Report #001

Assessment of Demand Response Potentials in Australian Non-Residential Buildings

23 May, 2022

CSIRO

About i-Hub

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

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

This Project received funding from ARENA as part of ARENA's Advancing Renewables Program.
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Assessment of Demand Response Potentials in Australian Non-Residential Buildings

This report is part of DCH1 project that is aimed at development of a cloud based building data management and application enablement platform. The DCH connects Internet of Things (IoT) systems from buildings and supports complex data analytics. The DCH will underpin the development of applications that improve renewable energy integration in buildings and unlock new opportunities for delivering Buildings to Grid (B2G) services.

This project will investigate features of the CSIRO Senaps data platform and their suitability for the DCH. It will combine these findings with results from the DCH2 Switch data platform subproject to develop the Data Clearing House.

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1. SUMMARY

1.1 Executive summary

Demand response (DR) is an important means for contemporary energy systems to deal with power generation uncertainty and load demand fluctuation. Among different DR strategies, the global temperature adjustment (GTA) is the most widely used technique that is used to modulate the temperature setpoint of air-conditioned spaces to deliver a flexible building load. This strategy is recognized as a feature that allows commercial building operators to adjust the space temperature setpoints for an entire facility with a single command from a single control location. It is effective in reducing load of all associated air handling units and cooling equipment with a single command without compromising the building indoor comfort conditions.

This research project has been undertaken to address the following research questions:

- To what extent can adjustment to building operating parameters contribute to demand response application in two reference building types.
- How the demand response potential varies by time of day, season, and climate zone.

More specifically, this research aims at -

- assessing demand response potential of Australian non-residential buildings (e.g., schools and offices) in response to 2°C thermostat setpoint adjustment.
- estimating state-wide cooling electricity demand and DR potentials from school and office buildings for different temperature and hour of the day bands.

The overall goal of this project is to support increased penetration of DR in non-residential buildings through a better understanding of the DR resource available through a global temperature adjustment (GTA) strategy. To achieve this goal, a set of baseline representative building & HVAC system models were developed for each type of non-residential building and different climate zones based on the Energy Efficiency Provisions in the National Building Code of Australia. Note that this report comprises the assessment results of DR potential for two building typologies: schools and offices. An extensive wide-ranging analysis has been performed involving two key variables, e.g., time of day and outdoor air temperature with a view to revealing parametric relationships for the fraction and/or magnitude of DR available for a specific building type, e.g., schools and offices from moving the setpoint by 2°C for an hour. It is worth noting that a past flexible demand opportunity assessment study led by CSIRO identified the 2°C thermostat setpoint adjustment threshold as one of the market-responsive resources [1].

Relative comparison between two building typologies indicates that the fraction of DR potential varies depending on building structural configurations, building morphology and operation related parameters, and HVAC system types. Results indicate that the state-wide cooling electricity demand of office buildings is around three times the number of school buildings. The state-wide DR potential in office buildings of NSW from increasing the setpoint by 2°C for an hour is estimated to be only one and a half times more than that of school buildings. This indicates that the state-wide DR potential does not vary at the same rate as the state-wide cooling electricity demand varies from one building typology to another. A closer observation of zone sensible cooling requirements in the simulated representative building for schools and offices in response to convective and radiant heat gains from building fabrics and other sources shows that building fabric along with building structural configurations are predominantly responsible for this large variation in the fraction of DR potentials. It is worth noting that the simulated school and office buildings characterize the typical school and office buildings in Australia.

This report provides a deep insight into parametric relationships for the fraction and/or magnitude of demand response available from the school and office buildings as functions of key variables such as time of day and outdoor air temperature. Building specific results associated with the state-wide cooling electricity demand and DR potentials are presented in the following sub-sections.

1.2 School Buildings

Figure 1 shows an estimate of the theoretical maximum cooling capacity (MW electrical equivalent) for all schools, including public and private of both categories, e.g., primary and secondary in each state, assuming all schools are fully air-conditioned. The national total is approximately 1 GW. These figures are upper limits as not all schools have air-conditioning. Due to the lack of state-wide data, it was not possible to calculate the actual installed air-conditioning cooling capacity for school buildings across Australia.

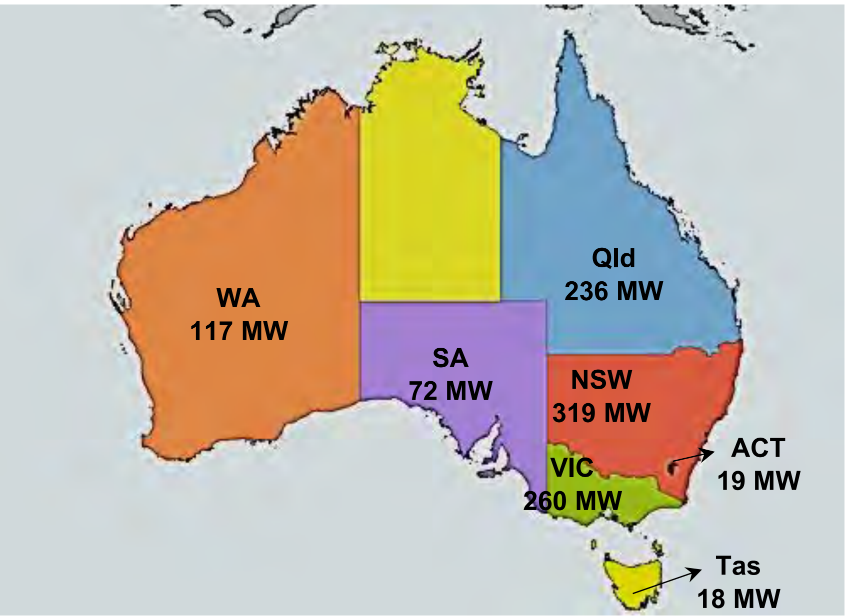

Figure 1. Theoretical maximum installed circonditioning capacity for school buildings across Australia

The key findings of this study in relation to the state-wide cooling electricity demand and DR potentials from school buildings in NSW are summarized in Table 1.

Table 1. Cooling electricity demand and demand response from NSW schools

State/City	Temperature Band	Fraction of peak capacity in use (%)	State-wide cooling electricity demand (MW)	DR potential from increasing the setpoint by 2°C for an hour (%)	State-wide electricity demand response (MW)
NSW/Sydney	31-35°C	52 - 68	165 - 217	39 - 42	64 – 90
	27-31°C	49 - 52	157 - 164	47 – 55	74 – 90
	23-27°C	30 - 39	95 - 123	60 - 65	62 - 73

The state-wide cooling electricity demand in NSW is estimated to be 160 MW for temperatures in the range 27 to 31°C, rising to 217 MW for an outdoor temperature of 35°C. The fraction of the installed capacity in use increases as the outdoor air temperature increases. For example, between 3 pm and 5 pm this fraction is estimated to be 33% for outdoor temperatures between 23 and 27°C. However, this rises to 51% for outdoor temperatures between 27 and 31°C and 68% for outdoor temperatures between 31 and 35°C. The relative DR potential is estimated to be 55% between 1 pm to 3 pm for outdoor temperatures between 27 and 31°C. This decreases by 10 ± 3% as the outdoor air temperature increases above 31°C due to the cooling equipment reaching it's maximum capacity. The state-wide electricity DR in NSW is estimated to reach a peak of 90 MW between 3 pm and 5 pm when the outdoor is between 27 and 35°C.

1.3 Office buildings

Figure 2 shows the estimated state-by-state installed cooling capacity (MW electrical equivalent) in offices based on the modelled building configuration and conventional chilled water HVAC system. The total value is 2.24GW.

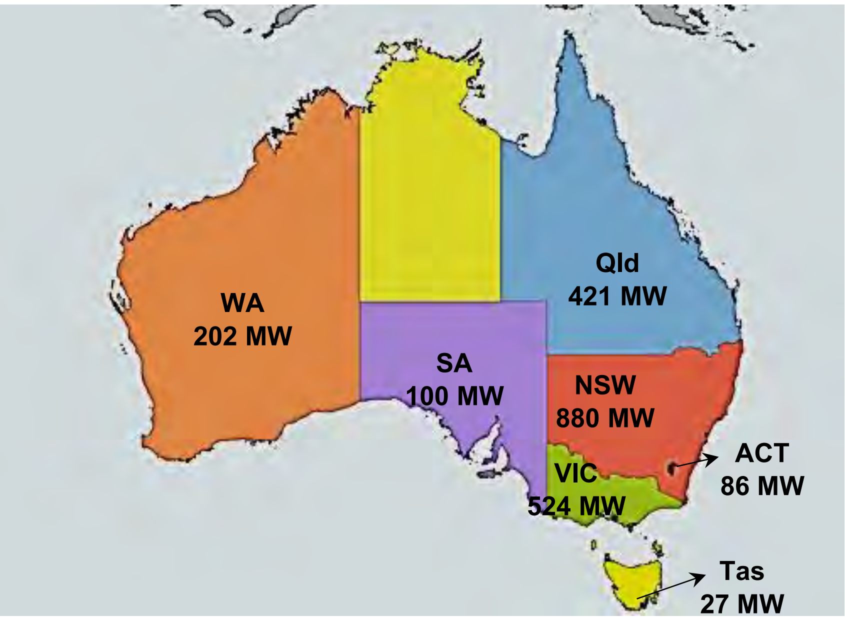

Figure 2. Theoretical maximum installed airconditioning capacity for offices buildings across Australia

The key findings of this study concerning the state-wide cooling electricity demand and DR potentials from office buildings in NSW are summarized in Table 2.

Table 2. Cooling electricity demand and demand response from NSW office buildings

State/City	Temperature Band	Fraction of peak capacity in use (%)	State-wide cooling electricity demand (MW)	DR potential from increasing the setpoint by 2°C for an hour (%)	State-wide electricity demand response (MW)
NSW/Sydney	31-35°C	64 – 66	563 – 584	22 – 23	122 – 134
	27-31°C	51 – 54	450 - 471	25 – 28	113 – 131
	23-27°C	38 – 45	334 - 396	27 - 35	101 to 113

The state-wide cooling electricity demand in NSW is estimated to be 460MW for temperatures in the range 27 to 31C rising to 584 MW for an outdoor temeprature of 35°C. The fraction of the installed air-conditioning capacity in use on a weekday increases by approxiamtely 22% as the outdoor air temperature increases from 23C to 35C. As for school buildings, the relative DR potential decreases as the outdoor temperature increases reaching a maximum between 1 pm and 3 pm for outdoor air temperatures in the range 23 to 27°C and decreasing by 1 ± 0.5% for each degree increase in outdoor air temperature. During hot weather conditions when the cooling units typically run at their full capacity to maintain the thermostat setpoints there is proportionally less potential to reduce their power use.The state-wide electrcity cooling demand response in NSW from office buildings is estimated to be reach a maximium of 134 MW between 9 am and 11 am when the outdoor air temperature falls within the 31-35°C temperature band.

2. ASSESSMENT OF DEMAND RESPONSE POTENTIALS IN AUSTRALIAN NON-RESIDENTIAL BUILDINGS

2.1 Background

The opportunity assessment project led by CSIRO and multiple stakeholders identified priority research areas to accelerate the adoption of flexible demand in Australia's electricity system. This project reports the untapped potential of flexible demand from the air-conditioning system by pushing thermostat settings up or down [2]. Also, a recent CSIRO study [3] estimated that air-conditioning demand response through setpoint offset strategies alone could reduce peak loads on the National Electricity Market (NEM) by 5.8%. or 1.2 GW. In continuation of previous studies led by CSIRO, this study includes an extensive wide-ranging analysis involving two key variables, e.g., time of day and outdoor air temperature with a view to revealing parametric relationships for the fraction and/or magnitude of DR available for a specific building type, e.g., schools and offices from moving the setpoint by 2°C for an hour.

Educational buildings account for the fourth largest share of energy consumption in commercial buildings in Australia, consuming approximately 17 PJ or 13% of the total as of 2009 [4]. The share of total energy consumption attributable to this building sector was projected to rise by 1% over the period 2009 to 2020, reaching 23.2 PJ by 2020. As per

Australian average energy intensity trends by building type reported by school buildings show rising energy intensity trends on average, reaching around 191 MJ/m^2 in 2020.

On the other hand, standalone office buildings represented the second largest share in 2009, with nearly 34 PJ or 25% of the total energy consumption [4]. As per the projected data, the share of total energy consumption attributable to standalone offices is around 23% in 2020. These statistical data on the share of energy consumption attributable to the school and standalone office buildings point out the necessity of voluntarily executing DR in the cooling systems of these two building typologies to ensure flexible demand during the peak load period.

2.2 Methodology and Data sources

The targeted model for whole-building system energy performance was developed using DesignBuilder software. The energy modelling process is trailed by the following steps (Figure 3):

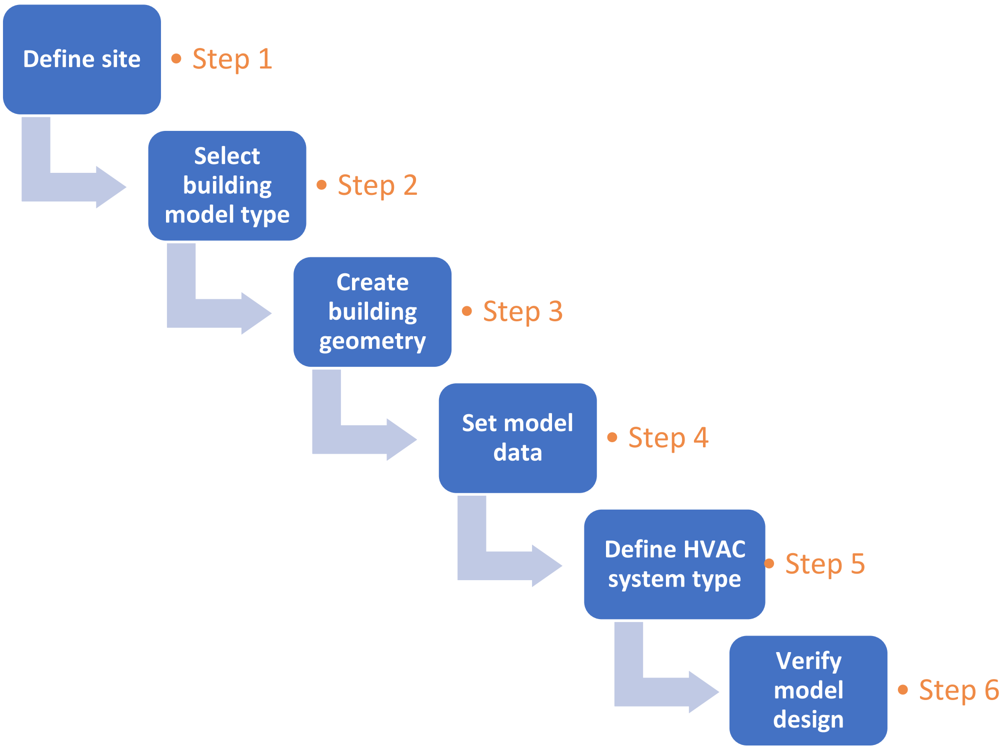

Figure 3. Building modelling steps using DesignBuilder software

As shown in Figure 4, three types of data were used in the model development and validation processes of representative buildings for schools and offices.

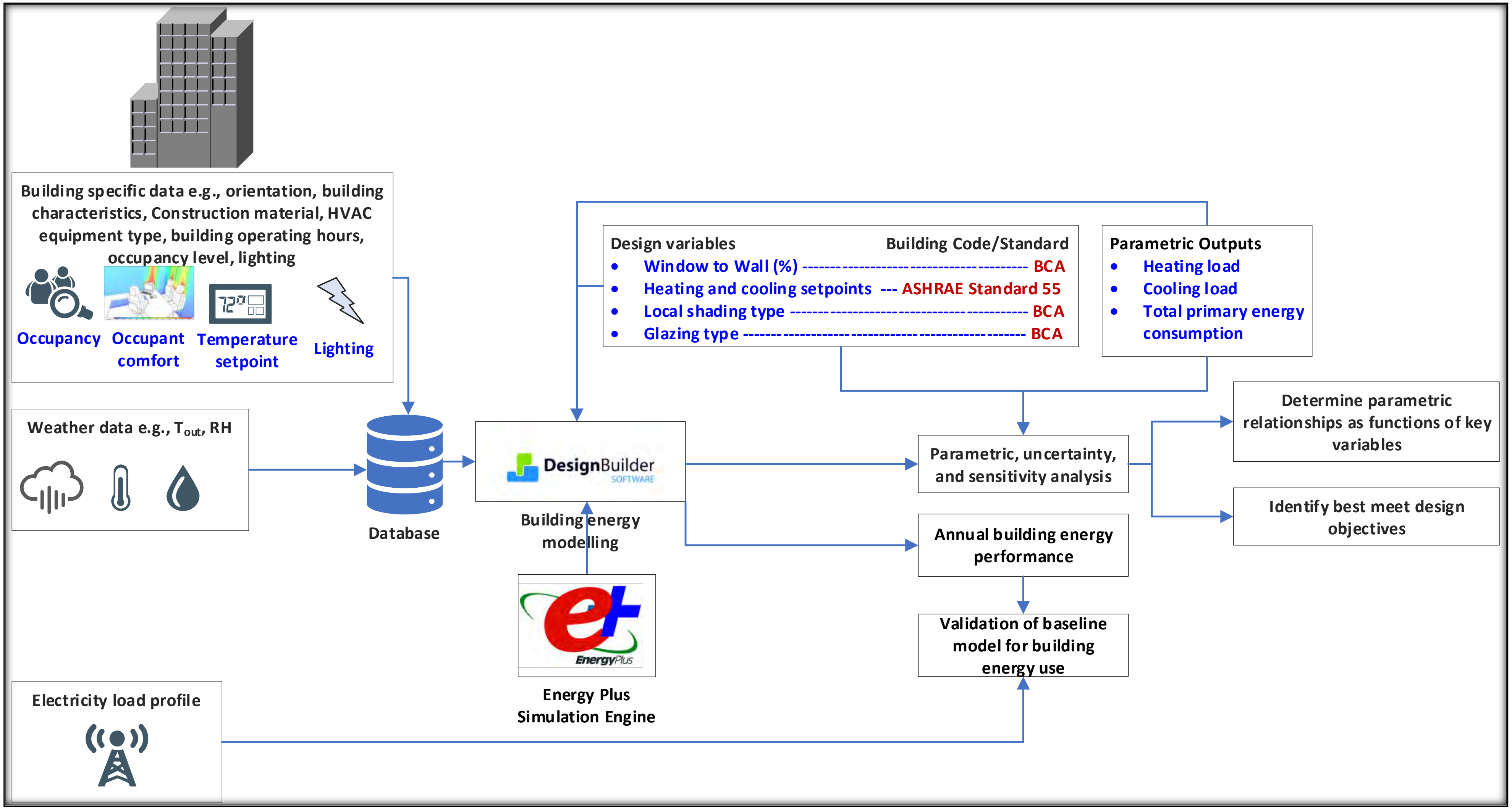

Figure 4. An overview of the methodology

2.2.1 *Building specific data*

Building specific data indicates characteristic data such as building activity, construction materials, openings (e.g., windows, sub-surfaces, holes, doors, vents), lighting, equipment for a particular building typology. According to the NCC 2019 Building Code of Australia, a school building belongs to Class 9b buildings, while an office building falls within Class 5 buildings. The NCC guideline acted as the reference to construct the baseline representative buildings for schools and offices.

2.2.2 *Weather data*

All EnergyPlus hourly Weather data (.epw file) for 78 locations of Southwest Pacific (WMO Region 5) – Australia, as shown in Figure 5, was downloaded from the EnergyPlus Weather site, and added to the DesignBuilder library. Weather files have hourly or sub-hourly data for each of the essential elements needed during the calculations (i.e., Dry-Bulb Temperature, Dew-Point Temperature, Relative Humidity, Barometric Pressure, Direct Normal Radiation, Diffuse Horizontal Radiation, Total & Opaque Sky Cover, Wind Direction, Wind Speed) as well as some auxiliary data such as Rain or Snow that assist in certain calculational aspects.

Figure 5. Australian map for EnergyPlus Weather data

2.2.3 *Electricity usage data*

The daily average electricity usage data for the school and office buildings in Australia collected by the CSIRO research group for the National Energy Analytics Research (NEAR) Program [5] was used as the reference data for model validation. The NEAR program data presents an estimate of energy consumption for a range of commercial building types.

2.2.4 *Calculation details*

DR potentials under different weather conditions

The assessment of demand response potentials under different weather conditions was carried out in three steps as detailed below:

Step 1:

The state-wide electrical equivalent of air-conditioning cooling capacity required to meet the cooling demand in the school buildings at peak load conditions in the extreme weather conditions was estimated from the calculated half-hourly cooling electricity data in a typical school building and corresponding state's student enrolment data sourced from the Australian Bureau of Statistics (Schools, 2021 | Australian Bureau of Statistics (abs.gov.au)) and can be expressed by Eq. (1).

$$\begin{aligned}&State - wide\ Cooling\ Capacity\ (electrical\ equivalent)\ in\ Schools = \\ &Typical\ Installed\ Airconditioning\ Capacity\ (electrical\ equivalent\ per\ student)\ in\ an\ airconditioned\ school * \\ &Number\ of\ Students\ in\ that\ Particular\ State \qquad (1)\end{aligned}$$

To calculate the state-wide electrical equivalent of air-conditioning cooling capacity for the office building, the stock data for the baseline study model of offices was retrieved from the Baseline Energy Consumption and Greenhouse Gas Emissions – In Commercial Buildings in Australia site cbbs-model-offices.xlsx (live.com) and used in calculation along with the simulated half-hourly cooling electricity data in a typical office building.

$$\begin{aligned}&State - wide\ Cooling\ Capacity\ (electrical\ equivalent) in\ Offices = \\ &Typical\ Installed\ Airconditioning\ Capacity\ (electrical\ equivalent\ per\ student) in\ a\ typical\ office\ building * \\ &Total\ Estimated\ Floor\ Area\ of\ the\ Building\ Stock \qquad (2)\end{aligned}$$

Step 2:

In the next step, the fraction of the installed cooling capacity being used on a school/an office day for each 'bin' under different weather conditions was determined from the simulated half-hourly cooling electricity data by splitting the data into three temperature bands, e.g., 23 - 27°C, 27 - 31°C, 31 - 35°C and four time dimensions, e.g., 9 am – 11 am, 11 am – 1 pm, 1 pm - 3 pm, 3 pm – 5 pm covering building occupied periods only (Eq. (3)).

$$\begin{aligned}&{}^{TB}_{TD}Fraction\ of\ the\ installed\ airconditioning\ capacity = \\ &{}^{TB}_{TD}Peak\ Load / \ Typical\ Installed\ Airconditioning\ Capacity\ (electrical\ equivalent) \qquad (3)\end{aligned}$$

Where TB and TD indicate a particular temperature band and time of day, respectively.

Full summer season data was considered to conduct this analysis. A total of 5376 data points representing 30-min interval cooling electricity data and corresponding outdoor air temperature time-series data that spans between 1 Oct 2018 through 30 Apr 2019 were considered in this analysis. Note that weekends were discarded from this analysis. Also, cooling electricity data for OAT<23°C and OAT>35°C are discarded from this analysis.

The state-wide cooling electricity demand from school/office buildings was calculated for each 'bin' and temperature band using Eq. (4).

$$\begin{aligned}&{}^{TB}_{TD}State - wide\ Cooling\ Electricity\ Demand\ from\ school/office\ buildings = \\ &The\ value\ obtained\ using\ Eq.(1)^{1}\ or\ Eq.(2)^{2} * The\ value\ obtained\ using\ Eq.(3)\ for\ a\ partcular\ TB\ and\ TD \\ &(4)\end{aligned}$$

Despite the fact that the previous analysis steps cover all states, the scope of this analysis in this step was limited to NSW state only. However, a broader analysis that will facilitate a deeper exploration of the variations of DR potentials across each state can be performed in future studies by including all states in this analysis.

Step 3:

In the final step, the fraction or magnitude of the DR potential from increasing the setpoint by 2°C for an hour in the occupied period was calculated by generating two simulated electricity consumption profiles for each hourly time step: a baseline setpoint profile and a DR setpoint profile and the change in load is estimated within the hour, h a DR event is called.

For a particular hourly timestep, the baseline cooling electricity consumption rate of the modelled office building within the DR event hour, h can be defined as $E_{base}^{cooling}$ and the cooling electricity consumption for the same timestep using the DR setpoint profile can be defined as $E_{DR}^{cooling}$. Therefore, the DR potential at each hourly time step can be expressed as:

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[1] Applicable for school buildings

[2] Applicable for office buildings

DR potential in terms of percentage - $DR(\%) = \frac{E_{base}^{cooling} - E_{DR}^{cooling}}{E_{base}^{cooling}}$ (5)

DR potential in terms of magnitude - $DR\ (W/m^2) = E_{base}^{cooling} - E_{DR}^{cooling}$ (6)

This DR event captures the hourly load shed potential with respect to its base case scenario. Note that a positive DR potential refers to the load shed capacity of the cooling system.

To establish parametric relationships for the fraction (Eq.5) or magnitude (Eq. 6) of DR available from increasing the setpoint by 2°C for an hour for a given type of building as functions of key variables such as time of day and ambient temperature, the calculated DR data was split into three temperature bands (e.g., 23 - 27°C, 27 - 31°C, 31 - 35°C) and four time dimensions (e.g., 9 am – 11 am, 11 am – 1 pm, 1 pm – 3 pm, 3 pm – 5 pm) covering building occupied periods only.

The state-wide Electricity Demand Response from school/office buildings was calculated for each 'bin' using Eq. (7).

$${}^{TB}_{TD}State - wide\ Electricity\ Demand\ Response\ from\ office\ buildings = The\ value\ obtained\ using\ Eq.\ (4) * {}^{TB}_{TD}DR\ (\%)$$
(7)

__The sensitivity of the DR potentials to time of day and ambient temperature__

The distribution of DR potential at each hourly time step of the building HVAC operational period was inspected to explore parametric relationships for the fraction and/or magnitude of demand response available for a given type of building (e.g., schools and offices) as functions of time of day. The linear/non-linear relationships between building DR potentials and outdoor air temperature were evaluated by fitting the suitable regression models to data.

2.3 Key Results – School Buildings

The baseline representative building for schools is a two-storey 11,600 m^2 Gross Floor Area (11,200 m^2 Net Lettable Area) building comprising four zones (Figure 6). Each of these zones represents an individual classroom. A detail about this building configuration can be found in the CSIRO report [6]. Each zone is equipped with a packaged terminal air-conditioner (PTAC) system. Each PTAC consists of fixed components: an outdoor air mixer, DX cooling coil, gas heating coil, and constant volume supply air fan.

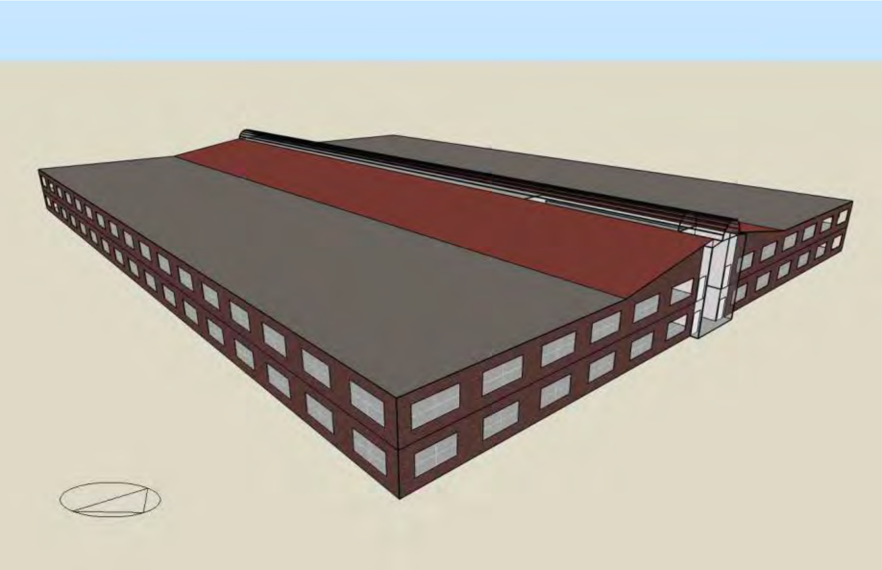

Figure 6. A rendered 3-D image of the modelled building for schools

2.3.1 Model validation

Multiple locations (e.g., Sydney Airport, Wagga Wagga, Williamtown, Richmond, Dubbo) representing a particular climatic zone in Australia were considered for the model validation. Note that all of these locations fall under the NSW climatic zone which is zone 5 according to the NCC 2019 Building Code of Australia. Figure 7 illustrates the degree of variation in calculated daily average electricity usage from one location to another. Results indicate that depending on the location, the daily average electricity usage can vary by approximately 1-5% in different months in terms of coefficient of variance. The daily average electricity usage data for the NSW school buildings collected by the CSIRO research group for the National Energy Analytics Research (NEAR) Program [5] were grouped by school level, e.g., primary/secondary and students' enrolment numbers. Each of these datasets indicates the daily average electricity usage for a particular school level and range of enrolment numbers, e.g., 100-249, 250-499, 500-999. To better reflect our constructed baseline building model, only the electricity usage data of NSW secondary school buildings were considered for the model validation. The measured maximum and minimum limits for the daily average electricity usage were generated from the three years of data of different enrolment numbers and compared with the calculated data (see Figure 7). This Figure shows that the calculated daily average electricity usage values of individual months for the specified locations do not fall within the maximum and minimum range of measured data in October, November, and December. A possible reason behind this could be that the number of students in a secondary school drops in the last three months. According to the NSW secondary school calendar, Year 12 only goes for three terms and graduates in late September/early October. So, definitely a smaller number of students are attending Term 4, and some classrooms may remain unoccupied during term 4 (14 Oct – 20 Dec). However, in the simulated building, the same number of students has been considered throughout the year, and all zones have been considered occupied during the school hours except the NSW school holiday periods. Also, in reality, there could be the behavioural issue of not running the air-conditioning system during the shoulder months. However, often these issues are not reflected in the model, and it is assumed that the operation of HVAC systems is predominantly controlled by the defined heating and cooling setpoint temperatures.

According to the Baseline Energy Consumption and Greenhouse Gas Emissions Report for Commercial Buildings published by the Department of Climate Change and Energy Efficiency in 2012 pitt&sherry [4], a school building's average annual electricity consumption is around 46.67 kWh/m^2. This data demonstrates that our calculated annual electricity consumption data for a school building, which were found to be between 52.28 kWh/m^2 to 54.51 kWh/m^2 for different locations, are in line with the baseline energy consumption data for schools.

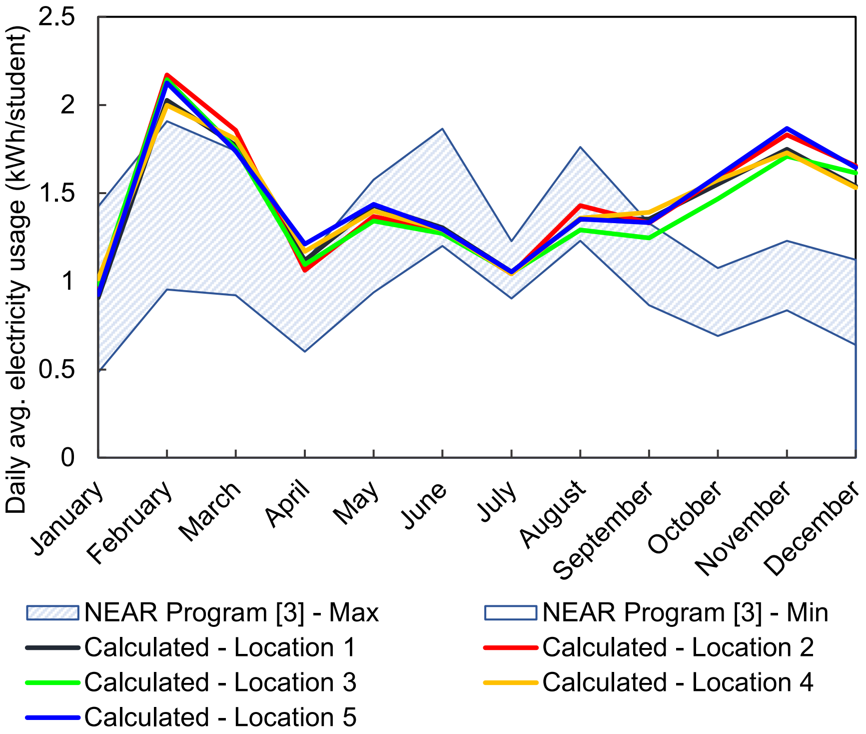

Figure 7. Comparison between measured and calculated daily avg. electricity usage for a typical school building in NSW

2.3.2 *Energy consumption breakdown*

Figure 8 illustrates the end-use shares for a typical school building in NSW based on simulated energy use data. Lighting and equipment dominate the electrical end-use shares, accounting for 42% and 30%, respectively. The cooling system accounts for 18% of electrical energy use, while fans make up 7% of the total school electricity energy use. Pumps' end-use share (<1%) was negligible and is not included in this Figure.

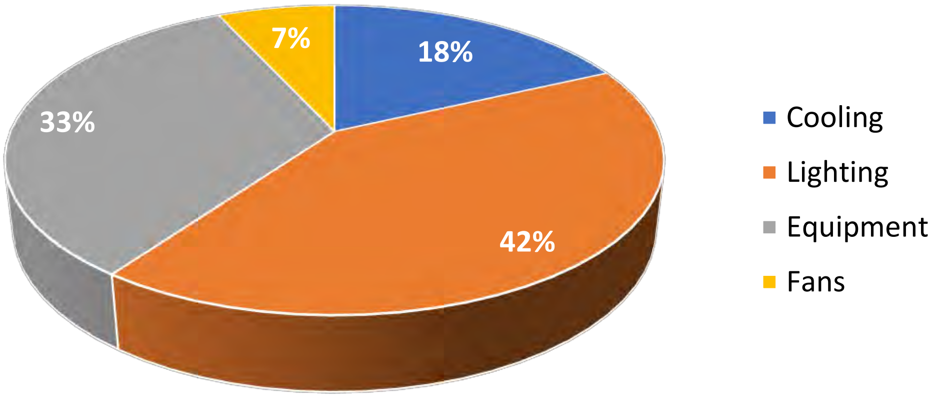

Figure 8. Typical energy consumption breakdown in a modelled school building for NSW

2.3.3 *Peak electricity demand – monthly basis*

Figure 9 presents a comparison among the share of peak electricity demand for electric components of the representative building for schools for a particular timestamp in different months of a typical year. The highest peak electricity demand was found to be on 8 Feb at 2 pm based on 10 min interval time-series data of electricity simulated by EnergyPlus. The chiller system holds the highest share of electricity during the summer months, followed by lighting, equipment, and extract fans. The peak demand in the winter months is low compared to the summer months. Results show that peak electricity demand can vary by around 51% due to seasonal variations.

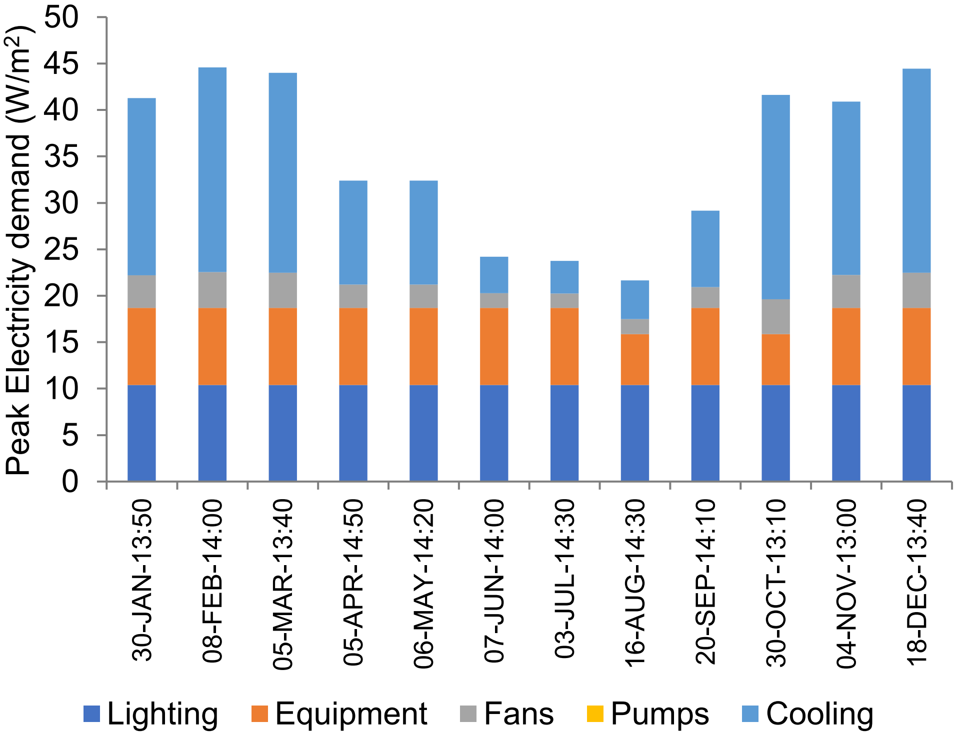

Figure 9. Peak Electricity Demand identified for a particular timestamp in different months – School buildings

2.3.4 Peak electricity demand day

Figure 10 presents a diurnal profile of energy intensity in a typical school building in NSW on the peak electricity demand day (8-Feb). Between 7 am and 5 pm, the air-conditioning system accounts for the highest amount of electricity, followed by lighting, interior equipment, and AHU extraction and supply fans. The electricity consumed by the air-conditioning system picked at 7 am when the system started running after idle condition to bring the zone temperature down to the specified temperature of the supply air stream as well as offset the heat gains by different sources. This Figure also shows that the lighting and equipment load (electrical) follow designated operation profiles of the weekday for Building Class 9B prescribed by NCC of Australia.

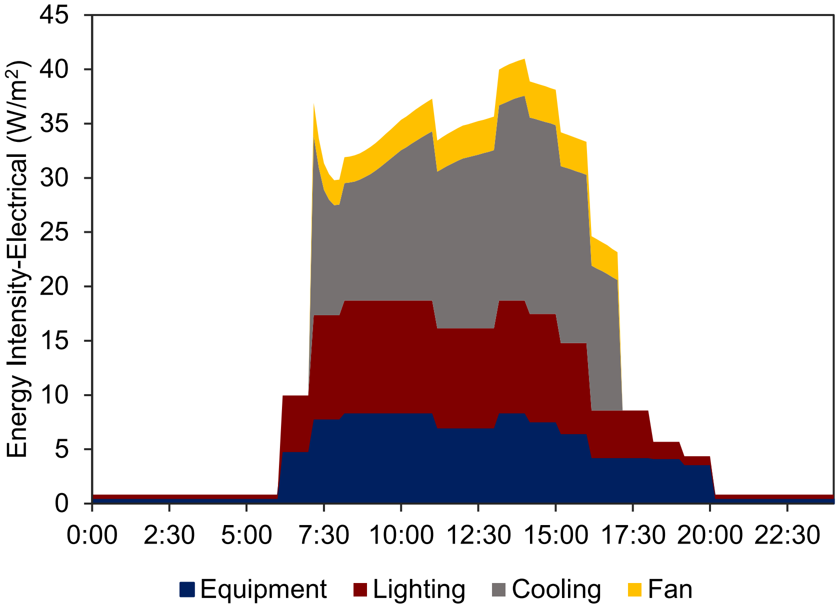

Figure 10. The disaggregated energy consumption data for a typical school building

Figure 11 depicts the source of heat gains, e.g., occupancy, lighting, computer, equipment, and solar, which contribute to the cooling load. This Figure also shows how building fabrics such as glazing, walls, ceiling, floors, partitions, roofs, and infiltration perform at different times due to the changes in ambient temperature. The roof is found to be a significant source of heat gains between 8:30 am and 6 pm, and the amount of heat gains fluctuate over time. The zone sensible cooling required to offset the heat gains was maximum at 2 pm. After 2 pm, the zone sensible cooling requirement started dropping, and this dropping continued until 5 pm.

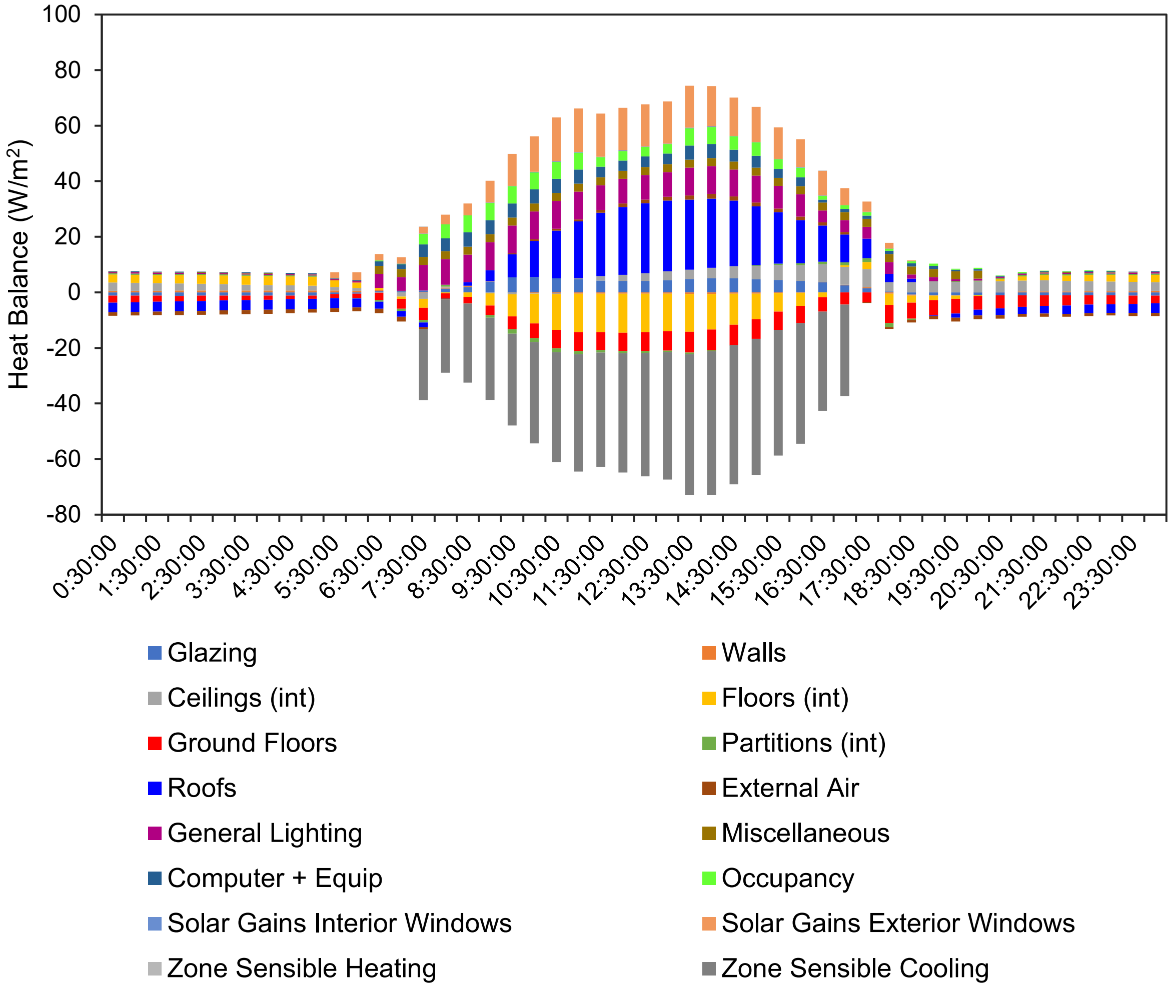

Figure 11. Heat gains and zone sensible cooling requirements of school building model on the peak electricity demand day

2.3.5 Cooling Electricity Demand under Different Weather Conditions

The box and whisker plot (see Figure 12) summarizes the distribution of cooling electricity demand at each hourly time step of the building HVAC operational period. The cooling electricity demand reached a peak at 3 pm, accounting for a 4.2 W/m^2 increase in cooling electricity demand in terms of median value compared to that at 9 am. The cooling electricity demand drops markedly between 3 pm through 5 pm. As shown in Figure 12, the cooling electricity demand largely varies at each hourly time step of the building HVAC operational period. This variation in cooling electricity demand is predominantly due to the ups and downs in outside air temperature (see Figure 13).

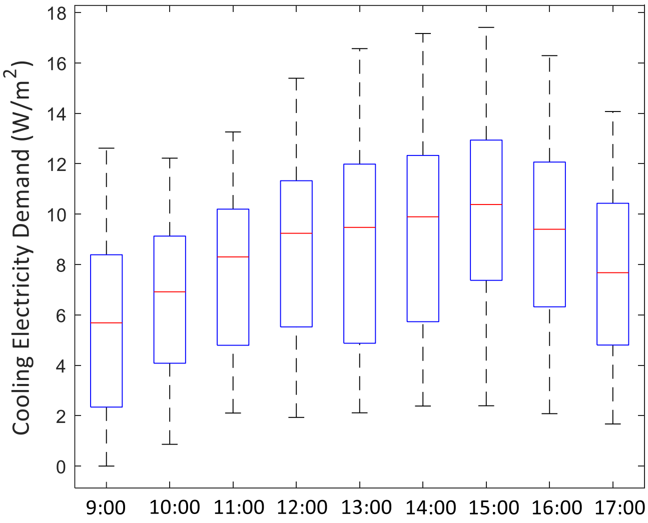

Figure 12. Hourly cooling electricity rate for the modelled school building in the summer season

Figure 13 illustrates a non-linear relationship between building cooling electricity rate and outdoor air temperature. The MATLAB Curve Fitting Toolbox function has been used here to perform regression by fitting a curve to data using a two-term power series regression model that can be expressed by:

$$y = ax^{b}+\mathrm{c} \tag{1}$$

Where x and y stand for outdoor air temperature and building cooling electricity rate, respectively. a, b, and c are the coefficients.

Equation 1 indicates that the rate at which cooling electricity demand is changed is generally proportional to the outdoor air temperature raised to some power.

Fit a two-term Power Series Model using the fit Function:

$$f(x) = ax^{b}+\mathrm{c}$$

Coefficients (with 95% confidence bounds):

$$a = 0.26\ (-0.32, 0.84)$$
$$b = 1.31\ (0.77, 1.84)$$
$$c = -14.8\ (-24.04, -5.57)$$

Table 3. Table of fits for a two-term power series regression model

Fit type	SSE	R-square	DFE	RMSE	Coeff
Power2	1088	0.85	536	1.425	3

The optimized start points for Power fits are calculated based on the dataset. The robust least-squares fitting method was applied, and Levenberg-Marquardt was chosen as the fitting algorithm.

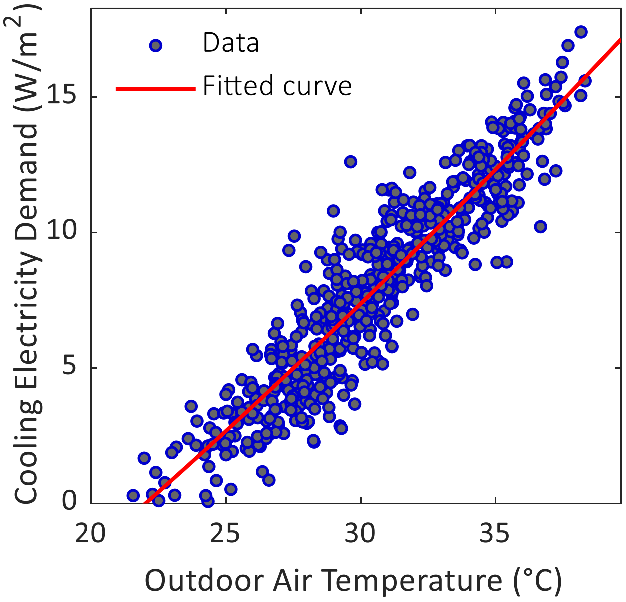

Figure 13. Cooling electricity rate vs. Outdoor air temperature for a typical school building

2.3.6 Demand Response Potential under Different Weather Conditions

The distribution of DR at each hourly time step of the building HVAC operational period is presented in Figure 14. This Figure shows that there are large variations of the DR potential during each hour of the building occupied period. These variations are predominantly caused by the weather conditions, such as the outside air temperature (see Figure 15). On average, DR Potential could be around 49-54% by increasing the setpoint by 2°C for an hour. This Figure shows no significant difference in DR potential in terms of percentage at different hours. Note that DR potential for a specific outdoor air temperature band (23°C to 35°C) was considered in this analysis. To better reflect the changes in DR potential at different hours, a parametric relationship has been established for a fraction of DR available by increasing the setpoint by 2°C for an hour for a given type of building (e.g., schools and offices) as functions of key variables such as time of day and ambient temperature.

To quantify the changes in DR potentials, the calculated DR data has been split into three temperature bands (e.g., 23 - 27°C, 27 - 31°C, 31 - 35°C) and four time windows (e.g., 9 am – 11 am, 11 am – 1 pm, 1 pm – 3 pm, 3 pm – 5 pm) covering building occupied periods only. Figure 15 summarizes the hourly DR Potential of a typical school building in NSW for different outdoor air temperature bands and time frames. For a particular time frame, the fraction of DR potential available from increasing the setpoint by 2°C for an hour moves toward lower values with the increase in outdoor air temperature and can vary by 10 ± 3% when the outdoor air temperature jumps from one temperature band to another. On the other hand, cooling electricity demand increases with increased outdoor temperature. Therefore, the fraction of DR potential curve maintains a downward slope if the magnitude of DR potential does not increase at the same rate as the cooling electricity demand increases with outdoor temperature. Figure 16 portrays the downward trend of DR potential (%) for each ‘bin’ with the increase in outdoor air temperature.

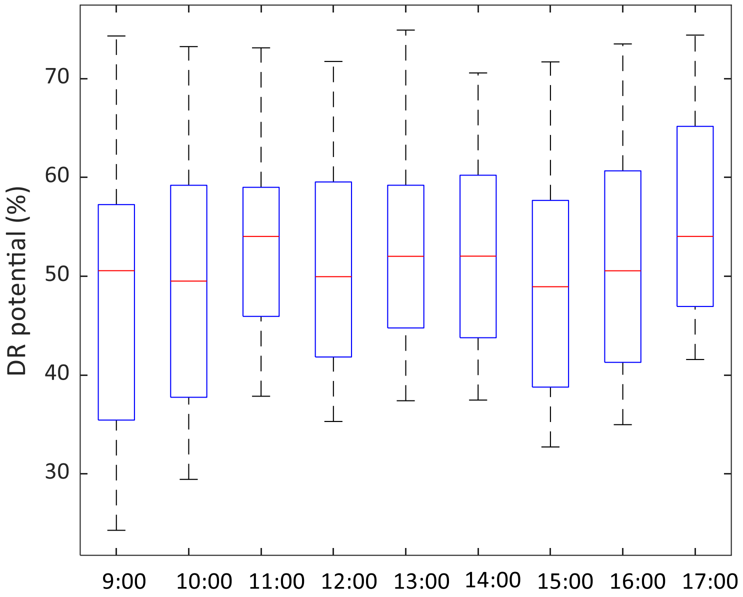

Figure 14. The distribution of hourly DR potential (%) of a typical school building from increasing the setpoint by 2°C for an hour

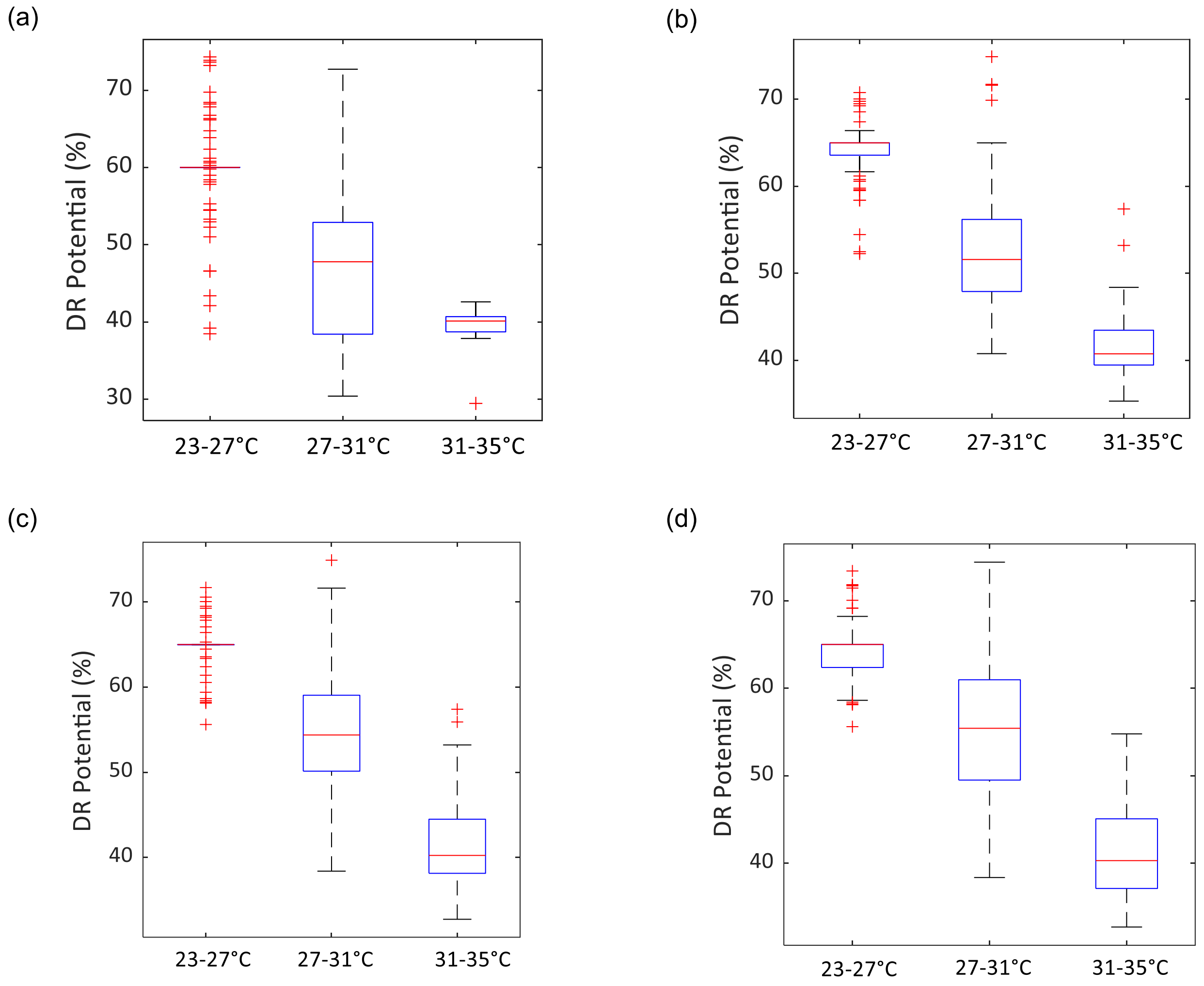

Figure 15. The distribution of hourly DR Potential of a typical school building in NSW for different outdoor air temperature bands (a) between 9 am to 11 am, (b) between 11 am to 1 pm, (c) between 1 pm to 3 pm (d) between 3 pm to 5 pm

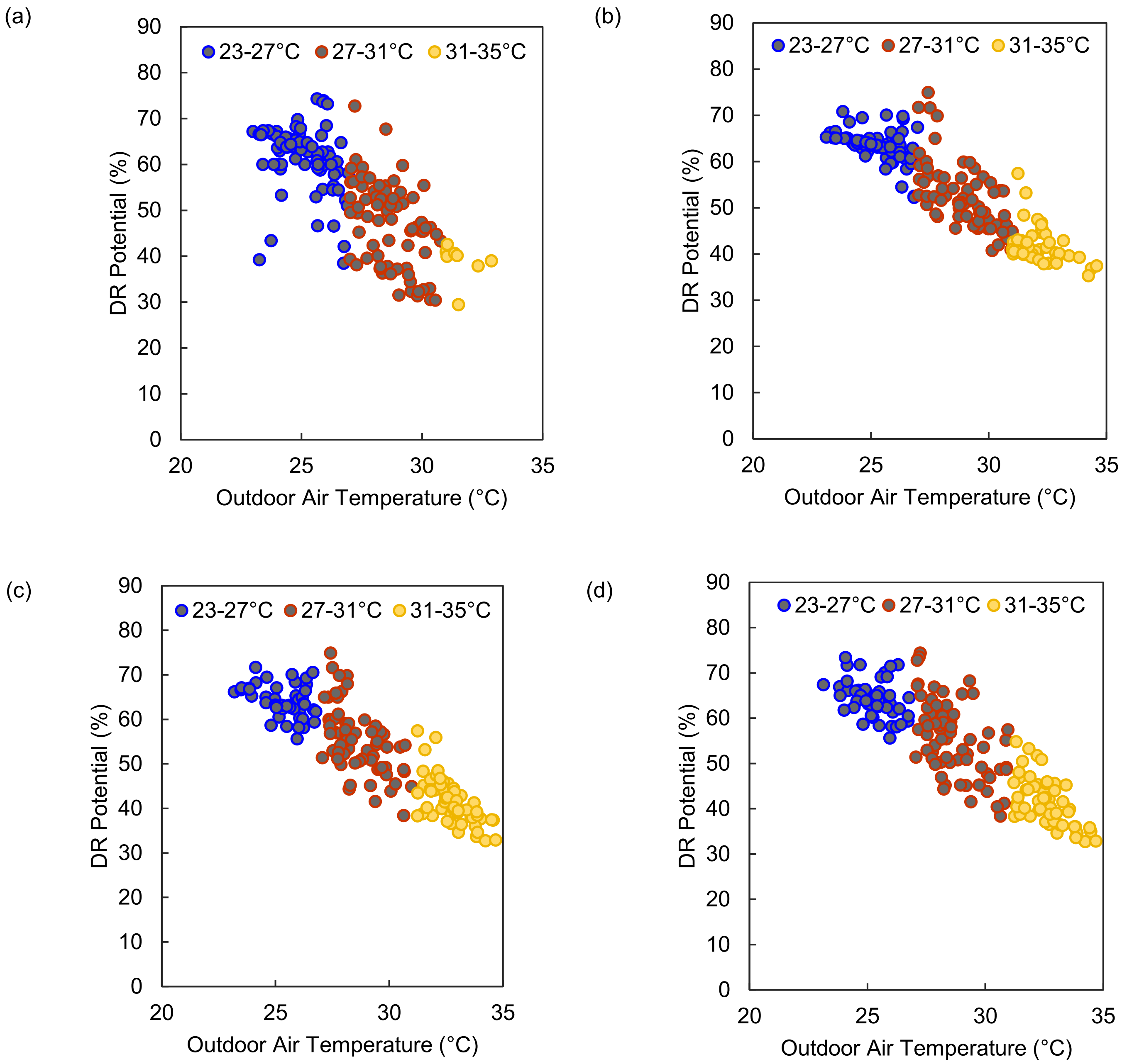

Figure 16. DR Potential vs. Outdoor air temperature at different times of the day for a typical school building in NSW (a) between 9 am to 11 am, (b) between 11 am to 1 pm, (c) between 1 pm to 3 pm (d) between 3 pm to 5 pm

2.4 Key Results – Office Buildings

The baseline representative building for schools is a ten-storey 6,003 m^2 Gross Floor Area (6,000 m^2 Net Lettable Area) building comprising ten zones (Figure 17). A detail about this building configuration and operation parameters can be found in the CSIRO report [6].

The HVAC system in this building encompasses an air loop, chilled water loop, condenser loop, and hot water loop. Each of these loops incorporates multiple HVAC components as listed below:

Air loop: an AHU, heating and cooling coils, and fans
Chilled water plant loop: one chiller and a supply pump
Condenser loop: one cooling tower and a supply pump
Hot water loop: one gas-fired boiler and a supply pump

Each of the ten zones is equipped with a dual duct VAV system that provides control over zone temperature by mixing the cold and warm air in various volume combinations.

Figure 17. A rendered 3-D image of the modelled building for offices

2.4.1 *Model validation*

The daily average electricity usage modelled for five locations in NSW climatic zone was compared against NEAR program data in Figure 18. Results indicate that depending on locations, the daily average electricity usage can vary by approximately 1-4% in different months in terms of coefficient of variance. The maximum and minimum limits for NEAR program data were generated by aggregating 288 office building data across all types of office buildings for a specific zone. Note that the NEAR program data used for validation covers four years of data (2016 to 2019) and all 4- and 5-star office buildings across NSW.

This Figure shows that the month-wise simulated daily average electricity usage in the NSW climatic zone is in agreement with the NEAR program data and follows a similar trend except in December. Typically, the occupancy number decreases in December month since many people take leave during this month, and this impacts the daily average electricity usage in a typical office building. However, this behavioural issue of occupants could not be captured by the model.

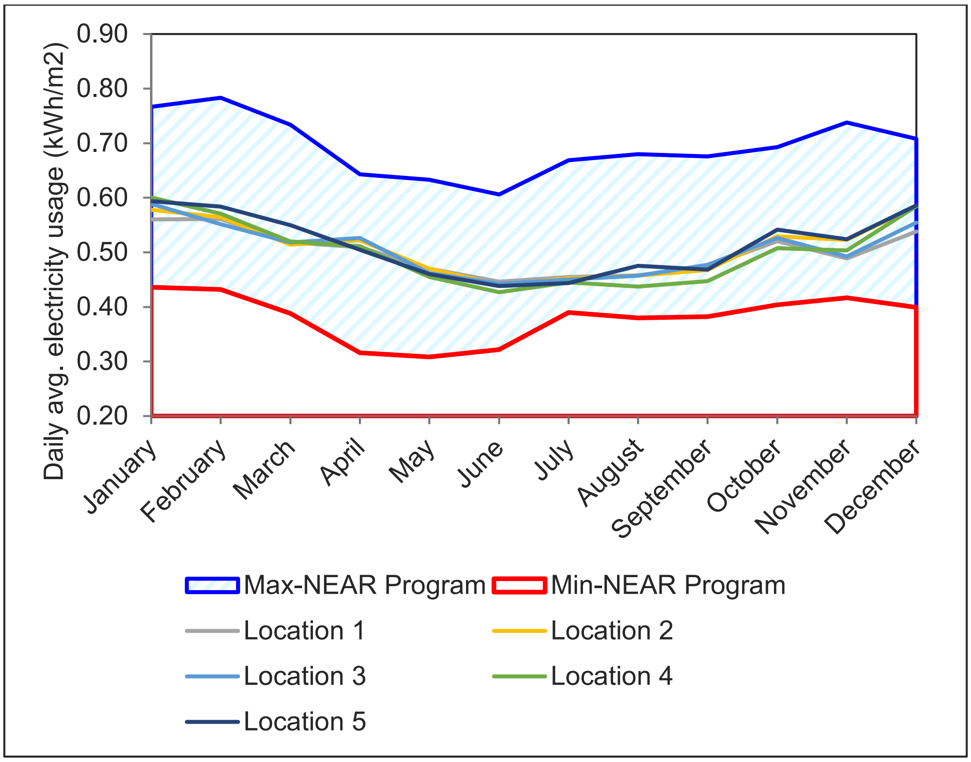

Figure 18. Comparison between measured and calculated daily avg. electricity usage for a typical office building in NSW

Figure 19 and Figure 20 provide a comparison between the simulated daily average electricity usage against NEAR program data for the VIC and QLD climatic zones, respectively. In both cases, five locations were picked representing VIC and QLD climatic zones (Figure 19 and Figure 20) in Australia.

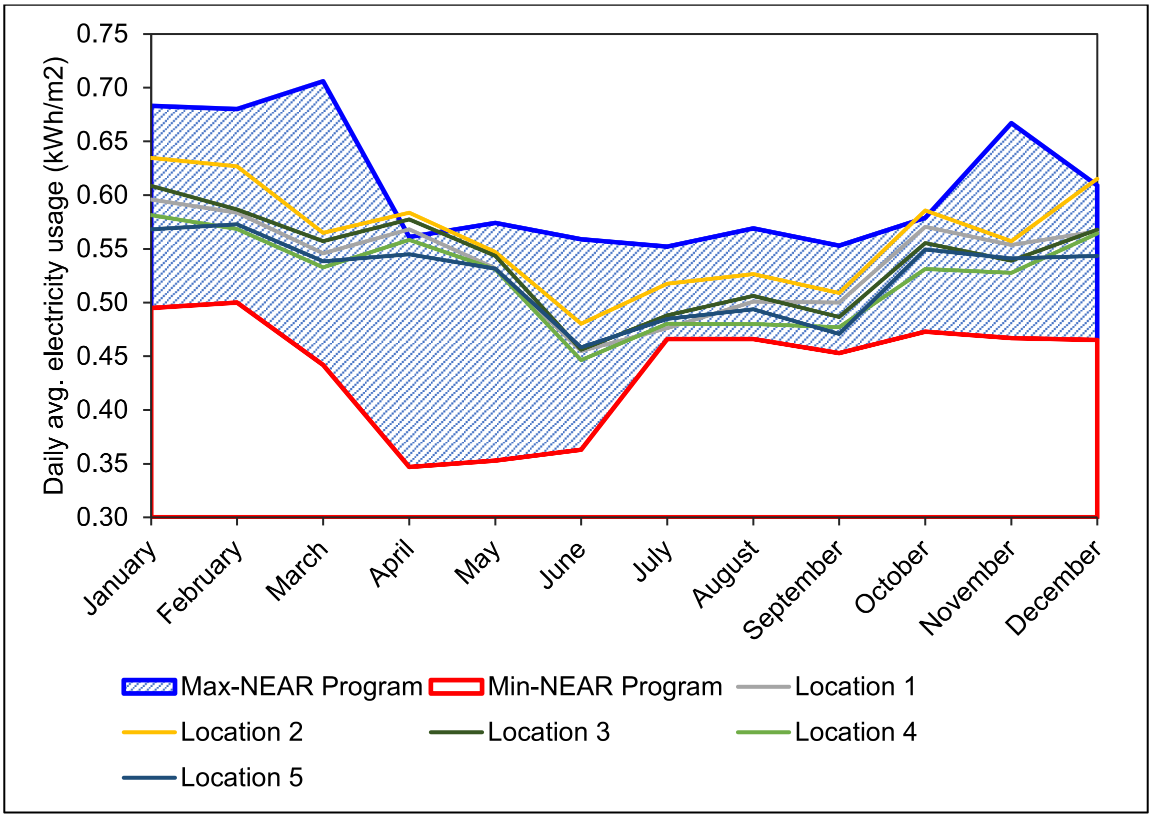

Figure 19. Comparison between measured and calculated daily avg. electricity usage for a typical office building in VIC

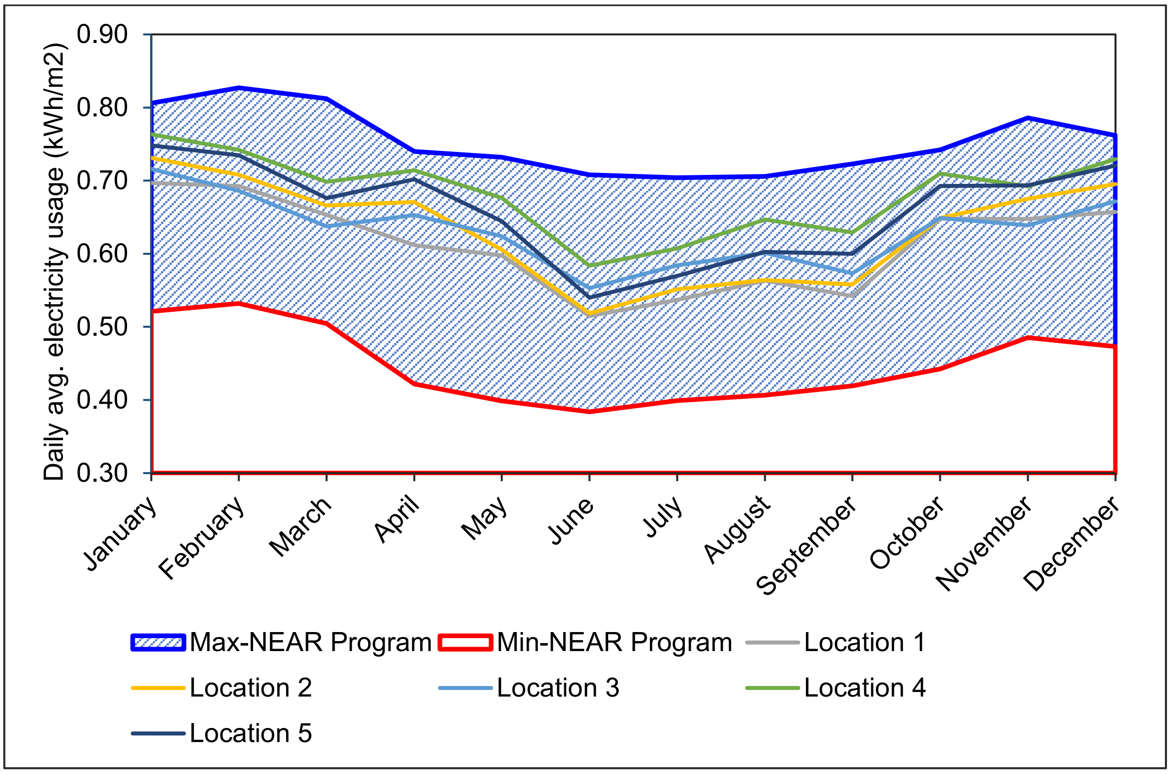

Figure 20. Comparison between measured and calculated daily avg. electricity usage for a typical office building in QLD

2.4.2 *Energy consumption breakdown*

The pie graph in Figure 21 shows the modelled energy consumption breakdown of a typical whole office building in NSW, being 33% AHU fans, 26% equipment, 25% lighting, 13% cooling, 2% heat rejection (cooling tower). Note that the share of equipment includes miscellaneous office equipment, such as process equipment, lift, etc.

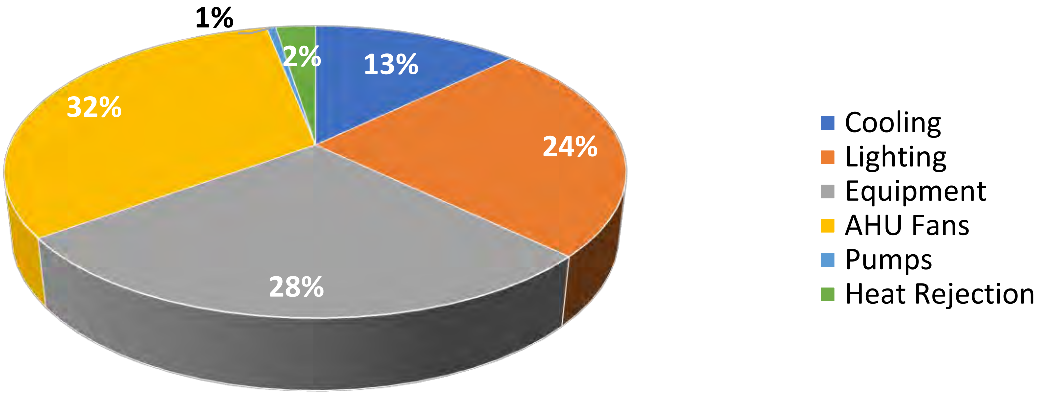

Figure 21. Typical energy consumption breakdown in a whole office building for NSW

2.4.3 *Peak electricity demand – monthly basis*

Figure 22 compares the share of peak electricity demand for electric components of the representative building for offices for a particular timestamp in different months of a typical year. The highest peak electricity demand was found to be on 8 Feb at 08:10 based on 10 min interval time-series data of electricity simulated by EnergyPlus. The chiller system holds the highest share of electricity during the summer months, followed by AHU supply and extract fans, equipment, lighting, cooling tower fan (heat rejection), and pumps. The peak demand in the winter months is lower than in the summer months. Results indicate that peak electricity demand can vary by around 23% due to seasonal variations.

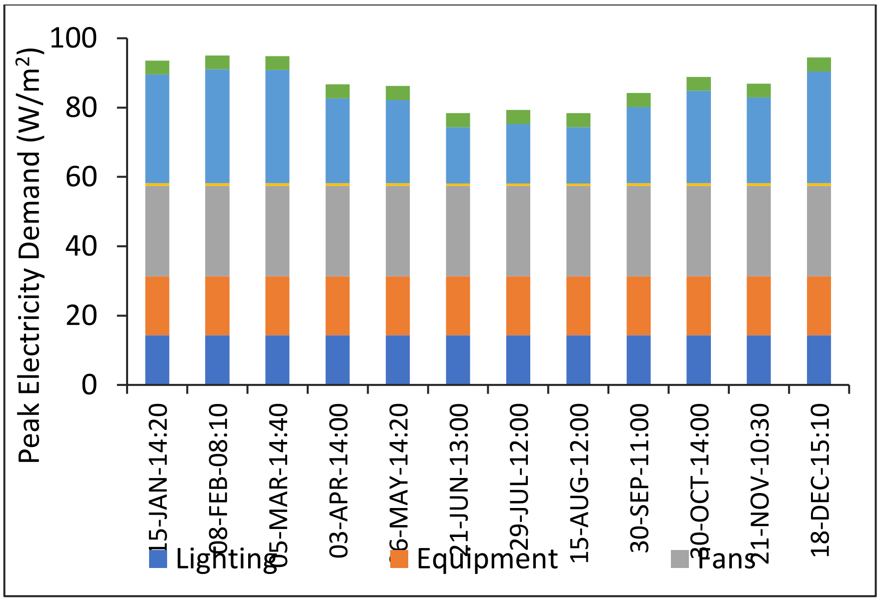

Figure 22. Peak Electricity Demand identified for a particular timestamp in different months – Office buildings

2.4.4 *Peak electricity demand day*

Figure 23 illustrates a breakdown of energy intensity in a typical office building on the peak electricity demand day (8-Feb). During occupied hours, the chiller system accounts for the highest amount of electricity, followed by AHU extraction and supply fans, interior equipment, lighting, and cooling tower fan. The electricity consumed by the chiller system rose sharply at 8 am to meet the additional cooling demand triggered by the cooling temperature setpoint changes at 9 am. The lighting and equipment load follow designated operation profiles of the weekday for Building Class 5 prescribed by NCC of Australia.

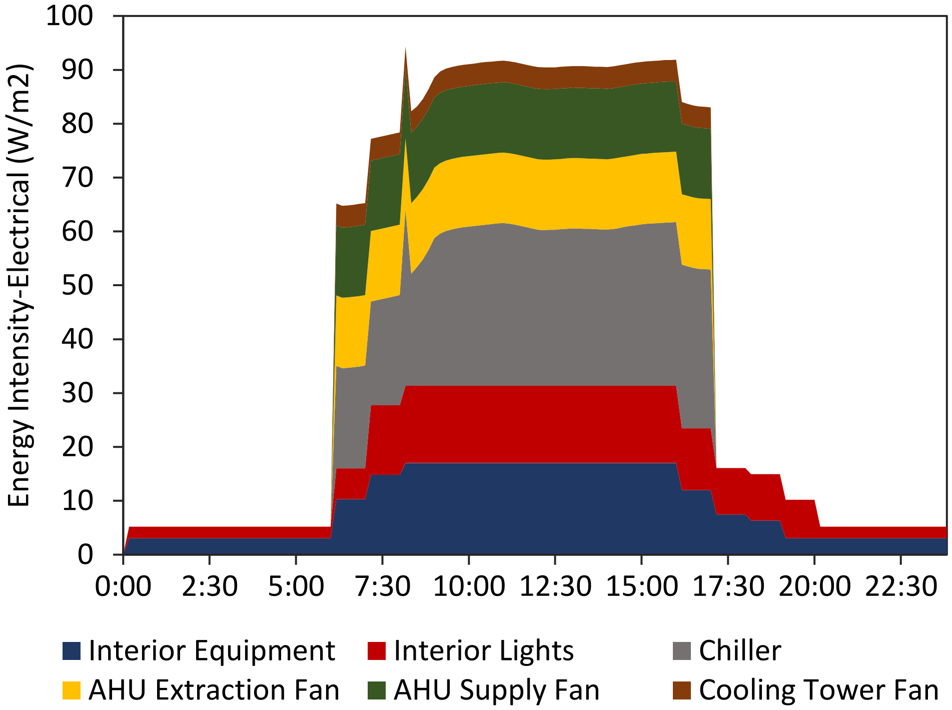

Figure 23. The disaggregated energy consumption data for a typical office building

Figure 24 presents the source of heat gains, e.g., occupancy, lighting, computer, equipment, and solar, which contribute to the cooling load on the peak electricity demand day. This Figure also shows how building fabrics such as glazing, walls, ceiling, floors, partitions, roofs, and infiltration perform at different times due to the changes in ambient temperature. The glazing is found to be a significant source of heat gains between 6:30 am and 6 pm. The zone sensible cooling required to lower its temperature to the specified temperature of the supply air stream and offset the heat gains was maximum when the cooling system is triggered at 6:30 am.

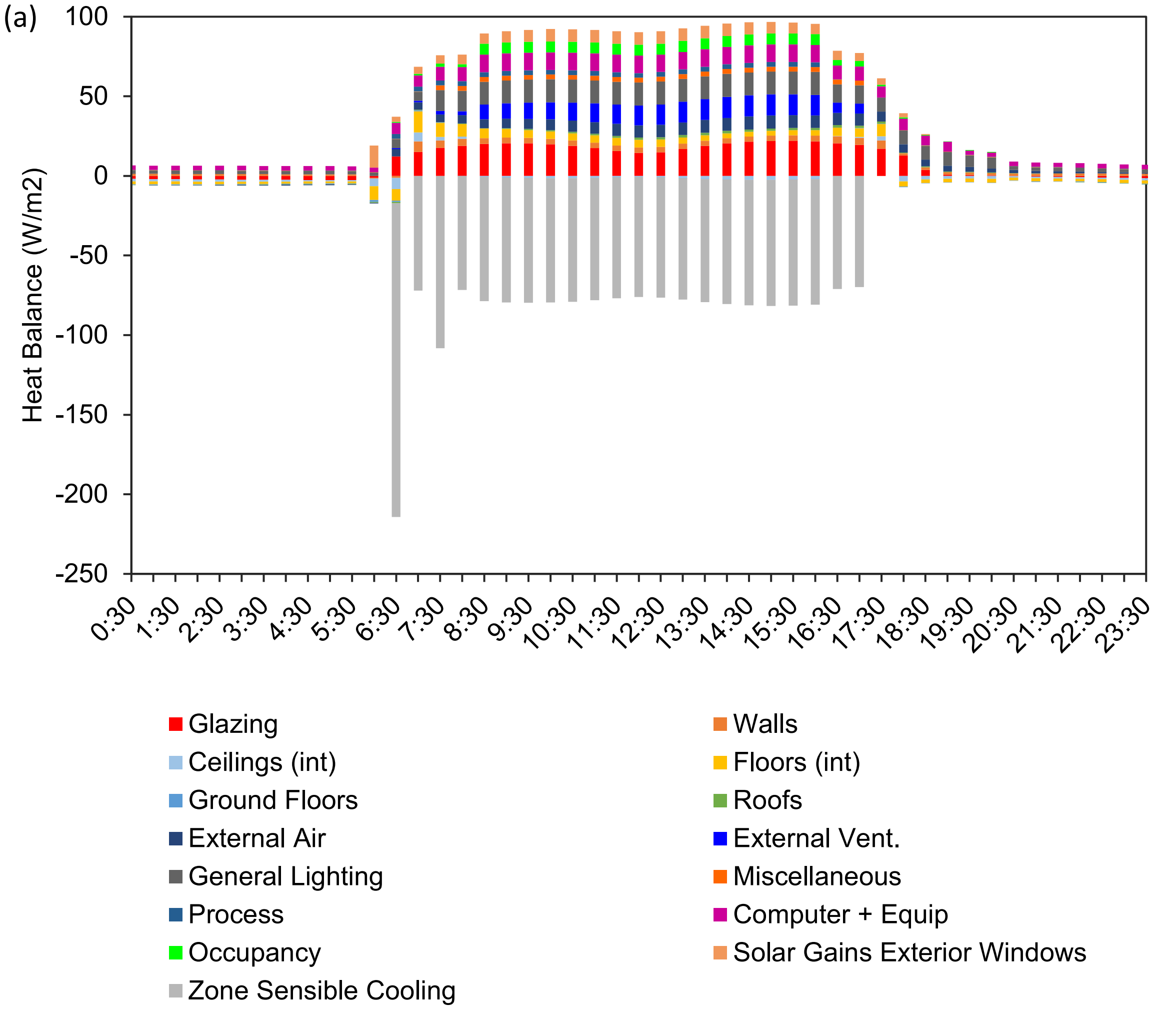

Figure 24. Heat gains and zone sensible cooling requirements of the office building model on the peak electricity demand day

2.4.5 Cooling Electricity Demand under Different Weather Conditions

As shown in Figure 25, the cooling electricity demand rate largely varies at each hourly time step of the building HVAC operational period. These variations in the cooling electricity demand rate are primarily due to the changes in outside air temperature (see Figure 26). The box and whisker plot (see Figure 25) summarizes the distribution of cooling electricity demand at each hourly time step of the building HVAC operational period. This plot shows an upward trend for the cooling electricity rate until 2 pm, accounting for around a 7.5 W/m^2 increase in cooling electricity demand in terms of the median value. The cooling electricity demand drops slowly between 3 pm through 5 pm.

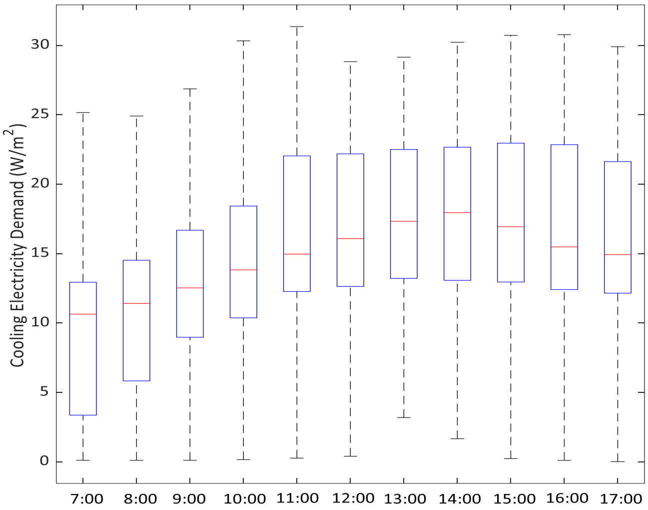

Figure 25. Hourly cooling electricity rate for the modelled office building in the summer season

Figure 26 illustrates a non-linear relationship between building cooling electricity rate and outdoor air temperature. The MATLAB Curve Fitting Toolbox function has been used here to perform regression by fitting a curve to data using a two-term power series regression model that can be expressed by:

$$y = ax^b + c \tag{1}$$

Where x and y stand for outdoor air temperature and building cooling electricity rate, respectively. A, b, and c are the coefficients.

Equation 1 indicates that the rate at which cooling electricity demand is changed is generally proportional to the outdoor air temperature raised to some power.

Fit a two-term Power Series Model using the fit Function:

$$f(x) = ax^b + c$$

Coefficients (with 95% confidence bounds):

$$a = -7.284e^7\ (-7.918e^7, -6.65e^7)$$
$$b = -5.087\ (-5.116, -5.057)$$
$$c = 23.68\ (23.64, 23.73)$$

Table 4. Table of fits for a two-term power series regression model

Fit type	SSE	R-square	DFE	RMSE	Coeff
Power2	112.2470	0.9985	1247	0.30	3

The optimized start points for Power fits are calculated based on the dataset. The robust least-squares fitting method was applied, and Levenberg-Marquardt was chosen as the fitting algorithm.

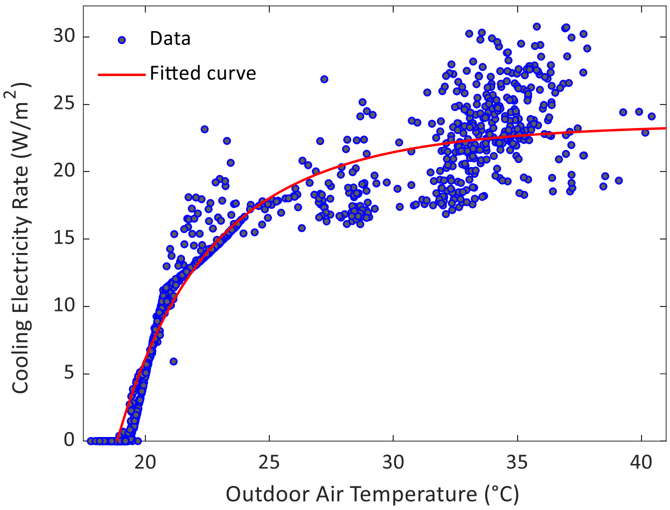

Figure 26. Cooling electricity rate vs. Outdoor air temperature for a modelled medium-sized office building

2.4.6 Demand Response Potential under Different Weather Conditions

To better understand how demand response potential varies by time of day and to summarize the distribution of DR at each hourly time step of the building HVAC operational period, a box plot is created and presented in Figure **27**. This Figure shows that there are large variations of the DR potential during each hour of the building occupied period. These variations are predominantly caused by the weather conditions, such as the outside air temperature (see Figure 29). On average, DR Potential could be around 22% by increasing the setpoint by 2°C for an hour. This Figure shows that there is no significant difference in DR potential in terms of percentage at different hours. Note that DR potential for a specific outdoor temperature band (23°C to 36°C) was considered in this analysis. To better reflect the changes in DR potential at different hours, the distribution of hourly DR potential from increasing the setpoint by 2°C for an hour is calculated in terms of magnitude (see Eq. 2). Figure 28 illustrates that at 12 pm, the rate of DR potential could be around 5 W/m^2 based on the median value, which is equivalent to 32% more than that at 9 am from increasing the setpoint by 2°C for an hour. Between 12 pm and 4 pm, the demand response potential remained quite stable. A probable reason behind this could be that outdoor weather condition does not vary much during this time. Besides, when the outside air temperature reaches or exceeds the design weather condition, the cooling units typically run at their full capacity to maintain the thermostat setpoints, and sometimes they fail. Therefore, there is little room for cooling units to reduce their power uses under this circumstance, even though thermostat setpoints raise a couple of degrees.

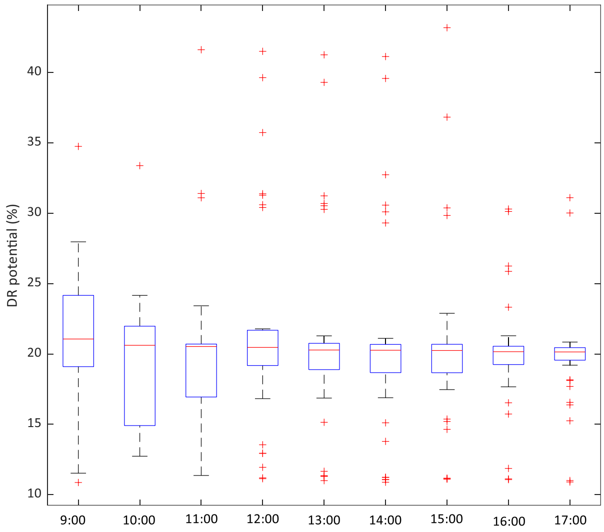

Figure 27. The distribution of hourly DR potential (%) of a typical office building from increasing the setpoint by 2°C for an hour

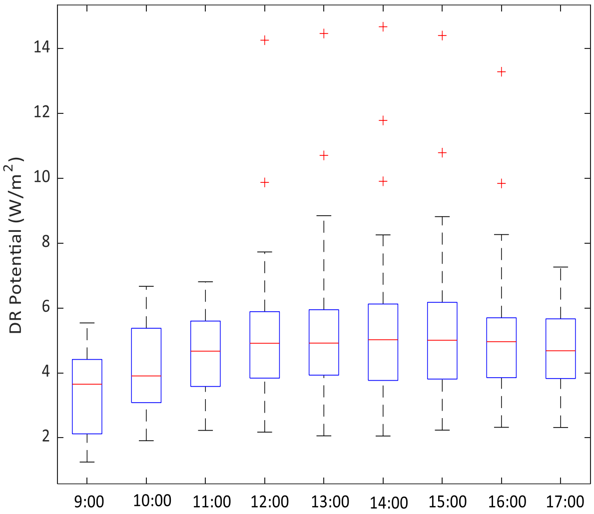

Figure 28. The distribution of hourly DR potential (W/m2) from increasing the setpoint by 2°C for an hour

The MATLAB curve fitting app has been used here to compare graphical fit results using different regression models, including the fitted coefficients and goodness-of-fit statistics using different regression models. The best fit results were exported to the MATLAB workspace to analyse the model. The best fit results were found with the third-degree polynomial. Polynomial models for curves are given by

$$y = \sum_{i=1}^{n+1} p_i \, x^{n+1-i} \tag{4}$$

Where $n + 1$ is the order of the polynomial, n is the degree of the polynomial, and $1 \leq n \leq 9$. The order gives the number of coefficients to be fit, and the degree gives the highest power of the predictor variable.

A third-degree polynomial is given by

$$\gamma = p_1 x^3 + p_2 x^2 + p_3 x + p_4 \qquad (5)$$

The best fit results used to characterize data using a global fit:

Linear model Poly3:

$$f(x) = p_1 * x^3 + p_2 * x^2 + p_3 * x + p_4$$

Where x is normalized by mean 29.98 and std 4.942 to eliminate the scaling problem.

Coefficients (with 95% confidence bounds):

$p_1 = -0.1176\ (-0.182, -0.05321)$
$p_2 = -0.05388\ (-0.1233, -0.01554)$
$p_3 = 1.34\ (1.212, 1.467)$
$p_4 = 4.119\ (4.027, 4.21)$

Table 5. Table of fits for the third-degree polynomial model

Fit type	SSE	R-square	DFE	RMSE	Coeff
Poly3	263.04	0.75	578	0.67	4

The model fit results indicate that the fitted curve is in line with the changes observed in the simulated data.

Figure 29 illustrates a non-linear relationship between building DR rate and outdoor air temperature and can be best described by a third-degree polynomial model expressed by Equation 5. Note that DR potential was calculated for the building occupied period only. This Figure shows that the DR potential during hot weather conditions can get saturated and then drop when the outside air temperature exceeds the design weather condition, and the cooling equipment reaches the design cooling capacity. This finding indicates that the sizing factor of cooling equipment is an important parameter to be considered when modelling commercial buildings.

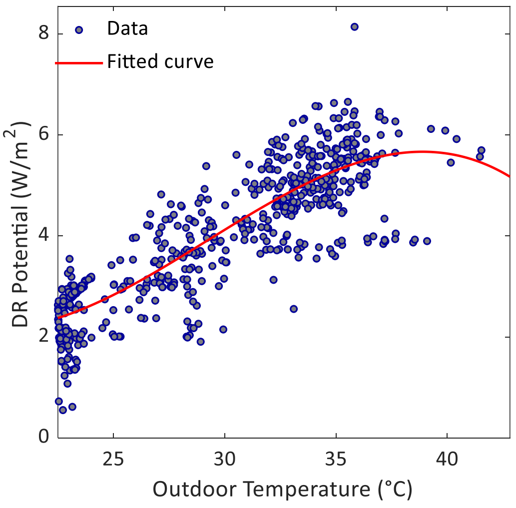

Figure 29. The DR potential vs. Outdoor air temperature for a modelled medium sized office building

3. CONCLUSIONS AND FUTURE DIRECTIONS

The results reported here represent a scoping study that aims at evaluating the demand response potential of Australian non-residential buildings. This report covers school and office buildings only.

3.1 Conclusions – School Buildings

The state-wide air-conditioning cooling capacity required to meet the cooling demand in the school buildings at peak load conditions in the extreme weather conditions was estimated from the baseline model for school buildings and is summarized in Table 6 for individual states.

Table 6. State-wide Maximum Installed Airconditioning Cooling Capacity if all schools were airconditioned

State/City	Typical installed a/c capacity (kW electrical equivalent per student)	Number of students	State-wide cooling capacity (MW electrical equivalent)
Qld/Brisbane	0.272	867,347	236
NSW/Sydney	0.256	1,243,835	319
ACT/Canberra	0.257	75,358	19
VIC/Melbourne	0.258	1,011,178	260
Tas/ Hobart	0.219	81,745	18
SA/Adelaide	0.264	274,302	72
WA/Perth	0.267	436,388	117
Theoretical National Maximum Installed Airconditioning Cooling Capacity across Australia if all schools were airconditioned			**1,041**

The results indicate that around 1 GW of air-conditioning is installed in the plant rooms of schools across Australia, given that all schools are airconditioned.

The state-wide Electricity Demand Response from school buildings was calculated for each 'bin' and is summarized in Table 7[3].

Table 7. The State-wide Electricity Demand Response from Schools for each 'bin'[4]

State/City	Temperature Band	Time of the Day	The fraction of the Installed Air-conditioning Capacity being used on a School Day (%)	State-wide Cooling Electricity Demand from Schools for each 'bin' (MW)	DR potential from increasing the setpoint by 2°C for an hour (%)	State-wide Electricity Demand Response from Schools for each 'bin' (MW)
NSW/Sydney	31-35°C	9 am – 11 am	51.8	165	39.0	64
		11 am – 1 pm	60.1	192	42.0	80
		1 pm - 3 pm	66.1	210	41.6	87
		3 pm - 5 pm	68.0	217	41.4	90
	27-31°C	9 am – 11 am	49.3	157	46.9	74
		11 am – 1 pm	51.68	164	52.5	86
		1 pm – 3 pm	50.9	162	55.1	89
		3 pm – 5 pm	50.9	162	55.5	90
	23-27°C	9 am – 11 am	38.6	123	59.5	73
		11 am - 1 pm	30.7	98	63.7	62
		1 pm – 3 pm	29.9	95	64.7	62
		3 pm – 5 pm	32.8	104	64.6	67

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[3] Detailed calculation procedures are explained in Section 2.2.4.

[4] Here each bin represents a particular time of the day for a specific temperature band

3.2 Conclusions – Office Buildings

The state-wide air-conditioning cooling capacity required to meet the cooling demand in the office buildings at peak load conditions in the extreme weather conditions was estimated from the baseline model for school buildings and is summarized in Table 8 for individual states.

Table 8. State-wide Maximum Installed Airconditioning Cooling Capacity in the Office Buildings

State/City	Typical installed a/c capacity (kW electrical equivalent per student)	Total NLA ('000 m^2)	State-wide cooling capacity (MW electrical equivalent)
NSW/Sydney	0.051	17,247	880
VIC/Melbourne	0.046	11,454	524
Qld/Brisbane	0.061	6,933	421
ACT/Canberra	0.035	2,471	86
WA/Perth	0.048	4,226	202
SA/Adelaide	0.046	2,197	100
Tas/ Hobart	0.035	775	27
Theoretical National Maximum Installed Airconditioning Cooling Capacity in the Office Buildings across Australia			2,240

The results indicate an estimation of the air-conditioning cooling capacity (2.24 GW) being installed in the office buildings across Australia, given that all offices are airconditioned. The total floor area of the building stock data for the baseline study model of offices used in this calculation includes the standalone stock data covering both government and private standalone offices.

The state-wide Electricity Demand Response from office buildings was calculated for each ‘bin’ and is summarized in Table 9.

Table 9. The State-wide Electricity Demand Response from Offices for each ‘bin’

State/City	Temperature Band	Time of Day	The fraction of the Installed Air-conditioning Capacity being used on an office day (%)	State-wide Cooling Electricity Demand from office buildings for each ‘bin’ (MW)	DR potential from increasing the setpoint by 2°C for an hour (%)	State-wide Electricity Demand Response from office buildings for each ‘bin’ (MW)
NSW/Sydney	31-35°C	9 am – 11 am	65.41	576	23.20	134
		11 am – 1 pm	63.91	563	21.65	122
		1 pm - 3 pm	66.09	582	21.68	126
		3 pm - 5 pm	66.37	584	21.59	126
	27-31°C	9 am – 11 am	52.83	465	28.17	131
		11 am – 1 pm	53.52	471	25.75	121
		1 pm – 3 pm	52.47	462	25.75	119
		3 pm – 5 pm	51.05	450	25.08	113
	23-27°C	9 am – 11 am	37.97	334	33.95	113
		11 am - 1 pm	44.99	396	28.01	111
		1 pm – 3 pm	41.64	367	34.76	127
		3 pm – 5 pm	43.19	380	26.50	101

3.3 Comparison of office and school buildings

Relative comparison between two building typologies indicates that the fraction of DR potential varies depending on building structural configurations, building morphology and operation related parameters, and HVAC system types. Results indicate that the state-wide cooling electricity demand of office buildings is around three times the number of school buildings. In contrast, the state-wide DR potential in office buildings of NSW from increasing the setpoint by 2°C for an hour is estimated to be only one and a half times more than that of school buildings. This indicates that the state-wide DR potential does not vary at the same rate as the state-wide cooling electricity demand varies from one building typology to another. A closer observation of zone sensible cooling requirements in the simulated representative building for schools and offices in response to convective and radiant heat gains from building fabrics and other sources shows that building fabric along with building structural configurations are predominantly responsible for this large variation in DR potential (%) (Section 2.3.4 and Section 2.4.4). The simulated school building is a two-storey building with a large floor area on each level. For this building type, the roof was found to be a significant source of heat gain, which largely varies with outdoor air conditions. In contrast, the office building is a high-rise ten-storey building with a comparatively smaller floor area on each level. For this building typology, the amount of heat gain by the roof is negligible. The glazing was found to be a significant source of heat gain for an office building and this amount does not vary much in day time. Also, these two buildings' window to wall ratios, occupancy, lighting and equipment operation profiles differ, which are partly responsible for the variation in the fraction of DR from school and office buildings at different times of the day. It is worth noting that the simulated school and office buildings characterize the typical school and office buildings in Australia.

3.4 Future Directions

This research could be further extended by –

- Incorporating more building typologies in the assessment of DR potentials and developing DR related recommendations for different climatic zones considering the varying degree of load profile for different building types.
- Performing an extensive study of the sensitivity analysis of the demand response potential to building and HVAC system related parameters such as the building fabric, orientation & shading, internal heat loads, and HVAC system sizing.
- Evaluating air-conditioning enhanced DR opportunities for different building typologies by incorporating a supplementary thermal storage system.

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