%	20.3	7%	67%
G1W 106	19.4	0%	100%	20.1	7%	77%
G1W 111	18.0	47%	99%	20.1	8%	70%
G1W 102	19.2	30%	89%	21.2	3%	47%
G1W 109	18.8	35%	84%	20.6	4%	59%
G1W 110	19.9	8%	81%	21.2	1%	41%
G1W 101	19.7	17%	81%	21.2	3%	45%
G1W 111	20.0	10%	77%	21.1	3%	43%
G1W 105	20.3	2%	74%	21.8	0%	33%
G2E 215	18.3	43%	96%	20.7	7%	59%
G2E 216	19.3	22%	89%	21.9	1%	34%
G2E 217	19.9	12%	78%	22.2	1%	29%
G2E 219	20.1	6%	76%	22.2	0%	27%
G2E 220	20.0	14%	74%	22.0	2%	33%
G2W 205	19.2	23%	86%	21.3	2%	43%
G2W 202	19.8	22%	84%	21.9	3%	37%
G2W 207	19.8	9%	79%	22.0	1%	33%
G2W 210	20.3	8%	78%	22.3	1%	26%
G2W 208	19.8	13%	77%	22.0	1%	27%
G2W 211	19.2	30%	73%	21.6	3%	39%
G2W 201	20.6	7%	67%	22.3	2%	30%
Mean	**19.3**	**21%**	**75%**	**21.1**	**8%**	**45%**

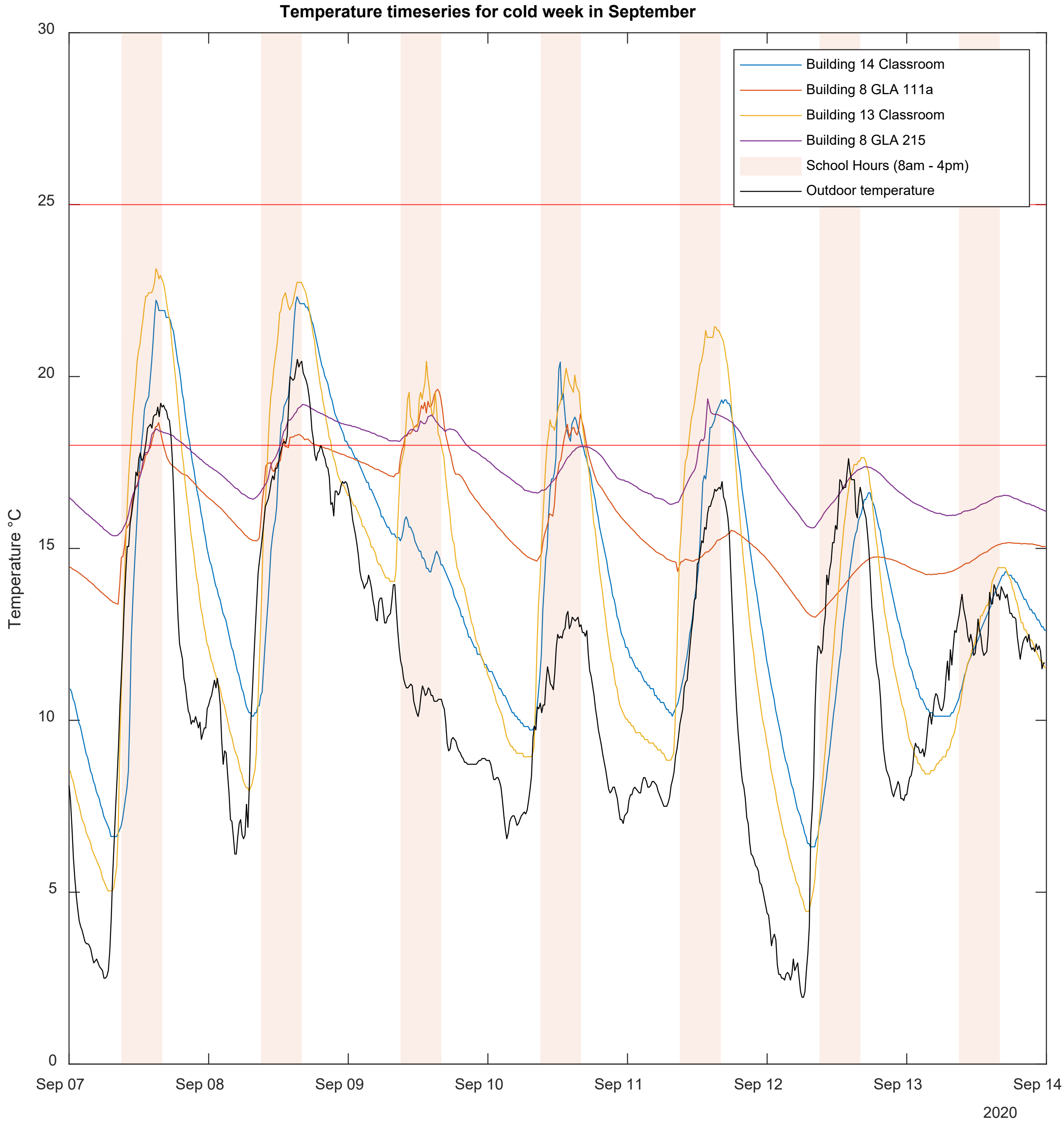


Figure 2-17. Time series temperature plot showing temperatures in the coldest room in each zone during the coldest (non-holiday) week in the sample period.

Comparing the transportable buildings 13 and 14, to the GLA Building 8, the transportable buildings, with their typically very poor insulation and lightweight construction, have much greater variation in indoor temperatures, which more closely follow the outdoor temperature, during non-occupied periods at least. In contrast, Building 8 spaces, with the concrete block wall and hydronically-heated concrete slab construction maintain a much more stable temperature, only dropping by around 2 °C overnight, but also being slower to warm up when the heating is turned on, typically not reaching the lower temperature band minimum threshold until the middle of the school day. It is suggested that the in-slab heating system is set to start pre-heating the building from much earlier in the morning and perhaps then turning it off earlier also, since the slab will hold room temperature reasonably well.

It is noted that most of the rooms in the school have been designed with good solar passive access for winter sun. However, comparing the two coldest rooms in Building 8, rooms 111a, student services reception, and room 215, a level 2 seminar room, these are both south-facing, but room 111a is noticeably colder, unless being heated. Room 111 is on the ground floor with no passive solar heat gains, whereas room 215 is on level 2 with solar access through clerestory windows above the central hallway and north facing windows from the hall into the classroom. The upstairs rooms will also tend to be warmer with the buoyant warmer air at this level. Room 111a also has split system AC, whereas room 215 relies upon solar passive and in-slab hydronic heating. Note during the coldest day recorded in this analysis (September 9th), when outdoor temperature falls from 14°C before school to 11°C at the close of school, the AC-heated room 111 was able to quickly warm up the room to within the wider comfort band, while room 215 managed to rise gradually by 1°C during the day.

It appears that on September 10th room 215 was unoccupied and the heating was off, whereas on September 11th it appears that room 111a was unoccupied and the heating was off.

Baseline carbon dioxide concentration

Carbon dioxide concentration is often used as a readily measured proxy for indoor air quality and ventilation rates, since it is a useful indicator of the ‘staleness’ of the indoor air due to the balance between ventilation rates and occupancy rates. Increased ventilation rates on a per occupant basis have been associated with reduced respiratory health effects and reduced student absences in schools. Minimum ventilation rate standards for moderate indoor air quality in schools are commonly around 7 L/s per occupant. NSW DoE specifies minimum outdoor air ventilation rates in line with AS1668.2 of 12 L/s per occupant in classrooms serving students up to 16 years of age, and mandates the provision of a CO_2 sensor to monitor and confirm that CO_2 concentration does not exceed 1500 ppm for more than 20 consecutive minutes. Peak carbon dioxide concentrations of 750 ppm and 1000 ppm respectively indicate ventilation rates of approximately 12 L/s and 7 L/s per occupant. Table 2-19 provide carbon dioxide concentration statistics for the selection of Amaroo School rooms monitored. A more granular display of the carbon dioxide data quartiles is given in Figure 2-18, in which it can be seen for example how prevalent the higher carbon dioxide values were in different spaces.

Table 2-20. Summary carbon dioxide concentration prevalence above recommended threshold levels for Amaroo School during school hours.

Device	Mean	Max	Data points over 800 ppm	Data points over 1000 ppm	% of days with max hourly mean CO_2 reading over 800 ppm	% of days with max hourly mean CO_2 reading over 1000 ppm.
Cic_A_B12_Eas	522.1	1165	1.27%	0.04%	21.09%	1.56%
Cic_A_B12_Wes	496.7	1122	0.53%	0.07%	7.03%	2.34%
Cic_A_B13_Cla	635.8	1856	15.88%	4.65%	87.50%	42.19%
Cic_A_B14_Cla	847.4	2976	46.42%	29.42%	92.19%	82.03%
Cic_A_G1W_101	906.3	2742	50.72%	36.94%	96.70%	96.70%
Cic_A_G1W_102	906.8	2993	51.49%	36.64%	94.51%	91.21%
Cic_A_G1W_106	526.3	1661	6.61%	2.11%	60.44%	30.77%
Cic_A_G1W_109	844.6	1975	50.55%	31.82%	94.51%	82.42%
Cic_A_G1W_110	831.1	2659	41.56%	27.88%	90%	78.89%
Cic_A_G2W_201	745.5	2010	35%	20.75%	92.31%	80%
Cic_A_G2W_202	851.6	2355	45.67%	30.61%	95.60%	81.32%
Cic_A_G2W_210	840.3	2569	45.08%	29.65%	94.51%	87.91%
Cic_A_G2W_211	846.4	1934	49.98%	31.35%	95.60%	82.42%

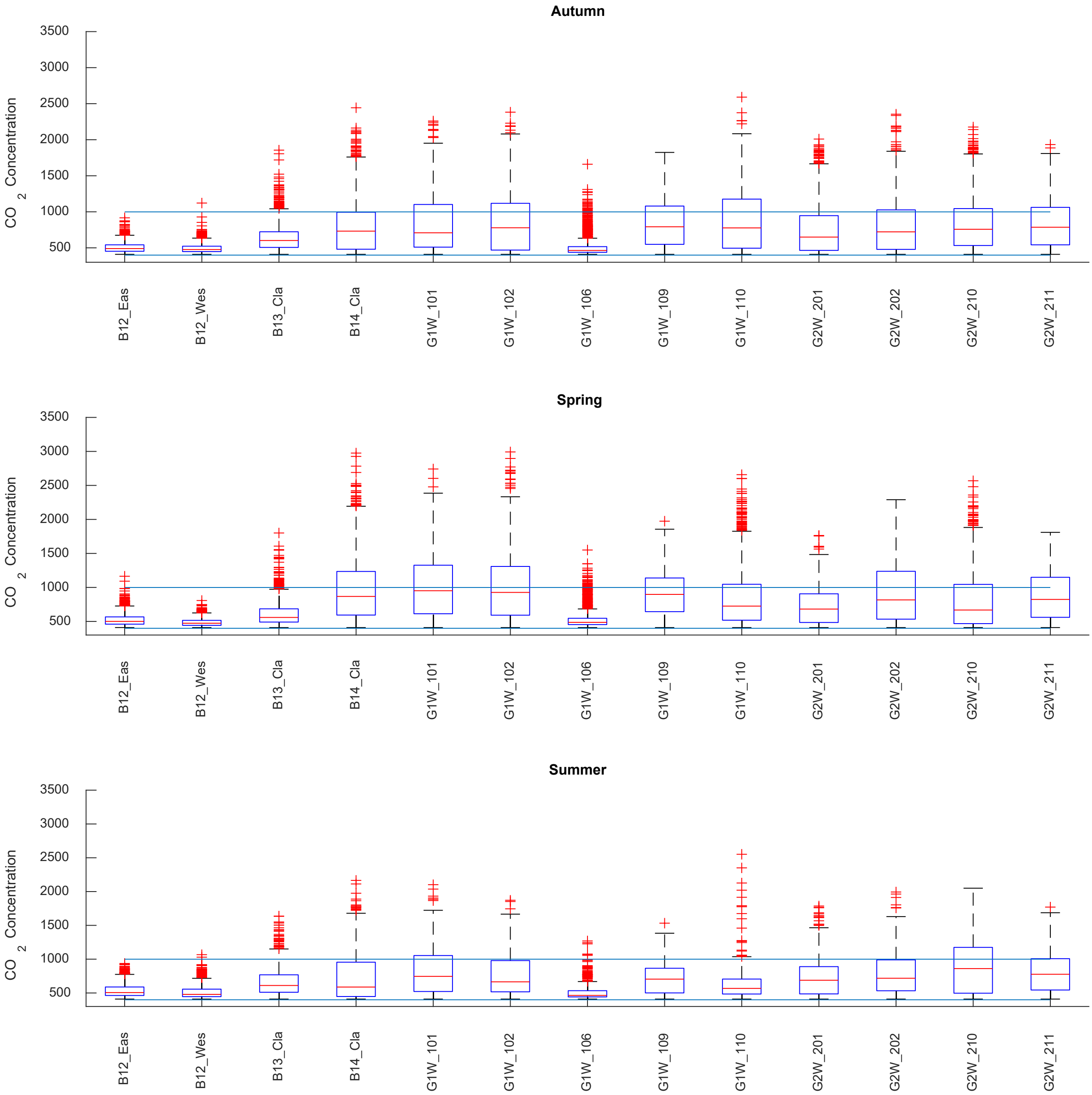


Figure 2-18. Boxplot displaying seasonal carbon dioxide concentration (ppm) variations over monitored period for each monitored room for Amaroo.

The preschool classrooms, B12 and B13, were generally much lower carbon dioxide concentrations compared to other classrooms. These classroom doors were frequently observed and widely reported to be generally opened as preschool children access outdoor play areas throughout the day.

Winter data was not available for this report, however it is can be seen that carbon dioxide concentrations tend to decrease in summer. This is likely due to the Canberra summer climate being more generally conducive to natural ventilation during summer days, and on particularly hot days for classrooms with no active cooling, natural ventilation may be used to exhaust internal heat loads.

Time series plots of carbon dioxide concentrations sampled from periods of higher concentrations are presented in Figure 2-19 and Figure 2-20. Carbon dioxide concentrations are clearly shown to rise rapidly at the start of the school day. The rates of decay at the end of the day varies substantially, which is likely linked with the air tightness and natural ventilation conditions of each space. Carbon dioxide concentrations appear to be higher in the afternoon, which coincides with highest indoor temperatures in the classrooms. This suggests an opportunity to improve ventilation without reducing thermal comfort.

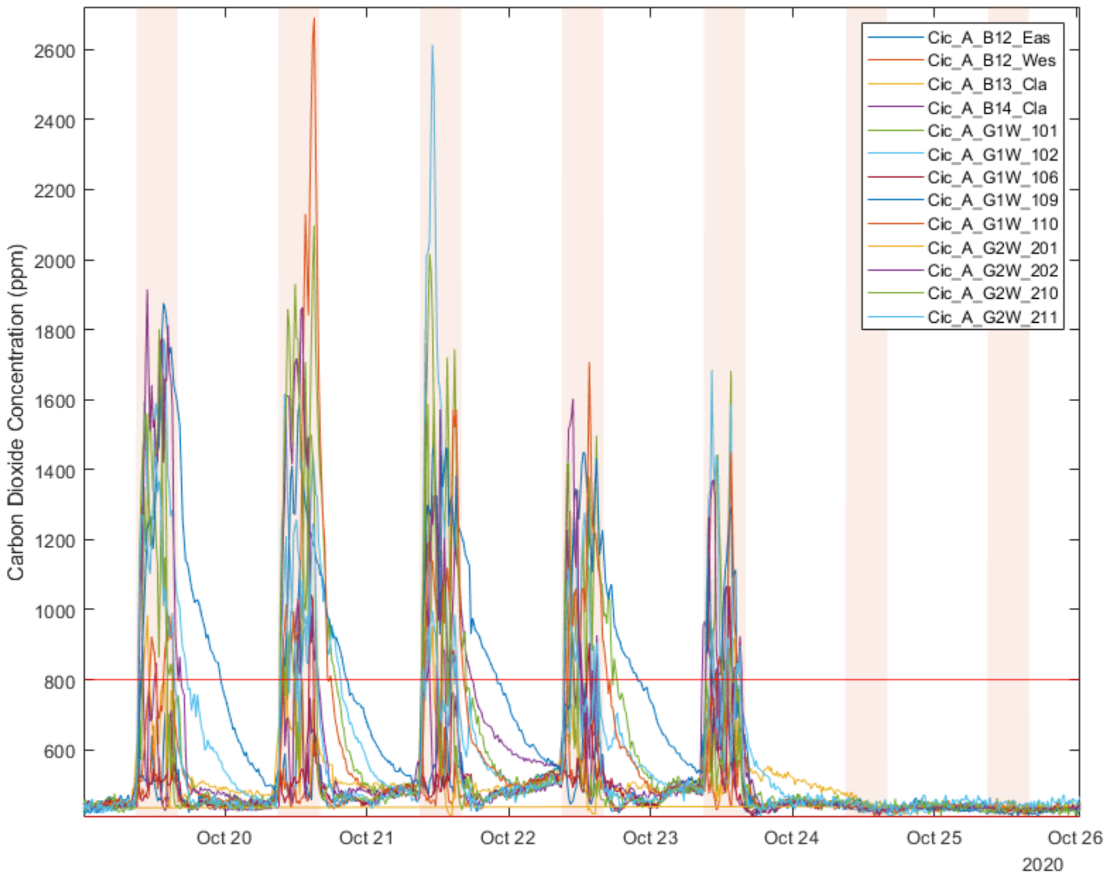


Figure 2-19. Time series plot showing carbon dioxide concentration for a week in which higher readings were recorded.

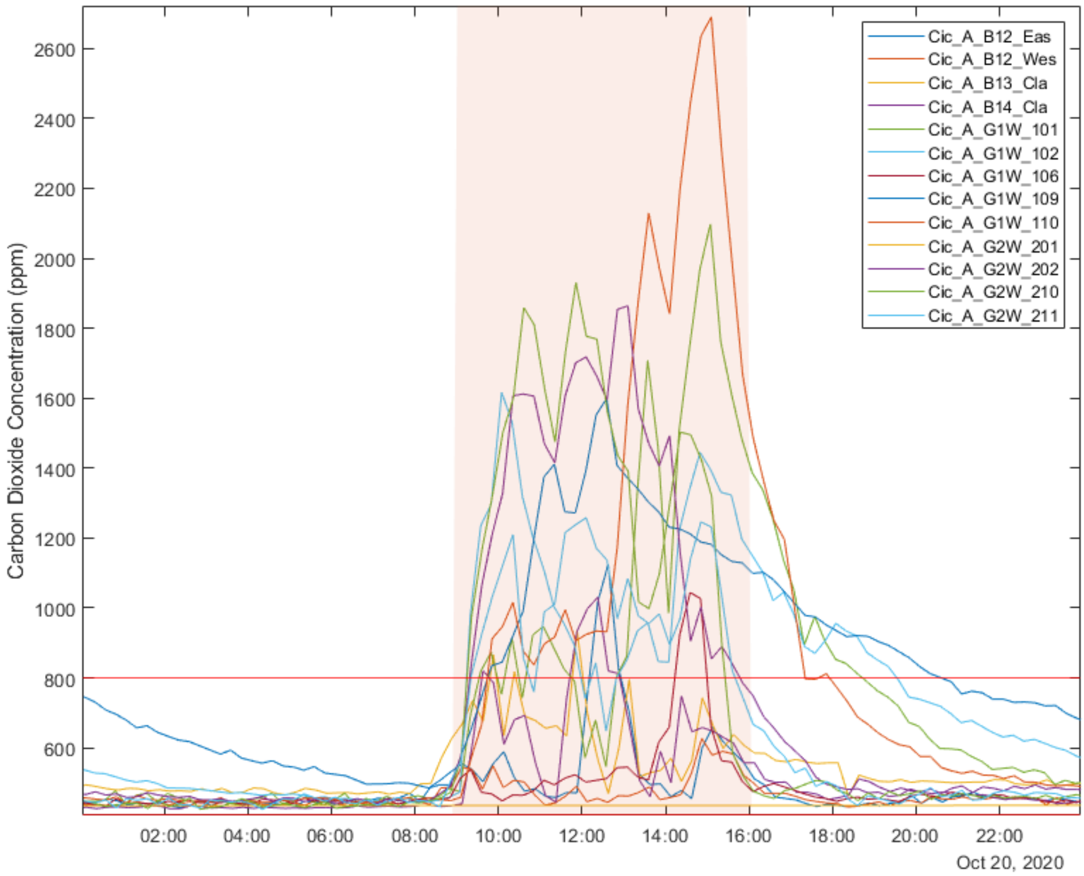


Figure 2-20. Time series plot showing carbon dioxide concentration for a single day in which a high reading was recorded.

3 VENUE 2 – FADDEN PRIMARY SCHOOL

3.1 Monitoring details

The schematics and lists, as presented in the figures in this section comprise the primary documentation for the real time monitoring system, with some supplementary explanatory notes included below.

3.1.1 Site energy utility metering

The locations of the energy utility meters for the site are indicated in Figure 3-1.

The smart electricity utility meter is located in the Main Switch Board in the Administration block. The total site consumption and solar PV system are gross metered at 15-minute interval with data remotely accessed from the ACT Education Envizi dashboard.

The gas utility meter is located in an enclosure on the site boundary northeast of the hall. This utility gas meter is fitted with pulse outputs. An obsolete 2G logger was removed and replaced with a project-specific Nube iO MicroEdge data logger, using the existing intrinsically safe cabling. This provides 15-minute gas consumption data.

3.1.2 Measurement Boundaries

The measurement boundary of the living laboratory for Fadden Primary School encompasses the whole primary school, as depicted in Figure 3-1. The separately metered and distinct preschool on an adjacent site is excluded. This site boundary was selected due to the central boiler serving the whole site and the monitoring budget allowed for this clear and comprehensive scope.

The measurement boundary for this whole site may be further sub-divided, to facilitate a range of potential technology upgrade evaluations, and may be usefully considered as five levels of monitoring, with reference to Table 3-1.

3.1.2.1 Site monitoring

Site monitoring is an essential requirement in order to evaluate the impact of HVAC technology upgrades upon the renewable generation at the site level. Site monitoring will also be useful in this living laboratory to directly evaluate any technology upgrade to the central gas boiler system. Site metering and monitoring layout is provided in Figure 3-3. Gross energy consumption (electricity and gas) and generation are measured at the utility meters, and external weather conditions are measured on site.

3.1.2.2 Building monitoring

Building monitoring layouts are provided in Figure 3-3 through Figure 3-9.

Where ad hoc combinations of hydronic heating, supplementary air conditioning units, evaporative cooling units and wall mounted electric heaters are installed within a building, with minimal central monitoring or control, the interactions between the various HVAC systems will be unavoidable.

This requires that the measurement boundary for potential technology upgrades of such HVAC equipment must be at least as broad as the building level.

Hydronic heating load is directly measured at Murramarang and Daintree learning pods to allow building-level technology evaluations for these buildings. This is achieved by measuring the hydronic water supply and return temperatures as well as the water flow through each air handler unit. The AHUs are located in mezzanine plant rooms, and the hydronic sub-system sensor units are installed in these plant rooms.

Electricity sensors are typically installed in the electrical switchboards, distribution boards and mechanical services switch boards. There is generally one electrical distribution board per building as well as the separate mechanical services switchboards.

3.1.2.3 HVAC appliance monitoring

Separately monitoring the energy input to each HVAC appliance is essential in order to evaluate the impact of an upgrade on any single HVAC unit, and in order to aggregate the total HVAC energy load for the site.

Heating gas consumption for the site-wide boiler is monitored at the utility gas meter. This is reportedly the sole use of gas on the site.

All electrical HVAC loads are individually monitored wherever it is practical to do so, including water pumps, AHU fans, supplementary AC units, evaporative cooling units, wall mounted electric heaters and exhaust ventilation fans, as listed in Table 3.1. These individual loads may then be aggregated to a room-level, building-level or site-level as required.

3.1.2.4 Room monitoring

Room monitoring layouts are provided in Figure 3-4 through Figure 3-9.

Indoor temperature and humidity are monitored for most conditioned spaces for this living laboratory. This is to ensure that indoor temperature service quality remains comparable between the reporting and baseline period, and that any differences in service quality may be compensated for in the mode.

IEQ sensors are located at a height of nominally 1.1m above floor level in a location that does not receive direct sunlight at any time of the day in any season, not immediately adjacent to any glazing or heating/cooling outlets, preferably not on an external wall.

Similar to the building-level monitoring, some HVAC systems service individual rooms; for example: supplementary AC units, evaporative cooling units and wall-mounted heaters. Where these are the only HVAC service for a room (that is, there is no hydronic heating service), then HVAC upgrades may be evaluated at a room-level.

3.1.2.1 Case study opportunities

The Murramarang and Daintree matched pair of learning pods have been fitted with some additional detail and quantity of IEQ monitoring to provide opportunities for a closer comparison of technologies if required. Hydronic heating energy is measured for each of these buildings; every room has an IEQ sensor installed and a door opening sensor is fitted to the main rear door of each classroom to indicate natural ventilation status. Compare the standard monitoring configuration of Figure 3-7 to the more detailed learning pod monitoring shown in Figure 3-8.

3.1.3 Monitoring equipment details

The monitoring system design provides for remote automated access for regular (typically daily) updates of data from each sensor. An indicative sensor network diagram with physical device photos is presented in Figure 2-3. Table 2.1 provides more specific technical details for each device with reference back to the monitoring equipment layout legend symbols.

A detailed list of each monitored parameter for this site is provided in Table 3-1. This list is generated from the HVAC equipment asset register, as well as the REETSEF parameter list.

Further details of each monitoring device are included below.

3.1.3.1 Electricity consumption

Wattwatchers Auditor-6M metering-grade electrical energy monitoring devices were installed to measure real power, power factor, and cumulative energy consumption logged at 5-minute intervals. Each device has six channels, which may be configured variously to monitor:

- 3 phase gross consumption + 3 phase gross PV generation
- 3 phase load + 3 off single phase loads in a switchboard
- 6 off single phase loads

These Auditor 6M devices have 3G SIM cards installed with a monthly subscription fee for this service per device.

3.1.3.2 Gas consumption

Site gas consumption is measured from the ACTEWAGL pulse output meter. A Nube iO MicroEdge pulse input logger connects to the LoRa network

3.1.3.3 Hydronic heating sub-system energy consumption

The Nube iO MicroEdge is used to monitor hydronic heating energy at the air handler units for the more detailed monitoring of Murramarang and Daintree learning pods. The MicroEdge pulse input reads hydronic flow from a water meter with an integrated reed switch pulse output. Two of the universal inputs are configured for laboratory-calibrated thermistors to monitor hydronic water temperature in both the flow and return lines at the air handler units.

3.1.3.4 LoRa IEQ sensor

The IEQ sensors selected for the Fadden living laboratory are the same as selected for Amaroo. Elsys EMS sensors are installed on the classroom doors of each of the Murramarang and Daintree learning pods in order to monitor natural ventilation conditions.

Refer to Section 2.1.3.3 for all other common details with Amaroo School.

3.1.3.5 BMS data

Data from the recently installed Reliable Controls BMS is planned to be utilised in the living laboratory data base.

3.1.3.6 Weather station

The Fadden weather station is installed on the roof of the Namadgi transportable. Refer to Section 2.1.3.5 for all other common details with Amaroo School.

3.1.4 Static data collection

The list of static data parameters required to determine the KPIs are listed in Table 2-3. This static data collection is completed during the initial site audit and is repeated periodically during site visits.

3.1.5 Monitoring equipment layouts and lists

The following pages constitute the package of schematics and tabled lists of monitoring systems, including:

- Device location plans (see Figure 3-1 to Figure 3-9)
- Monitoring parameter list (Table 3.1)

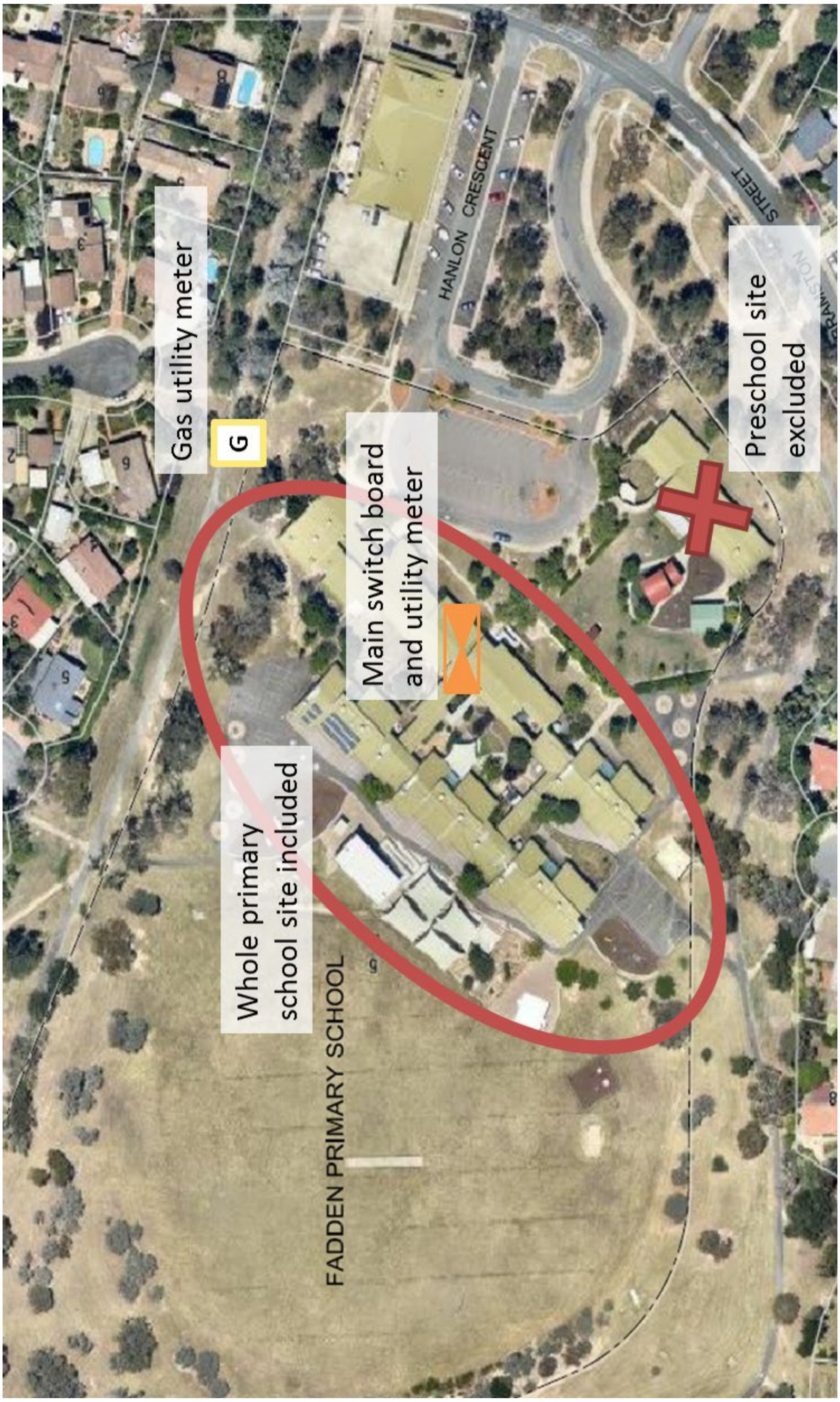


Figure 3-1. Fadden Primary School living laboratory measurement boundary.

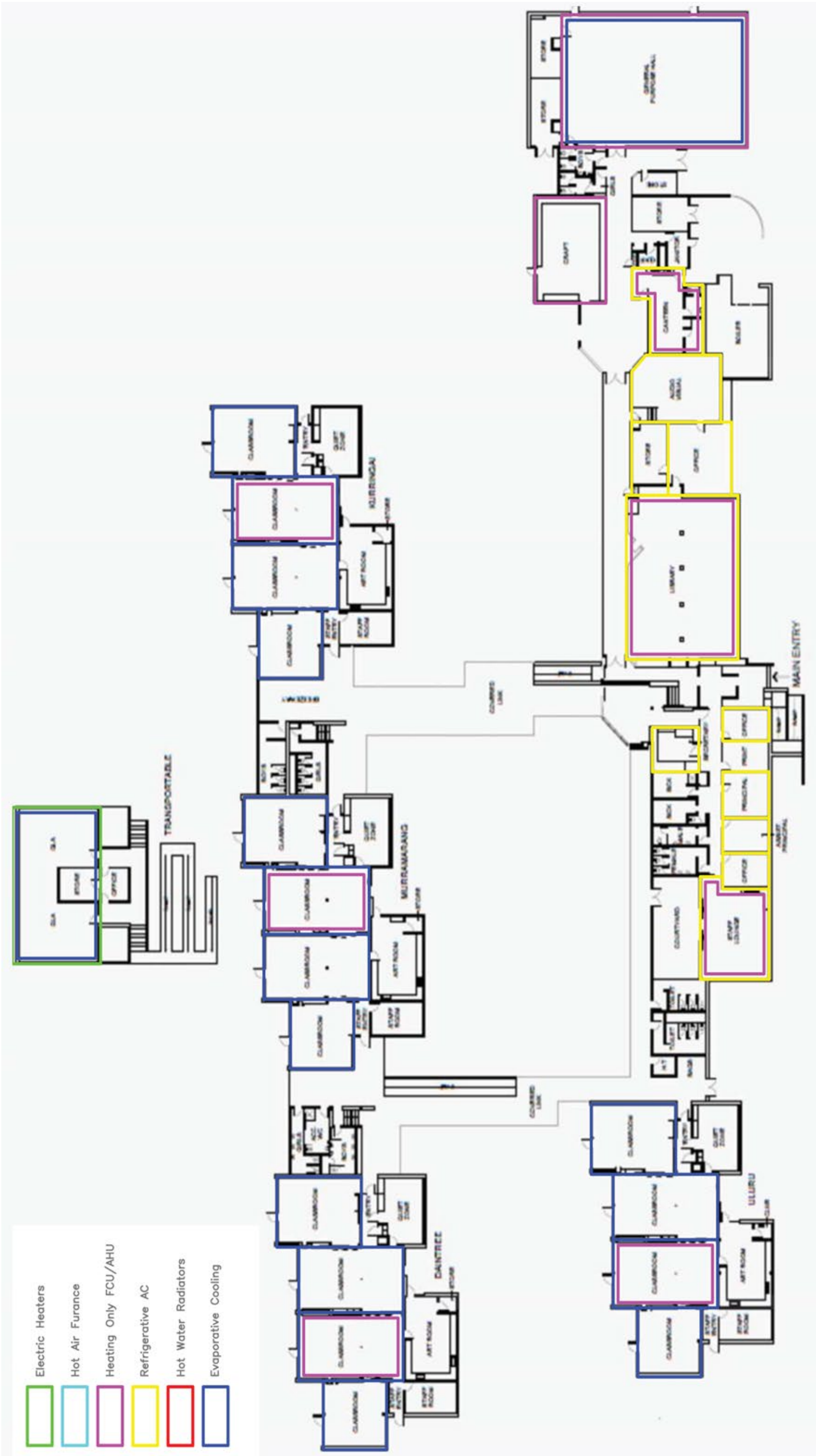


Figure 3-2. Fadden mechanical services zone drawing (ACT Government, 2017).

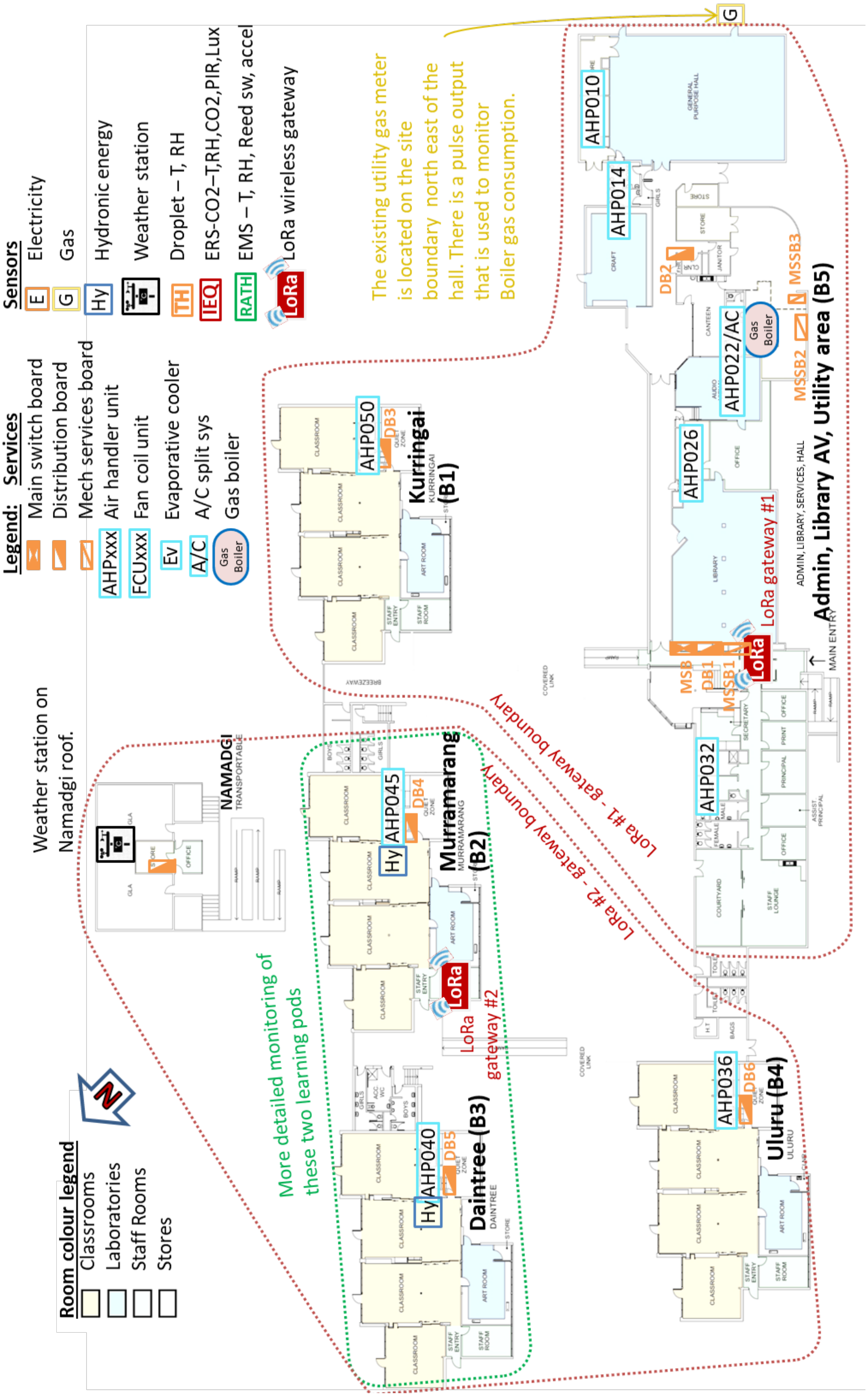


Figure 3-3. Fadden Primary School site metering and monitoring layout.

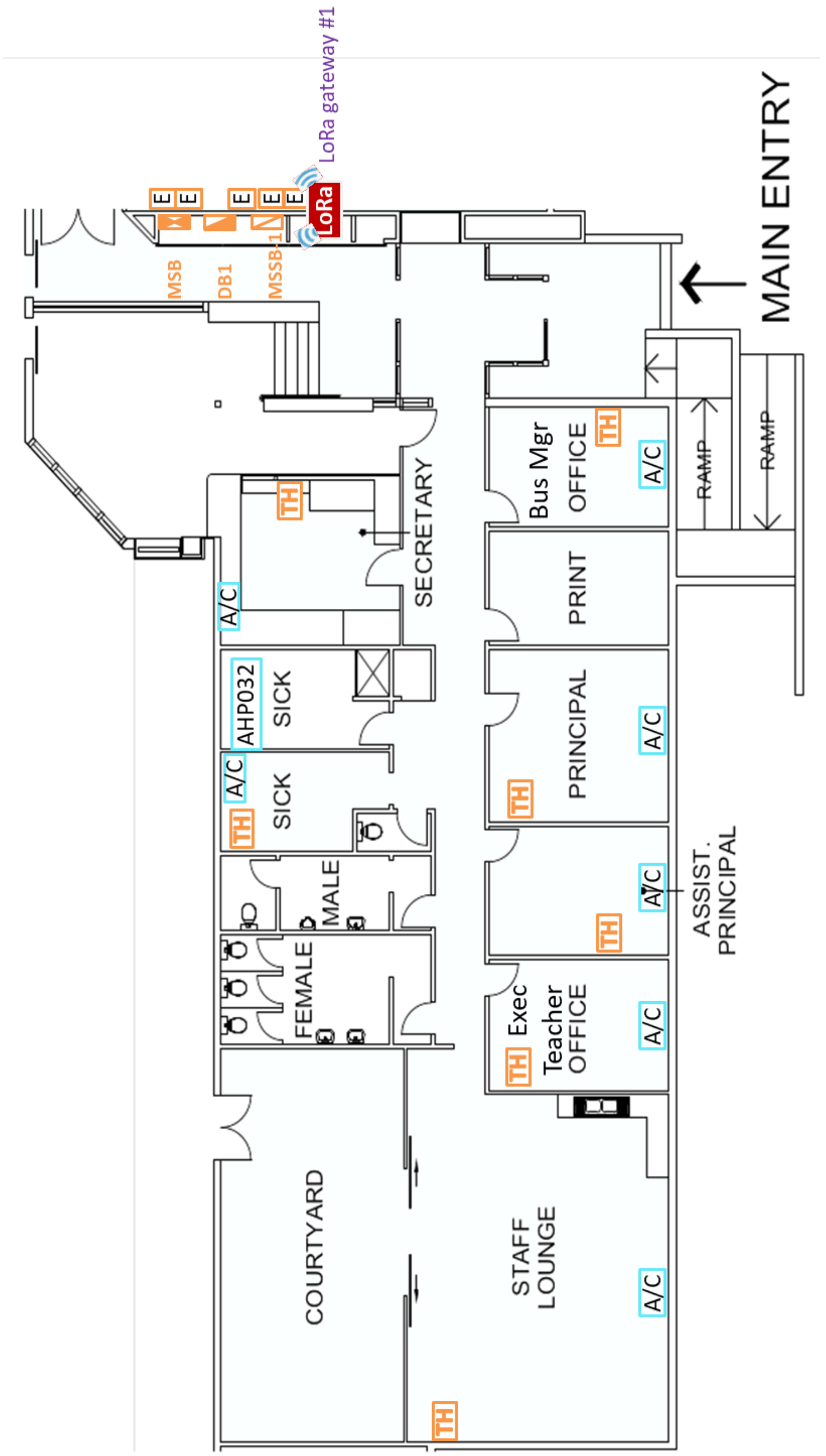


Figure 3-4. Fadden monitoring device layout - administration block (B5).

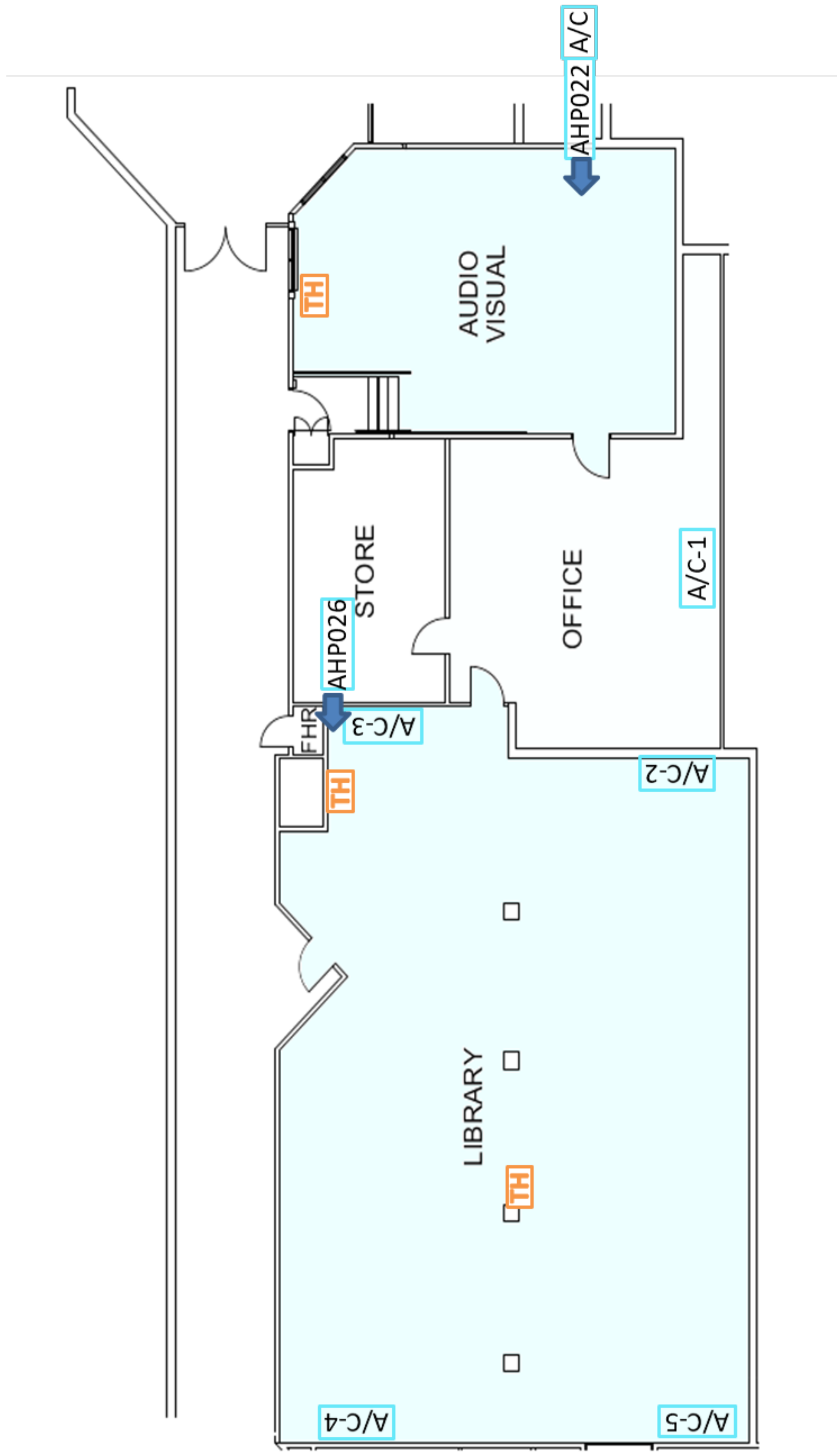


Figure 3-5. Fadden monitoring device layout - library and AV room (B5).

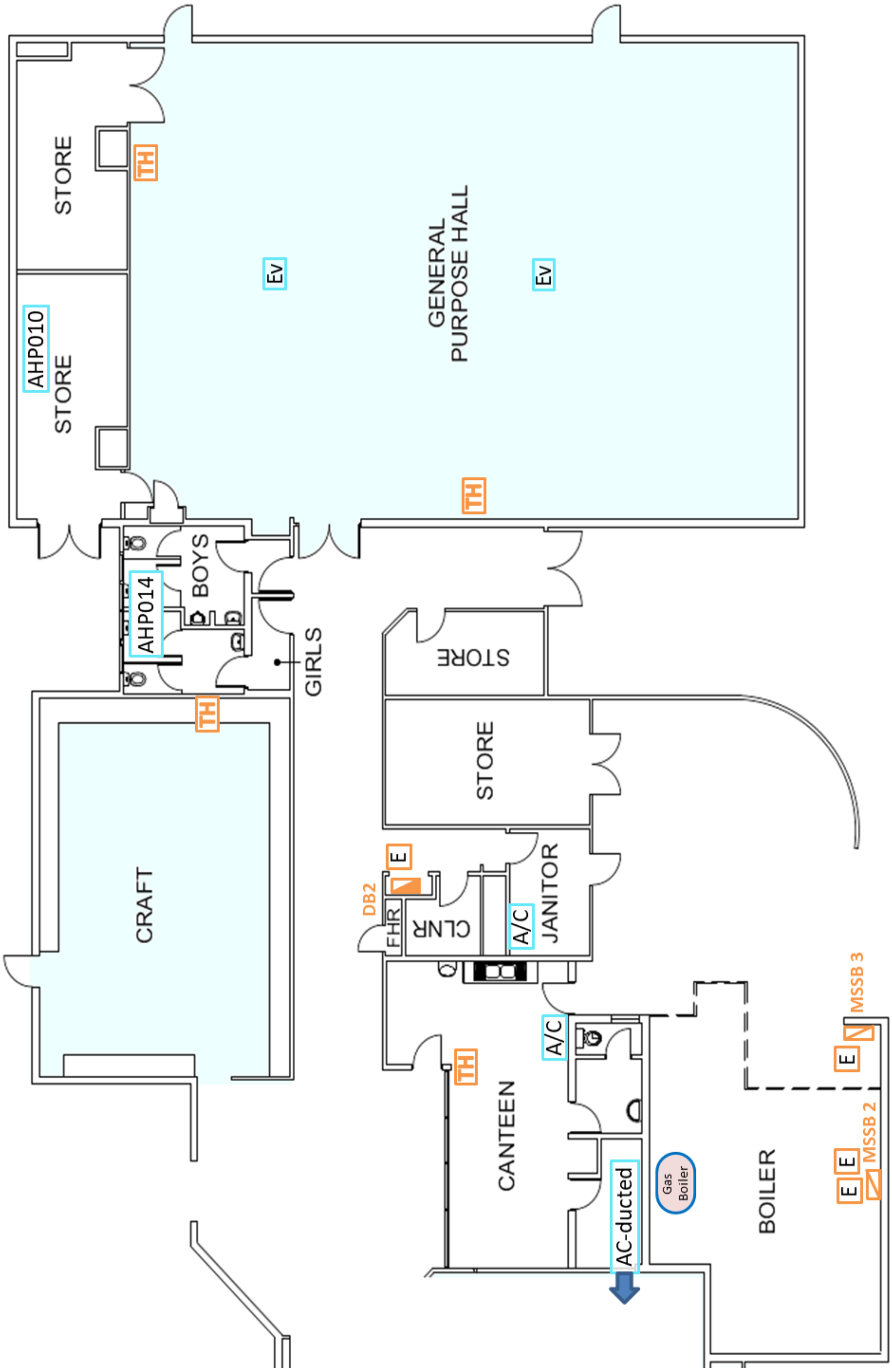


Figure 3-6. Fadden monitoring device layout - hall, craft and services (B5).

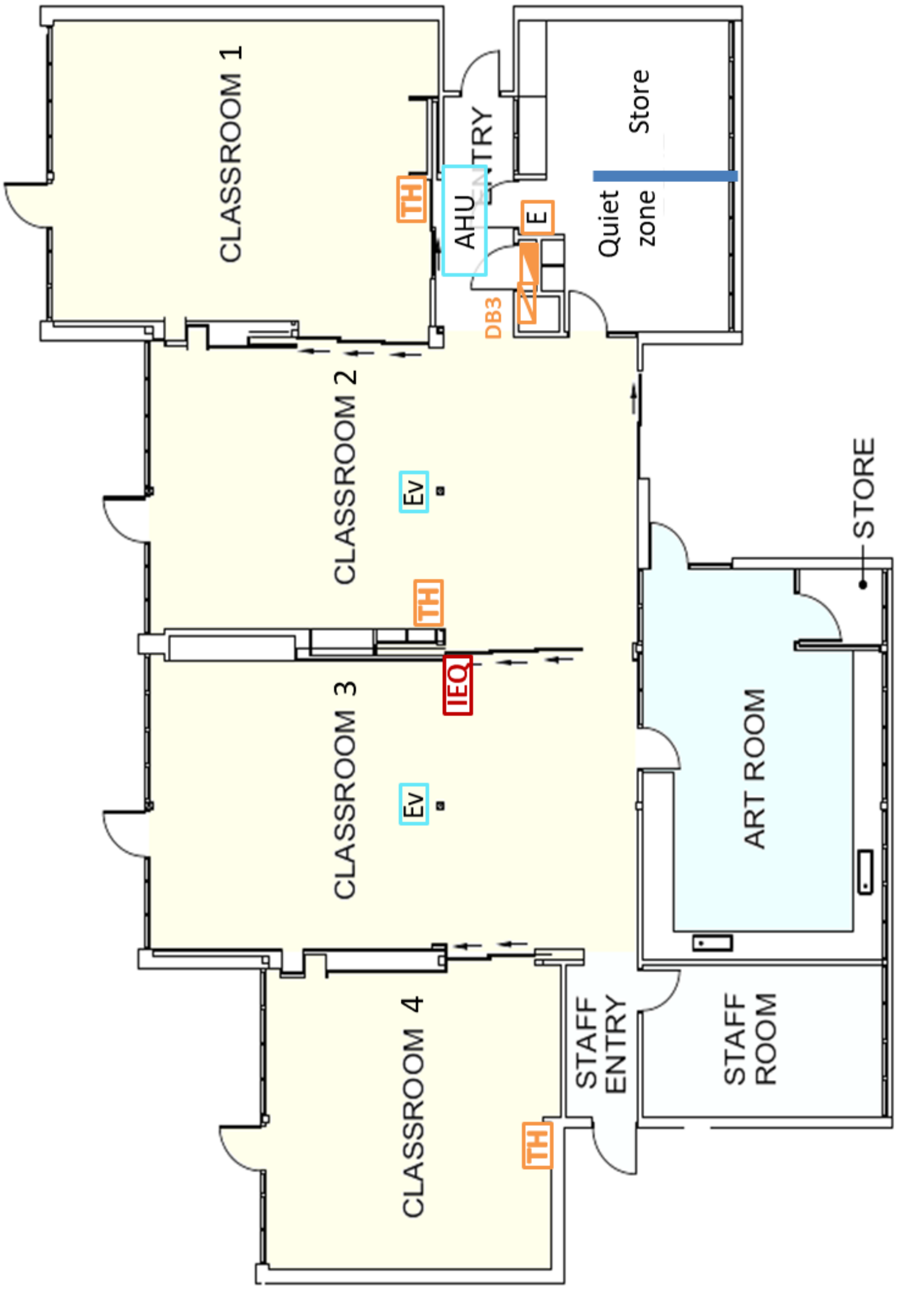


Figure 3-7. Fadden monitoring device layout - learning Pods (Kurringai-B1 and Uluru-B4).

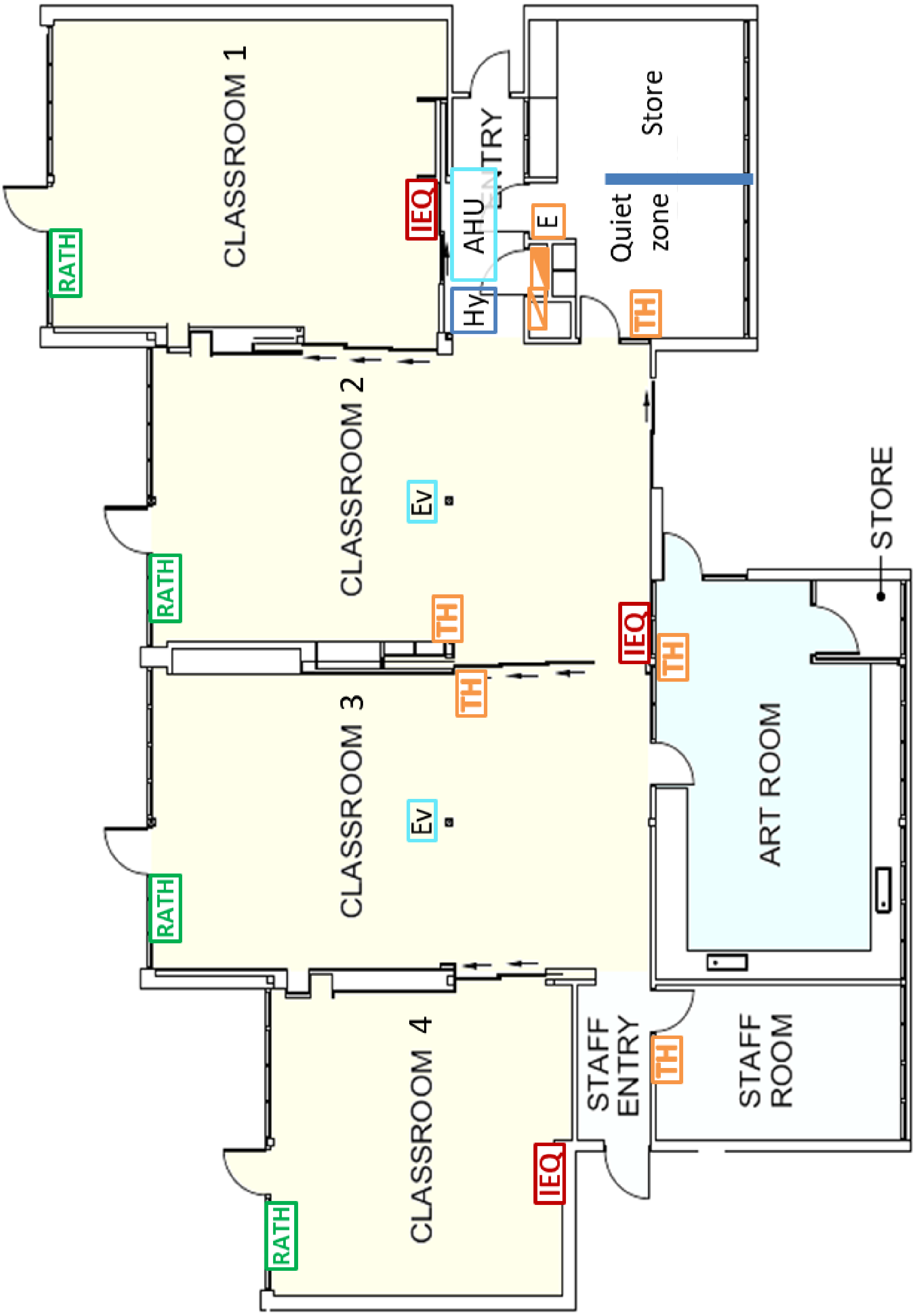


Figure 3-8. Fadden monitoring device layout - learning pods (Murramurang-B2 and Daintree-B3).

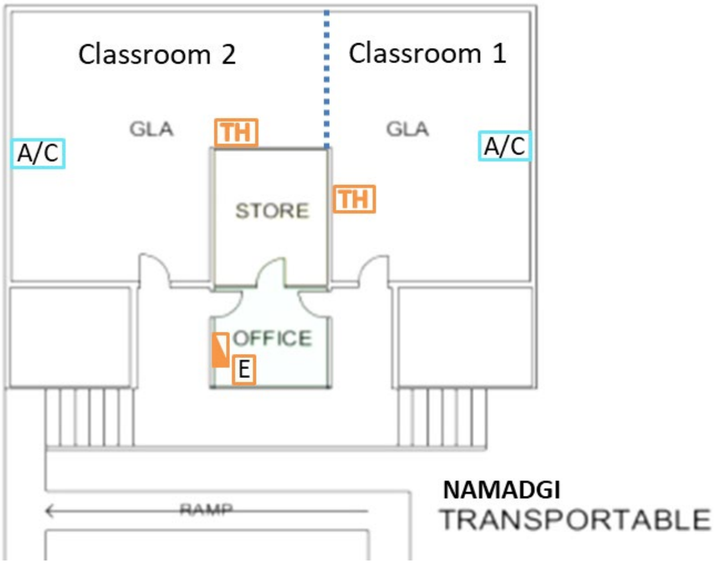


Figure 3-9. Fadden monitoring device layout – Namadgi transportable.

Table 3-1. Fadden monitoring list – by data parameter.

Symbol	Description	Units	Quantity	Location	Sample period and remote/local
	Site monitoring				
$E_{gas\ boiler}$	Gas consumption for site-wide boiler	*MJ*	*1*	Utility meter	15 min LoRa
$E_{elec\ gross}$	Electricity gross site demand	*kWh*	*1*	MSB	15 min smart meter
$E_{PV\ gross}$	PV gross generation	*kWh*	*1*	MSB	15 min smart meter
$E_{PV\ gross}$	PV gross generation	*kWh*	*1*	MSB	15 min LoRa
T_{out}	Temperature outdoors	*°C*	*1*	Weather station	15 min weather WiFi
RH_{out}	Relative humidity outdoors	*%RH*	*1*	Weather station	15 min weather WiFi
GHI	Global Horizontal Irradiance	W/m^2	*1*	Weather station	15 min weather WiFi
V_{wind}	Wind speed	*m/s*	*1*	Weather station	15 min weather WiFi
Dir_{wind}	Wind direction	*Deg*	*1*	Weather station	15 min weather WiFi
Rain	Rainfall	*mm*	*1*	Weather station	15 min weather WiFi
	Building monitoring				
$E_{DB\ 1-6}$	Building-level electricity consumption by distribution board	*kWh*	*7*	DB	5 min 3G
$E_{AC\ A,B}$	AC split system energy (some paired on common circuit)	*kWh*	*17*	DB	5 min 3G
$E_{FAN\ A,B}$	Ventilation fan energy (AHU, SAF, GEF)	*kWh*	*15*	MSSB	5 min 3G
$E_{EvapCool\ A,B}$	Rooftop evaporative cooler fan energy; use spare DB channels	*kWh*	*18*	DB	5 min 3G
$Q_{hyd\ A}$	Hydronic water flow at location ‘A’	*L*	*2*	Plant room	15 min LoRa
$T_{hyd\ in\ A}$	Temperature hydronic water supply for space ‘A’	*°C*	*2*	Plant room	15 min LoRa
$T_{hyd\ in\ A}$	Temperature hydronic water supply for space ‘A’	*°C*	*2*	Plant room	15 min LoRa
	Room-indoor monitoring				
$T_{A,B}$	Temperature indoors for building ‘A’, room ‘B’	*°C*	*40*		15 min LoRa
$RH_{A,B}$	Relative humidity indoors, building ‘A’, room ‘B’	*%RH*	*40*		15 min LoRa
$CO_{2\ A,B}$	Carbon dioxide concentration indoors	*ppm*	*8*		15 min LoRa
$Occ_{A,B}$	Occupancy sensor		*8*		15 min LoRa
Lux	Lighting level	Lux	*8*		15 min LoRa
$F_{open\ A,B}$	Fenestration (window) opening		*8*	B2, B3 rear doors	15 min LoRa

3.2 Baseline living laboratory performance characterisation

3.2.1 Baseline Energy consumption summary

The following section presents a site level summary of energy consumption at Fadden Primary School in the period Jan 2015 – Dec 2019, calculated based on historical meter data assembled in the ACT utility management system.

The main energy end-use for Fadden is Gas to supply heating during the winter months. In total 61% of energy consumption is for Gas, with gas as the largest energy source from May to October. Fadden generates a modest amount of electricity via the 10kWp PV system.

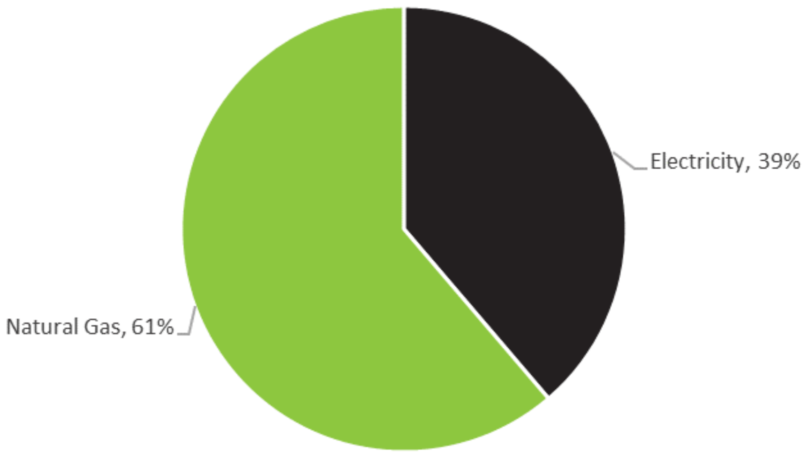


Figure 3-10. Summary of energy sources for Fadden Primary School, 2015 - 2020

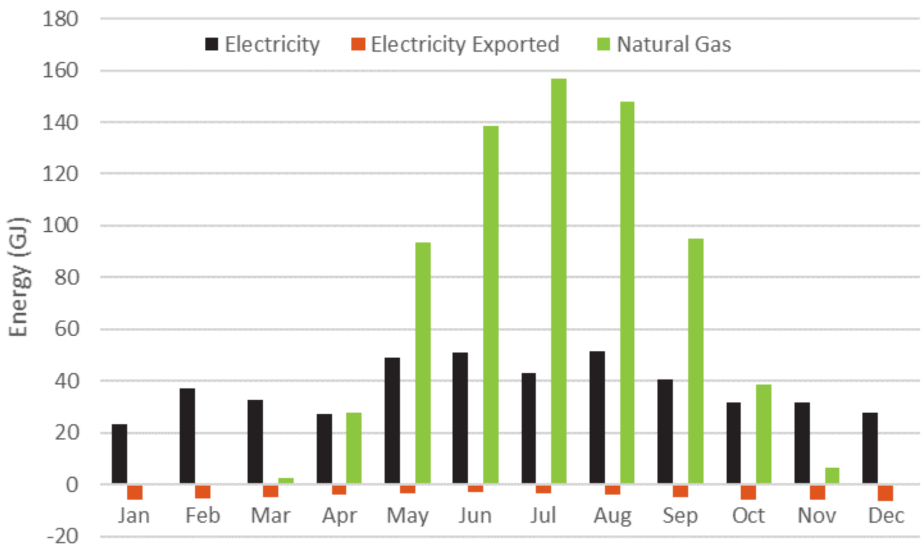


Figure 3-11. Average monthly energy consumption and generation for Fadden Primary School for 2015 – 2020

3.2.2 Baseline REETSEF Data Analysis

The following initial baseline data is drawn from a number of sources. Energy data includes smart meter and utility billing data collected from the ACT government account management tool, as well as short interval data collected through installed Wattwatchers monitoring devices. The internal and external temperature and weather information is from the installed monitoring equipment and Tuggeranong BOM weather station.

REETSEF KPI 1. Avoided GHG emission (tCO_2-e and $).

CO_2-e is the sum of GHG emission for all fuel sources in use at the site, and was calculated as per the National Greenhouse Accounts Factor method for fuel combustion (gas) or scope 2 emissions electricity. The Fadden site uses both gas and electricity: scope 2 emissions from electricity were calculated using the emissions factor of 0.81 kg CO_2-e/kWh; combustion emissions from gas were calculated using the emissions factor of 51.53 kg CO_2-e/GJ.

Baseline CO_2-e emissions have been calculated using historic billing data, available for full years 2016, 2017, 208 and 2019.

Table 3-2. Fadden KPI 1 – Avoided GHG emission.

Year	2016	2017	2018	2019	Average
GHG emissions (t CO_2-e)	159.91	135.47	120.47	112.17	132.01
GHG emissions intensity (kg CO_2-e/enrolment)	491	437	392	388	429
GHG emissions intensity (kg CO_2-e/m^2)	48.71	41.26	36.70	34.17	40.21
Social cost of GHG emissions[5]	$7,779.77	$6,590.71	$5,860.97	$5,457.04	$6,422.12

REETSEF KPI 2. Avoided air pollution

The social benefit due to avoided air pollution puts a cost value to air pollution (PM_{10}, NO_x, and SO_2) impacting populations close to power station. The calculation applies a damage benefit to each MWh[6] of energy saved of $13.8/MWh for electricity, and $0.74/MWh for Gas[7].

Baseline cost of air pollution for this site is therefore:

Table 3-3. Fadden KPI 2 – Avoided air pollution.

Year	2016	2017	2018	2019	Average
Electricity consumption (GJ)	514.93	424.24	396.05	369.74	426.24
Gas consumption (GJ)	854.93	776.60	608.61	562.35	700.62
Cost of air pollution	$ 2,149.62	$ 1,785.88	$ 1,643.28	$ 1,532.93	$ 1,777.93

REETSEF KPI 3. Peak 30 minute electricity demand.

Peak demand was calculated as the highest 30 min electricity demand. Peak demand will be reported monthly and annually (i.e. highest 30 min consumption per month and year.

[5] Conversion from emission (tCO_2-e) to societal benefit ($) uses an estimated social cost of carbon of US$35/$tCO_2$ as a conversion factor from http://www.climateinstitute.org.au/verve/_resources/TCI_SocialCostOfCarbon_PolicyBrief_September2014.pdf

[6] https://apo.org.au/sites/default/files/resource-files/2009/03/apo-nid4196-1189331.pdf

[7] https://www.atse.org.au/wp-content/uploads/2019/01/the-hidden-costs-of-electricity.pdf

Table 3-4. Fadden KPI 3 – Peak 30 minute electricity demand (yearly).

Year	Peak 30 minute demand (kWh)	Occurrence
2018	31.2	22/06/2018 9:15 am
2019	29.4	1/08/2019 8:45 am
2020	31.5	6/08/2020 8:45 am

Table 3-5. Fadden KPI 3 – Peak 30 minute electricity demand (monthly).

Month	Maximum monthly peak 2018--2020 (kWh/30 min)	Mean monthly peak 2018-2020 (kWh/30 min)	Minimum monthly peak 2018-2020 (kWh/30 min)	Occurrence of maximum peak demand
January	25.7	21.0	14.6	30/01/2019 14:15
February	25.6	24.5	22.5	25/02/2020 13:45
March	22.3	20.4	19.4	4/03/2019 13:15
April	21.6	19.2	15.1	11/04/2018 14:45
May	28.4	26.8	24.7	24/05/2018 9:15
June	31.2	29.7	28.8	22/06/2018 9:15
July	31.1	30.0	28.3	31/07/2020 8:45
August	31.5	30.0	29.0	6/08/2020 8:45
September	27.0	26.1	24.9	3/09/2018 8:45
October	26.8	22.0	19.5	27/10/2020 8:15
November	24.4	21.5	18.2	21/11/2019 13:45
December	25.5	23.1	21.6	18/12/2019 13:15

REETSEF KPI 4. Peak 30 minute electricity export.

As for KPI 3, peak export was calculated as the highest 30 min electricity export. For this gross metered site, this “export” is really gross electrical generation. Peak export is reported monthly for each full month of the baseline monitoring period in Table 3-6. Historic billing export data for Fadden was only available at a monthly interval, therefore it was impossible to report peak export. However, monthly total export values are provided in Table 3-7.

Table 3-6. Fadden KPI 4 – Peak 30 minute electricity export. Note units of kWh/30 min, rather than max instantaneous power generation (kW)

Month	Peak monthly 30 minute export (kWh/30 min)
October 2020	4.8
November 2020	4.7
December 2020	4.8
January 2021	4.5
February 2021	4.6
March 2021	4.2

Table 3-7. Fadden KPI 4 – historic monthly 30 minute electricity export, based on historic utility data.

Month	Maximum monthly export 2018-2020 (kWh)	Mean monthly export 2018-2020 (kWh)	Minimum monthly export 2018-2020 (kWh)
January	1,796	1,658	1,486
February	1,656	1,438	1,318
March	1,523	1,355	1,067
April	1,242	1,112	848
May	1,028	992	949
June	869	800	684
July	1,047	908	775
August	1,246	1,142	1,063
September	1,520	1,217	418
October	1,713	1,584	1,445
November	1,900	1,671	1,471
December	1,882	1,750	1,654

REETSEF KPI 5. Wholesale cost of peak 30 minute electricity demand.

To determine whether the facility peak demand was co-incident with periods of energy market peak demand, the wholesale cost of peak demand at the time of occurrence was calculated using historic co-incidental wholesale spot prices from AEMO[8].

Table 3-8 Fadden KPI 5 - Wholesale cost of peak 30 minute electricity demand.

Year	Peak 30 minute demand (kWh)	Occurrence	Co-incident wholesale price (c)	Percentile of monthly wholesale cost rank
2018	31.16	22/06/2018 9:15	111.04	82%
2019	29.36	1/08/2019 8:45	80.94	63%
2020*	31.5	6/08/2020 8:45	43.87	61%

REETSEF KPI 6. Total self-consumption rate (0-1).

The self-consumption rate of renewable generation (SC) is the proportion of on-site renewable generation that is consumed on-site by the facility on a metering interval basis. For the 10 kWp metered array at Fadden, the average self-consumption rate for the baseline period was 92.5%. As noted in KPI4, historic interval generation data was not available for Fadden, and therefore this

[8] https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/data-nem/aggregated-data

KPI can only be calculated on a monthly basis for the baseline period. The typical daily consumption profile can be seen in Figure 3-12.

Table 3-9. Fadden KPI 6 – Total self-consumption rate for baseline period.

Month	Self-consumption rate, all periods
October 2020	94%
November 2020	92%
December 2020	90%
January 2021	91%
February 2021	93%
March 2021	96%

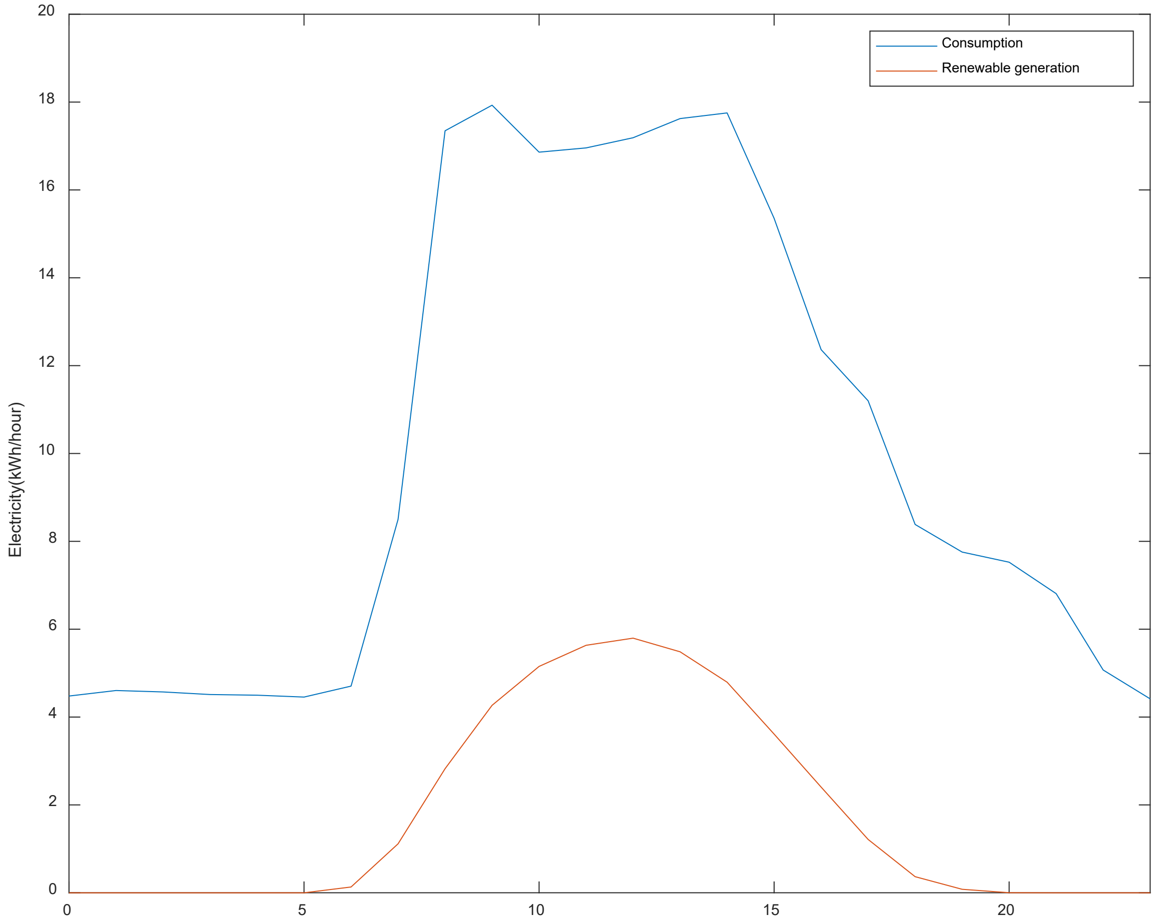


Figure 3-12. Average daily energy consumption profile for Fadden during the baseline monitoring period.

REETSEF KPI 7. HVAC self-consumption rate (0-1).

Considering only the electricity consumed for HVAC operation in the living laboratory section of the facility, the self-consumption rate of renewable energy from the 10 kWp gross metered system for the period from Sept 2020 to 24 April 2021 was 50.4%, i.e. on average 50.4% of energy generated was used onsite by co-incident HVAC operation on a 30 minute interval basis. Monthly HVAC self-consumption rates are provide in Table 3-10.

Table 3-10. Fadden KPI 7 – HVAC self-consumption rate

Month	Self-consumption rate
October 2020	54%
November 2020	51%
December 2020	47%
January 2021	43%
February 2021	57%
March 2021	54%

These modest self-consumption rates for the relatively small 10 kWp PV system are indicative of HVAC services dominated by the site-wide gas-fired boiler for hydronic heating, with the main electrical HVAC load coming from AC split systems mainly in staff areas. The self-consumption value of site renewable generation would be improved by conversion of the boiler to an electrical energy source such as a heat pump. Increasing the size of the PV system would be particularly beneficial in conjunction with such an electrical upgrade to the site HVAC services.

REETSEF KPI 8. Total renewable energy fraction

Renewable Energy Fraction (REF) is the proportion of energy use for a facility ($E_{elec,gross,i}$) that is generated by on-site renewable generation ($E_{PV,gross,i}$), calculated on a 30 minute interval basis. For the monitored period, the overall REF was 21.3%. Monthly renewable energy fractions are provided in Table 3-11.

These low renewable energy fractions are indicative of the relatively small 10 kWp PV system on the site and highlight the opportunity to increase the size of this PV system.

Table 3-11. Fadden KPI 8 – HVAC renewable energy fraction

Month	Renewable energy fraction
October 2020	18%
November 2020	21%
December 2020	27%
January 2021	30%
February 2021	18%
March 2021	14%

REETSEF KPI 9. HVAC renewable energy fraction

Considering only the electricity consumed for HVAC operation in this whole of school site living laboratory, and the gross metered 10kWp PV system, the Renewable Energy Fraction for the period from Sept 2020 to 24 April 2021 was 41.4%, i.e. on average 41.4% of electricity used for HVAC was co-incident with renewable energy generation (on a 30-minute interval basis). Note that any generation beyond consumption is not considered in this KPI. Monthly renewable energy fractions are provided in Table 3-12 and a typical electrical daily profile is shown in Figure 3-13.

Table 3-12. Fadden KPI 8 – HVAC renewable energy fraction

Month	Renewable energy fraction
October 2020	43%
November 2020	48%
December 2020	50%
January 2021	52%
February 2021	45%
March 2021	41%

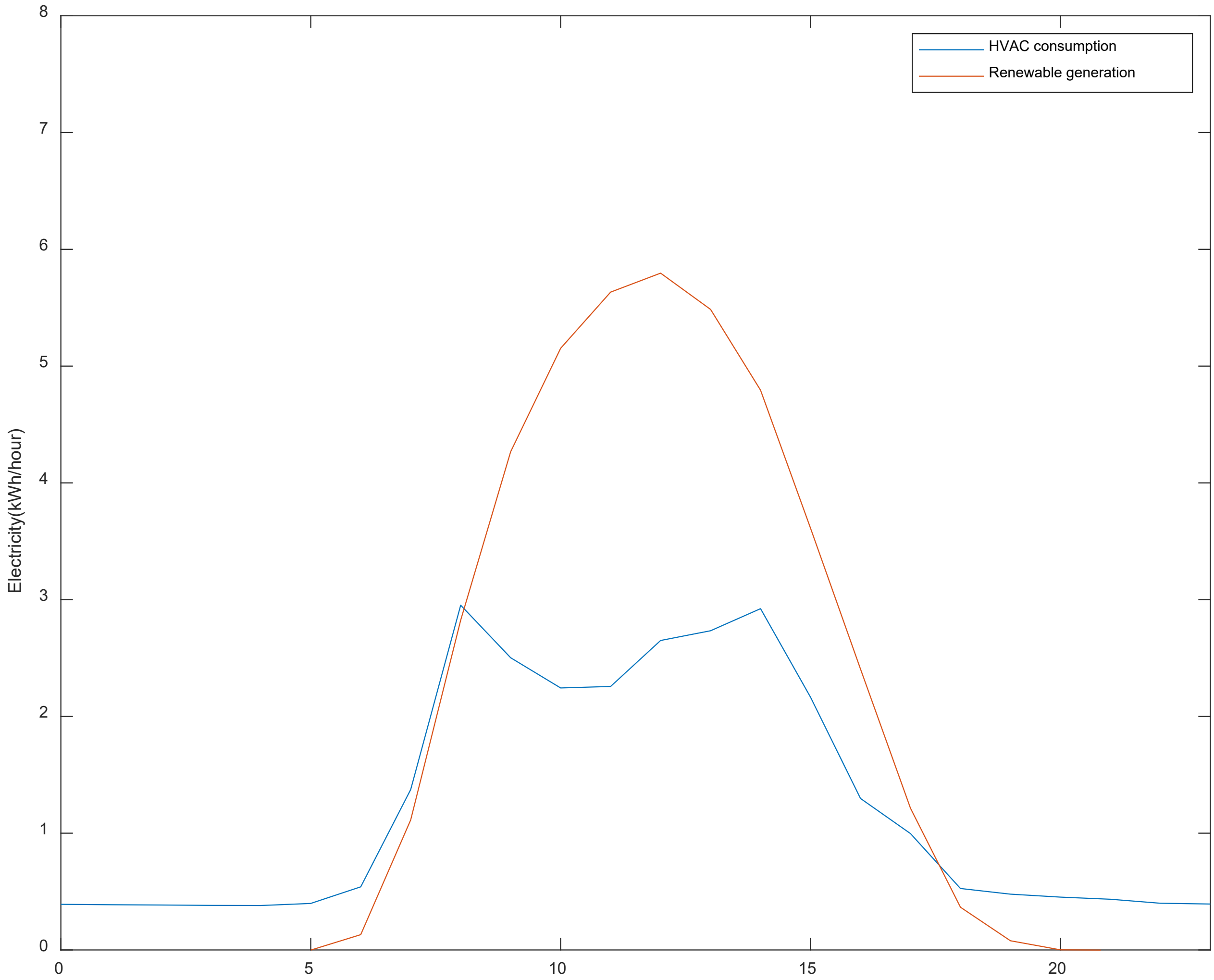


Figure 3-13. Average daily HVAC energy consumption and generation profile for Fadden Primary School.

The time alignment of the site electrical HVAC load to the site PV generation is remarkably well matched. HVAC renewable energy fractions are reasonably high for the site only because the site HVAC is dominated by a gas boiler. As noted above, the value of renewable generation on this site could be greatly increased with the conversion of the main site boiler to an electrical energy source. However, the HVAC renewable energy fraction would dramatically decrease, highlighting the potential to concurrently increase the PV system size.

REETSEF KPI 10. Net Facility Load Factor.

Net Facility Load Factor (NFLF) is the average load divided by the peak load during a specified time period and is a measure of how 'peaky' an energy use profile is. The 3-year NFLF for Fadden was 0.18. The annual and monthly NFLFs are provided in Table 3-13 and Table 3-14 respectively.

Table 3-13. Fadden KPI 10 – Net Facility Load Factor (yearly)

Year	Net Facility Load Factor
2018	0.19
2019	0.20
2020	0.18

Table 3-14. Fadden KPI 10 – Net Facility Load Factor (monthly)

	2018	2019	2020	Average
January	0.25	0.17	0.16	0.19
February	0.26	0.25	0.22	0.24
March	0.26	0.23	0.24	0.24
April	0.20	0.19	0.24	0.21
May	0.26	0.26	0.24	0.25
June	0.27	0.25	0.26	0.26
July	0.24	0.23	0.23	0.24
August	0.30	0.26	0.24	0.27
September	0.26	0.26	0.24	0.25
October	0.25	0.24	0.19	0.23
November	0.31	0.21	0.23	0.25
December	0.21	0.18	0.19	0.19

REETSEF KPI 11. Demand response capacity

There is currently no demand response capacity at Fadden. Since peak demand for this site is on winter mornings and the grid peak demand events are summer afternoons after school hours, the potential to impact grid-level peak demand events with site HVAC demand response control is limited.

REETSEF KPI 12. Energy cost

Energy cost was calculated from historic billing data for each full year for which data was available. The annual energy usage and cost from billing data is shown in Table 3-15 below. Usage is directly from the smart gross consumption meter for the site. Net usage is calculated by subtracting the gross PV generation.

Table 3-15. Fadden KPI 12 – Energy cost.

		2016	2017	2018	2019	2020
Electricity Import	Usage (kWh)	143,036.00	117,964.20	110,036.92	102,625.00	99,971.00
	Cost ($/kWh)	$18,615.00	$16,551.43	$15,696.36	$24,294.00	$21,600.26
	Unit cost	$0.13	$0.14	$0.14	$0.24	$0.22
Electricity Export	Usage (kWh)	-14,190.00	-16,154.48	-15,757.90	-16,037.84	-13,190.80
	Cost ($/kWh)	-$7,133.31	-$8,120.86	-$7,921.52	-$8,062.22	-$6,631.00
	Unit cost	$0.50	$0.50	$0.50	$0.50	$0.50
Natural Gas	Usage (MJ)	854,932.00	776,604.00	608,611.00	562,345.00	568,749.00
	Cost	$18,875.82	$20,883.24	$15,626.60	$14,990.99	$15,232.32
	Unit cost ($/MJ)	$0.02	$0.03	$0.03	$0.03	$0.03
Total Net Energy	Usage (MJ)	1,318,777.60	1,143,119.02	948,015.47	874,058.78	881,157.72
	Cost	$30,357.51	$29,313.81	$23,401.44	$31,222.77	$30,201.58
	Unit cost ($/MJ)	$0.02	$0.03	$0.02	$0.04	$0.03

REETSEF KPI 13. Energy Use Intensity / Productivity

Energy use intensity is a measure of how much energy is used in a facility normalised for comparison with relative benchmarks. Current school sector EUI KPIs are typically based on kWh/m^2 or alternatively kWh/enrolment.

Table 3-16. Fadden KPI 13 – Energy use intensity / productivity

Year	**2016**	**2017**	**2018**	**2019**	**Average**
Electricity consumption (GJ)	514.93	424.24	396.05	369.74	426.24
Gas consumption (GJ)	854.93	776.60	608.61	562.35	700.62
Total Energy Consumption (GJ)	1,369.86	1,200.84	1,004.66	932.09	1,126.86
Electricity intensity (GJ/m2)	0.16	0.13	0.12	0.11	0.13
Gas intensity (GJ/m^2)	0.26	0.24	0.19	0.17	0.21
Total energy intensity (GJ/m^2)	0.42	0.37	0.31	0.28	0.34
Electricity intensity (GJ/enrolment)	1.78	1.47	1.37	1.28	1.47
Gas intensity (GJ/enrolment)	2.96	2.69	2.11	1.95	2.42
Total energy intensity (GJ/enrolment)	4.74	4.16	3.48	3.23	3.90

3.2.3 Baseline IEQ

Baseline temperature

For the current report, temperature data has been collected for the period from 28 August 2020 to 13 April 2021. Summary statistics, and a range of visualisation of the monitored temperature data are provided below. The data shown is only for school hours (defined as 8am – 4pm) and holiday, weekend and after-hours data have been excluded. It is important to note that the baseline sample period does not include any winter data. As such, further analysis is provided of the short period of cold weather data to estimate the building performance during the colder periods. See Section 2.2.3 for further information on the selection of the temperature thresholds.

Table 3-17. Summary temperature statistics for Fadden primary school (8am -4pm school days only from 8 August 2020 to 13 April 2021).[9]

Room ID	Mean temp (°C)	Min temp (°C)	Max temp (°C)	%<18°C	%<21°C	%>24°C	%>25°C	21< % <24°C	18 < % < 25°C
Admin Sec	21.9	17.1	26.1	1%	30%	8%	1%	62%	99%
Admin Pri	22	17.2	26.1	0%	35%	15%	5%	50%	95%
Admin Lib	20.8	15.2	24.8	6%	54%	3%	0%	43%	94%
Admin Sic	21.3	16	24.4	6%	40%	3%	0%	57%	94%
Admin Lib	21	14.9	25.7	7%	50%	7%	2%	43%	92%
Admin Sta	22.1	16.9	28.3	1%	38%	25%	10%	37%	89%
Admin Dep	22.8	17.3	26.8	0%	17%	30%	12%	53%	88%
Admin Bus	21.2	13.2	26.5	11%	42%	10%	3%	47%	86%
Admin Cra	20.4	14.9	25	16%	53%	2%	0%	46%	84%
Admin Aud	20.6	14.7	25.1	17%	50%	2%	0%	48%	83%
Admin Exe	23.2	17.7	28.2	0%	11%	31%	17%	58%	83%
Admin Can	20.1	14.8	25.1	20%	59%	1%	0%	40%	80%
Admin Hal	20.1	16.4	25.1	23%	60%	2%	0%	38%	77%
Daintree C02	21.5	16.7	25	1%	38%	3%	0%	58%	99%
Daintree C02	21.5	17.2	25.5	1%	41%	7%	1%	53%	98%
Daintree C03	21.4	17	24.9	2%	42%	5%	0%	53%	98%
Daintree C01	21.9	17.1	25.9	1%	28%	11%	2%	61%	97%
Daintree C04	21.7	16.6	25.6	2%	33%	8%	1%	59%	97%
Daintree Art	20.9	16.5	25.4	6%	53%	6%	1%	42%	94%
Daintree Sta	20.6	16	24.7	9%	56%	1%	0%	43%	91%
Daintree Qui	19.6	14.5	23.8	22%	78%	0%	0%	22%	78%
Kurringai C01	21.6	16.5	26.6	2%	35%	6%	2%	60%	97%
Kurringai C03	21.4	15.9	24.8	3%	40%	5%	0%	54%	97%
Kurringai C04	21.4	16.6	26.6	2%	45%	7%	2%	48%	96%
Kurringai C02	21.1	16.1	26.4	4%	47%	4%	1%	49%	95%
Murramarang C01	21.7	17.2	30.6	2%	34%	8%	2%	58%	96%
Murramarang C02	21	15.6	27.7	5%	48%	6%	1%	46%	94%
Murramarang C04	20.8	15.5	26.8	6%	53%	3%	1%	43%	93%
Murramarang C02	20.9	14.2	28	7%	52%	6%	1%	43%	91%
Murramarang C03	20.9	14.4	27.7	8%	51%	4%	1%	46%	91%
Murramarang Sta	20.3	12.7	27.1	16%	61%	4%	1%	35%	83%
Murramarang Art	20.2	12.9	27.2	18%	61%	4%	1%	35%	81%
Murramarang Qui	20	12.8	26.4	22%	64%	3%	1%	33%	77%
Namadgi C02	20.5	11.6	27	13%	57%	5%	1%	38%	85%
Namadgi C01	20.4	10.6	26.2	17%	52%	4%	1%	43%	82%
Uluru C02	21.3	17.4	27	1%	47%	5%	1%	48%	98%
Uluru C03	21.5	17.7	25.6	1%	37%	6%	1%	57%	98%

[9] Note: An error was identified in the data analysis process used for the interim baseline report, whereby the data reported in the summary temperature statistics included data for all hours. This, combined with the short and cold sample period available for the interim baseline reports, explains the notably different results, in particular for hours below 18 °C.

Uluru C01	20.8	16.5	28	3%	58%	4%	1%	39%	97%
Uluru C04	21.2	17.3	26.2	1%	50%	7%	2%	44%	97%
Mean	**21.1**	**15.6**	**26.3**	**7%**	**46%**	**7%**	**2%**	**47%**	**91%**

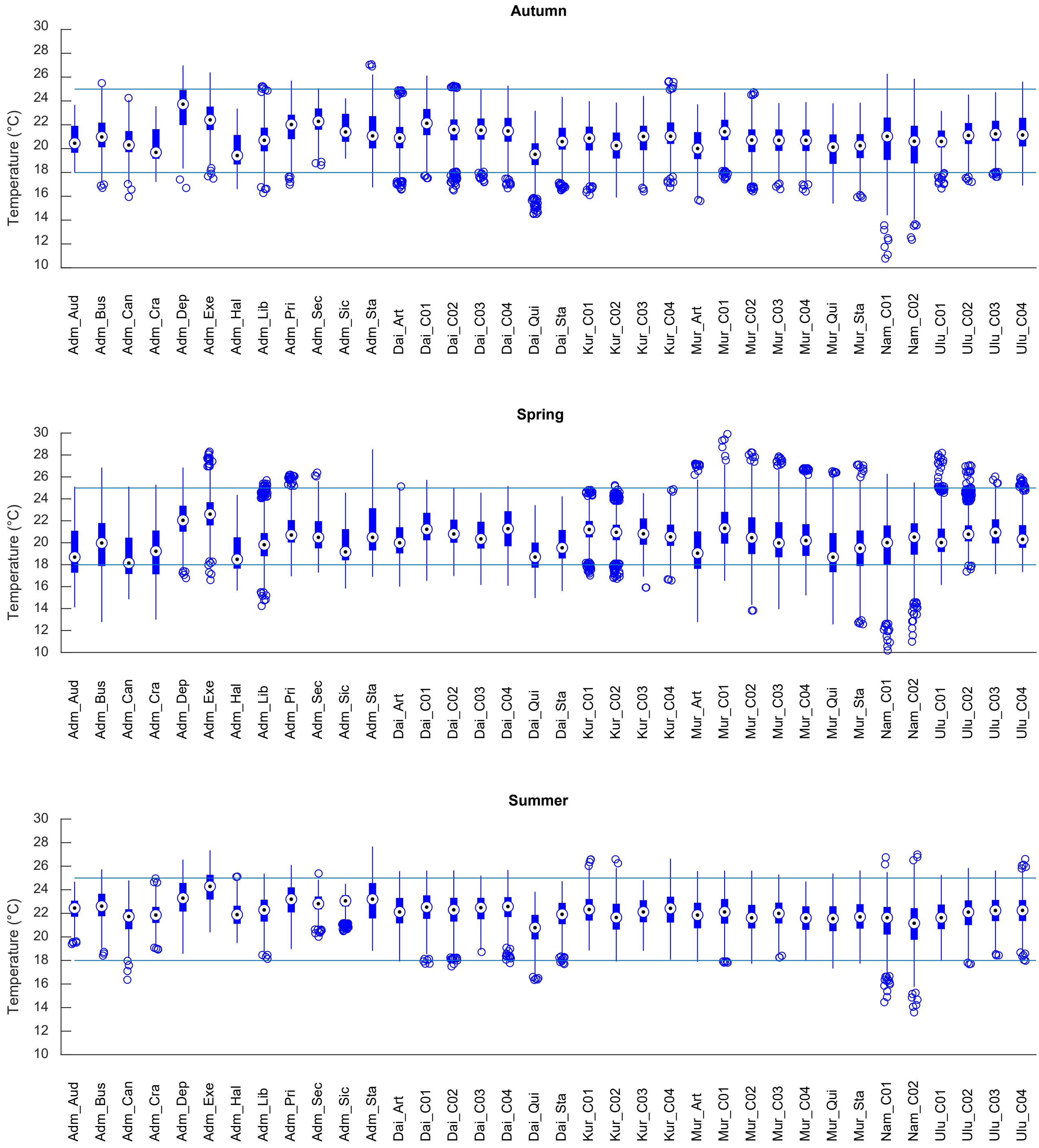


Figure 3-14. Boxplot displaying seasonal temperature variations over monitored period for each monitored room for Fadden.

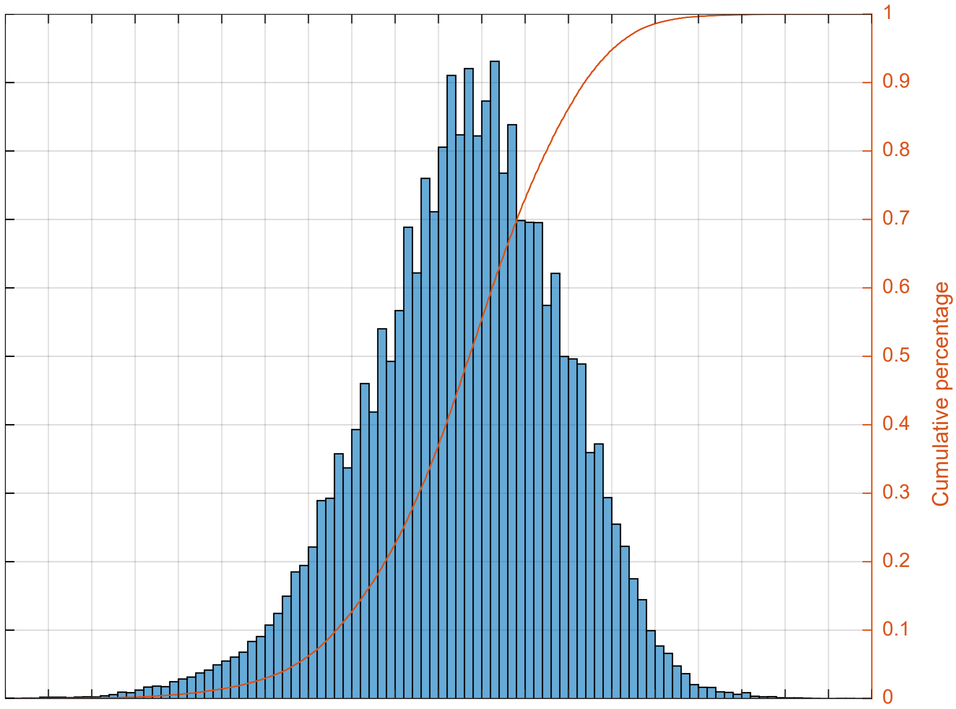
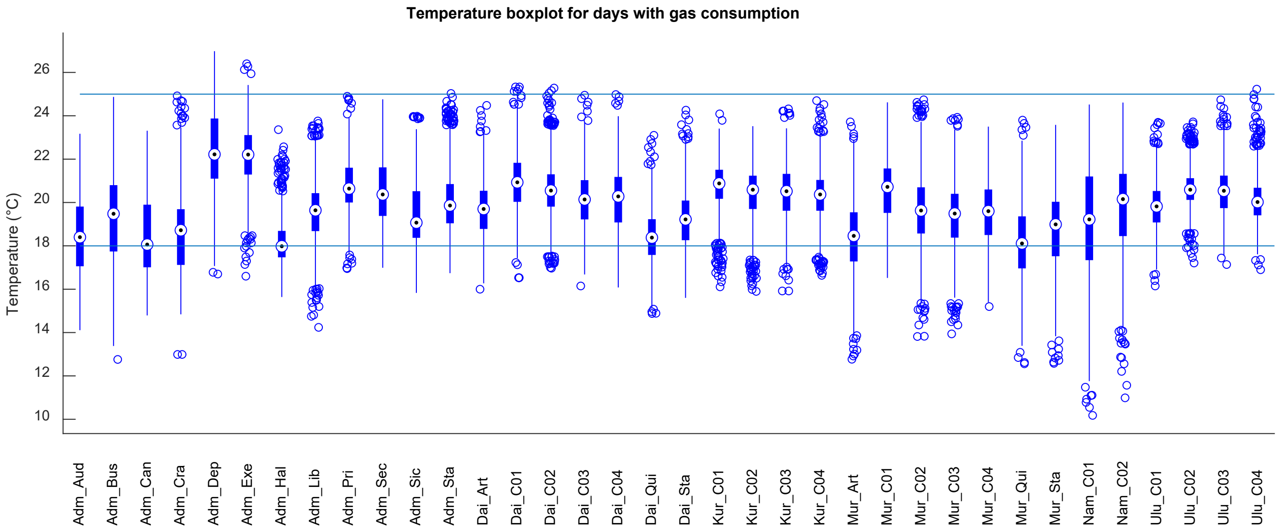


Figure 3-15. Temperature histogram and cumulative distribution for all internal temperature sensors for Fadden.

The summary data presented in Table 3-17, Figure 3-14 and Figure 3-15 suggests, in the baseline condition there are some issue with thermal comfort, in particular winter underheating, within the facility. During school hours, the recorded temperatures were within the wider temperature band (18 – 25°C) for much of the monitored period (mean = 91%, range 77 – 99%), however, on average conditions were only within the more stringent comfort band (21 – 24°C) for less than half the time (mean = 47%, range 22 – 62%).

Given there was no winter data available for the current baseline, further investigation was undertaken to understand if issues of underheating may be expected to be prevalent during cold periods. Firstly, data were split into days with and without gas consumption for heating. A summary of the recorded temperature for each zone is provided in Figure 3-16 and Table 3-18. Obviously, it would be expected that days in which there was no heater usage will have a higher external temperature, and therefore higher internal temperatures. However, it can be clearly seen that, for many rooms, the heating system is not providing temperatures within both the wide and narrow comfort bands for substantial periods of time. On average, spaces were below 21°C 76.4% of the time that the heater was in use, compared with 27.3% of time during which the heater was not in use.

It can also be seen that many rooms have a significant portion of time below 18°C (e.g. Daintree Quiet Room: 39%, Murramarang Quiet Room: 48%, and Murramarang Art room: 38%, although these auxiliary teaching rooms may be less frequently occupied). A time series plot, showing the coldest rooms in each block, is provided as Figure 3-17 for a cold week in September. This figure shows periods during the mornings, in some cases for many hours, where rooms are not recording temperatures within the desired range.



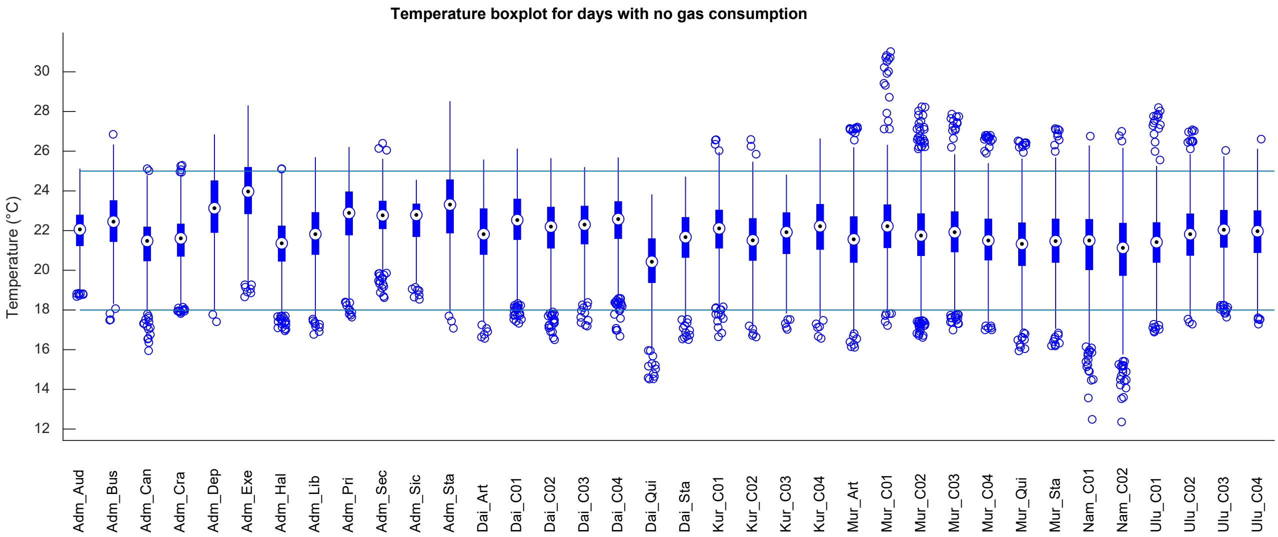


Figure 3-16. Boxplot displaying temperature variations over monitored period for each monitored room for Fadden. Subplots show data from periods in which there was gas consumption for heating (plot 1) and no gas consumption for heating (plot 2).

Table 3-18. Summary temperature statistics for Fadden primary school showing temperatures for days when heating was in use and days without.

	Days with gas consumption			Days without gas consumption		
Room ID	**Mean temp (°C)**	**%<18 °C**	**%<21 °C**	**Mean temp (°C)**	**%<18 °C**	**%<21 °C**
Admin Aud	18.5	41.30%	92.40%	22	0%	19.70%
Admin Hal	18	52.60%	98.70%	21.3	0.90%	43.80%
Admin Hal	18.3	51.70%	97%	21.3	2.80%	34.20%
Admin Can	18.4	46.50%	92.60%	21.3	1.40%	36.30%
Admin Lib	19.4	12.90%	91.10%	21.8	0.50%	27.80%
Admin Cra	18.8	38.40%	86.10%	21.5	0.90%	30%
Admin Sic	19.5	14.90%	82.50%	22.5	0%	11%
Admin Lib	19.7	14.90%	82.20%	21.9	1.10%	27.70%
Admin Bus	19.3	26.30%	78.30%	22.5	0.20%	17.70%
Admin Sta	20.2	2.30%	77%	23.4	0.20%	11%
Admin Sec	20.5	1.40%	64.50%	22.7	0%	6.50%
Admin Pri	20.8	0.70%	62.30%	22.8	0.20%	15.20%
Admin Dep	22.4	0.70%	22.80%	23.1	0%	12.60%
Admin Exe	22.1	0.70%	21.20%	24	0%	4.20%
Daintree Art	19.7	11.10%	86%	21.8	1.80%	29.70%
Daintree Qui	18.4	39%	98.40%	20.4	9.50%	63.50%
Daintree Sta	19.2	19.70%	90.50%	21.5	1.50%	32.30%
Daintree C03	20.2	5.10%	74.60%	22.2	0.20%	18.70%
Daintree C04	20.2	6.30%	71%	22.4	0.20%	14.90%
Daintree C02	20.6	1.90%	69.20%	22.2	0.40%	21.30%
Daintree C02	20.5	2.70%	67.40%	22	0.40%	23.10%
Daintree C01	20.9	2.20%	53.10%	22.5	0.70%	16.30%
Kurringai C01	20.7	3.30%	56.10%	22.2	0.70%	20.20%
Kurringai C04	20.3	3.60%	75.20%	22.1	1.20%	24.20%
Kurringai C03	20.3	7.20%	70.10%	21.9	0.90%	25.70%
Kurringai C02	20.3	6.90%	66%	21.6	1.60%	34.50%
Murramarang Art	18.4	38.40%	95.20%	21.5	3.50%	37.40%
Murramarang Qui	18.2	47.60%	94.90%	21.3	4.60%	43.10%
Murramarang Sta	18.7	34.30%	93.70%	21.4	3.50%	38.90%
Murramarang C04	19.5	15.20%	87.90%	21.5	0.90%	36.30%
Murramarang C03	19.4	17.80%	85.40%	21.9	1.30%	26.60%
Murramarang C02	19.5	15.60%	82.90%	21.8	1.30%	30.10%
Murramarang C02	19.7	12.10%	81.30%	21.7	2%	32.10%
Murramarang C01	20.6	4.50%	58%	22.2	0.40%	22.20%
Namadgi C01	19.1	31.50%	72%	21.3	6.40%	38.50%
Namadgi C02	19.8	20%	71.10%	21	8.60%	47.40%
Uluru C01	19.8	4.40%	86.70%	21.5	1.30%	37.60%
Uluru C04	20.1	1.90%	80.60%	22	0.70%	28.70%
Uluru C02	20.6	0.30%	71.90%	21.8	1.10%	29.30%
Uluru C03	20.6	1.80%	68.30%	22	0.20%	22.20%
Mean	**19.8**	**16.5%**	**76.4%**	**21.9**	**1.6%**	**27.3%**

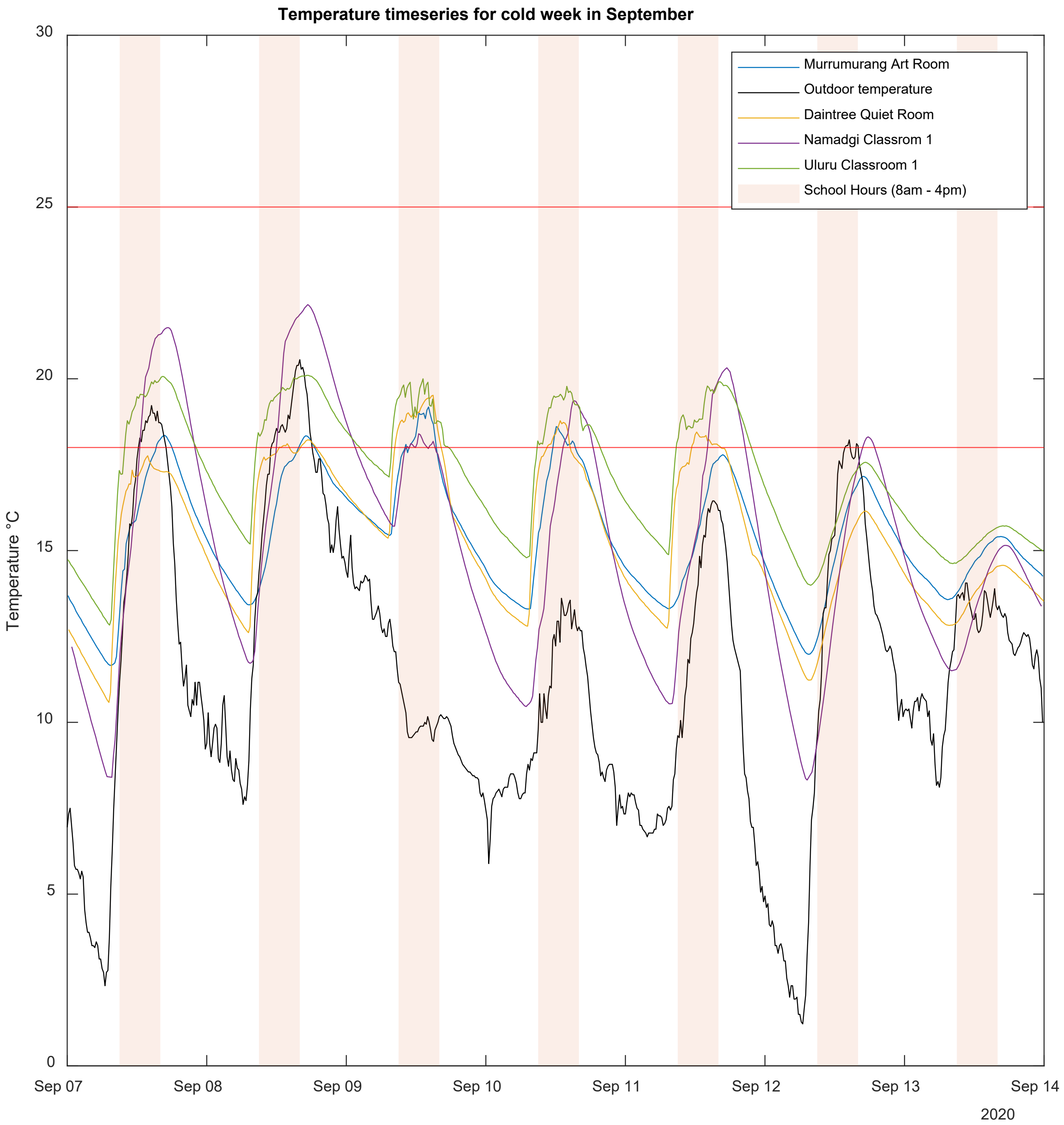


Figure 3-17. Time series temperature plot showing temperatures in the coldest room in each zone during the coldest (non-holiday) week in the sample period.

Building thermal envelope performance may be observed in Figure 3-17. Notice on September 9th when a cold change came through just before school started dropping outdoor temperature from 12°C to 10°C. All of the classrooms displayed effective heating to reach and maintain a minimum of 18°C, depending upon the controller setpoint for each room. Note the different performance of the Namadgi classroom 1, with slower rise in temperature, and faster decay back towards outdoor temperature at the end of the day when HVAC systems are switched off. Namadgi is a transportable building with typically very poor insulation, low thermal mass and older AC split systems. The building envelope performance is further illustrated during the weekend of September 12th and 13th with the building in free running mode (no active HVAC). The indoor temperature of the transportable follows the large outdoor temperature swings much more closely when compared to the rooms in the main building. This is very similar to what was observed for the transportable classrooms at Amaroo.

Baseline carbon dioxide concentration

Carbon dioxide is used a proxy for indoor air quality, for which the threshold value is often considered to be 1000 ppm. See Section 2.2.3 for further discussion of these thresholds.

Table 3-19 shows carbon dioxide concentration statistics for the selection of Fadden School rooms monitored. A more granular display of the carbon dioxide data quartiles is given in Figure 3-18, in which it can be seen for example how prevalent the higher carbon dioxide values were in different spaces. Figure 3-19 and Figure 3-20 also provide an example of weekly and daily variations of CO_2 concentrations, respectively.

Table 3-19. Summary carbon dioxide concentration statistics for Fadden primary school

Device	Mean	Max	Data points over 800 ppm	Data points over 1000 ppm	Days with max hourly mean CO_2 reading over 800 ppm	Days with max hourly mean CO_2 reading over 1000 ppm.
Cic_F_Dai_C01	594	1391	13.2%	3.3%	71.7%	35.0%
Cic_F_Dai_C02	549.3	1225	4.8%	0.4%	41.7%	6.7%
Cic_F_Dai_C04	642.8	1810	19.5%	10.1%	79.2%	55.0%
Cic_F_Kur_C03	567.6	1323	7.8%	0.9%	55.6%	11.1%
Cic_F_Mur_C01	595.3	1849	14.5%	4.2%	77.5%	39.2%
Cic_F_Mur_C02	541.9	1310	4.6%	0.8%	38.3%	10.0%
Cic_F_Mur_C04	571.1	1761	7.1%	1.5%	50.0%	15.8%
Cic_F_Ulu_C03	562.5	1065	3.4%	0.1%	34.2%	1.7%

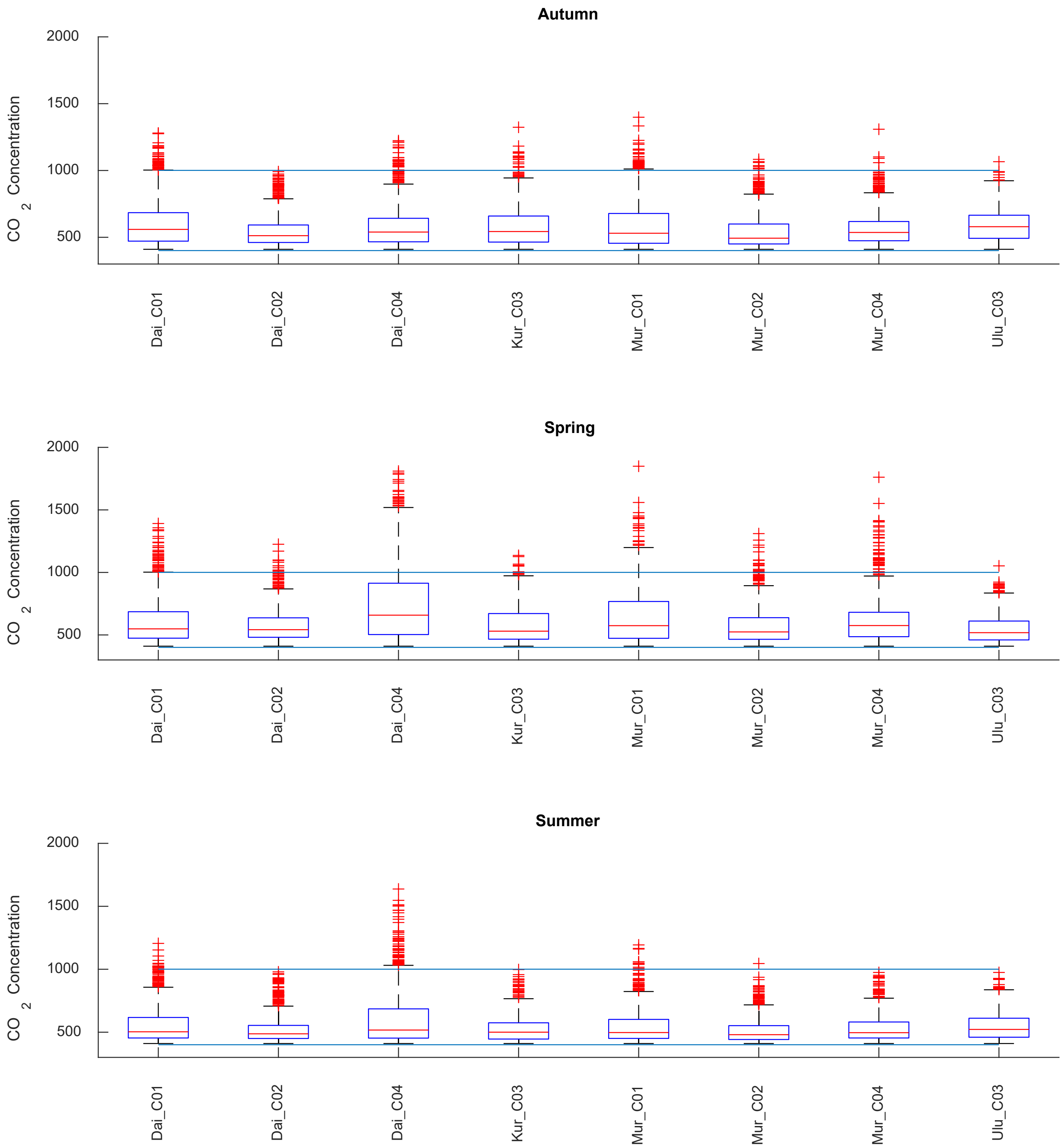


Figure 3-18. Boxplot displaying seasonal carbon dioxide concentration (ppm) variations over monitored period for each monitored room for Fadden Primary School.

Carbon dioxide concentrations for Fadden Primary School are generally substantially lower when compared to Amaroo GLA building, and are closer to the low levels of Amaroo Preschool. This may be attributable to the ground level design with the doors opening onto the rear playing field area often being left open, although this is less so in winter. It is also likely that the air permeability of the older 1980s Fadden Primary School construction is substantially worse that the newer Amaroo School.

The relatively low carbon dioxide concentrations measured at Fadden are indicative of much higher ventilation rates per occupant. If these higher ventilation rates remain effective during the colder winter months, then this would be expected to increase the heating energy consumption, or reduce indoor temperature.

If these high ventilation rates are due to high air permeability of the building envelope, then improving draught sealing of the buildings would be expected to reduce the peak winter morning HVAC load by retaining more of the heat from the previous day. Blower door testing may be useful to further investigate this.

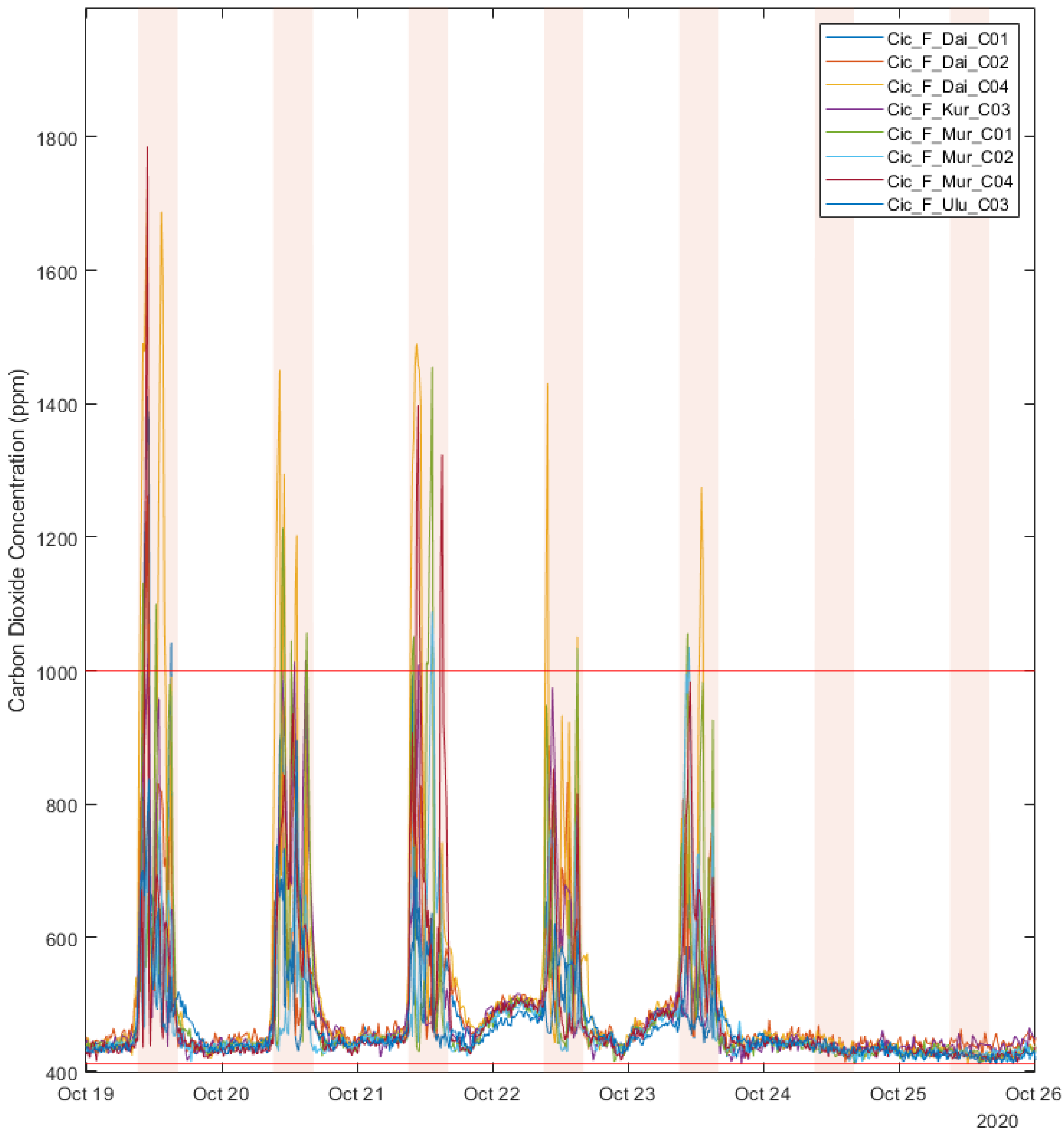


Figure 3-19. Time series carbon dioxide concentration plot showing a week in which a high reading was recorded (for Daintree Classrooms 2 and 4).

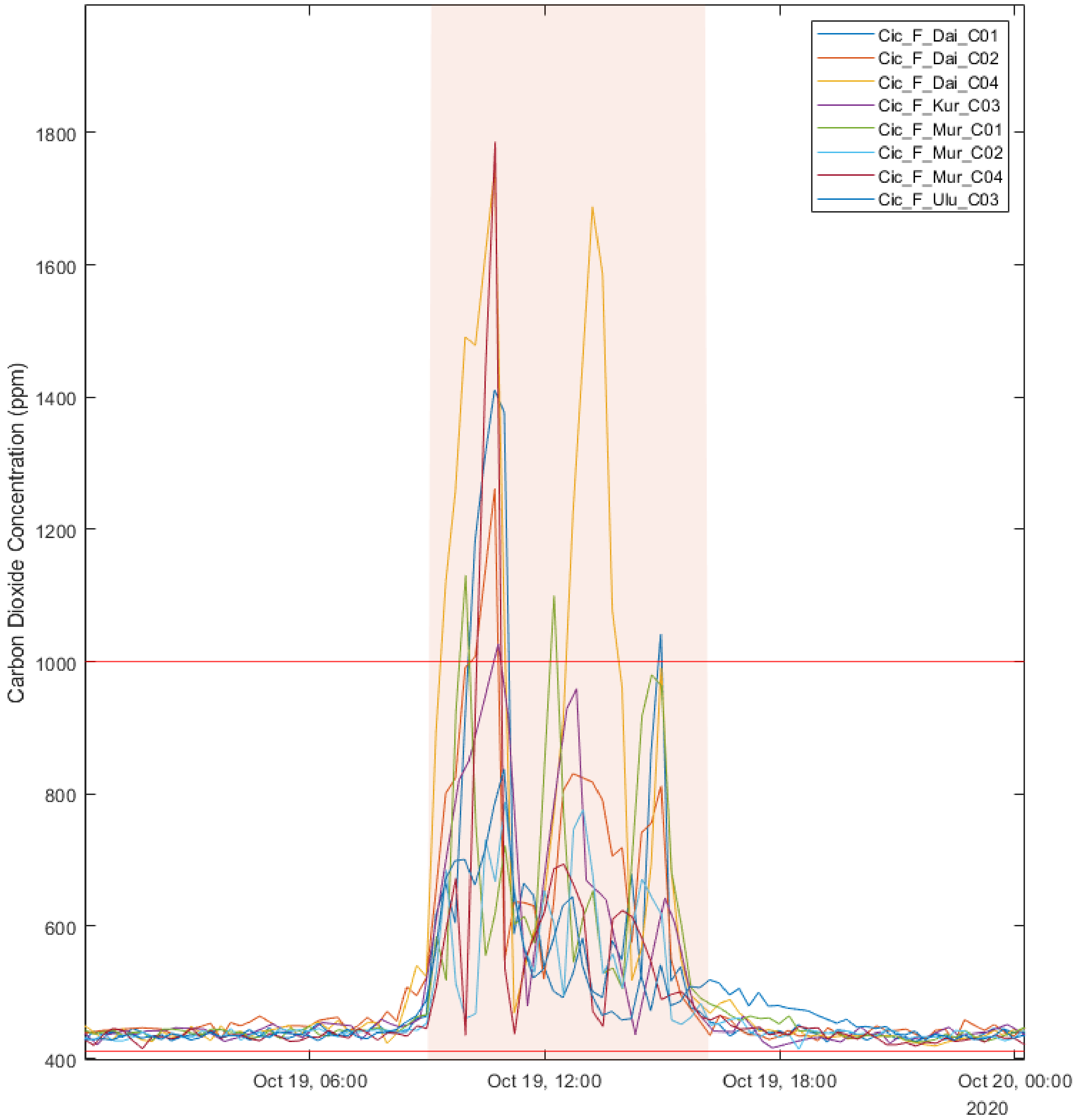


Figure 3-20. Time series temperature plot showing carbon dioxide concentration for a single day in which a high reading was recorded (for Daintree Classrooms 2 and 4).