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Abstract

Natural Ventilation (NV) in buildings has a significant potential to reduce building energy use, provide thermal comfort and improve indoor air quality. NV potential is highly dependent on climatic conditions and may change over time due to global warming. To ensure a sustained and efficient NV design, it is necessary to identify the maximum potential of NV in a given climate and its sensitivity to climate change. Accordingly, this research aims to i) quantify the Climatic Potential of Natural Ventilation (CPNV) under present climate conditions and explore how this potential may change over time in the future in different Australian climate zones, ii) propose a new index named the Climatic Potential of Extended Natural Ventilation (CPENV) which identifies to what extent NV can be exploited if elevated airspeed requirements are met, and iii) evaluate the sensitivity of both CPNV and CPENV indices to global warming. Results showed that CPNV could be extended up to 18% with a required airspeed. The results also highlighted that the Total Climatic Potential of Natural Ventilation (TCPNV) could increase up to 27% or decrease up to 14.3% based on the present climate zone in the future.

Keywords: Natural Ventilation; Climate Change; Energy Savings; Ceiling fan

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1. Introduction

Greenhouse Gas (GHG) mitigation is one of the global issues affecting all humans [1-6]. As a result of global warming, it is predicted that the severity and frequency of extreme climate events such as heat/cold waves, water scarcity, droughts and floods will become more often in the future [7]. Studies have also proved that such severe climate conditions increase the likelihood of conflict occurrence and forced migration [8]. Therefore, developing effective and practical solutions to mitigate climate change risks and adapt to future climate conditions is vital. To predict the future climate conditions, the Intergovernmental Panel on Climate Change (IPCC), in the fifth assessment report [7], presents four different scenarios called Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5, RCP6 and RCP8.5. These pathways predict future climate conditions with different possible trajectories for GHG concentrations. Among these scenarios, RCP2.6 is the mitigation pathway leading to a global temperature rise well below 2 °C by 2100. To achieve this target (preferably to 1.5 °C) as set in the Paris agreement, reducing energy consumption, particularly in energy-intensive sectors, is vital and highlighted in the literature [9-12]. Energy consumption in the building sector accounts for approximately 40% of total global energy-related emissions in 2019 [13]. Of all energy consumers in buildings, air conditioning systems constitute nearly 20% of total building electricity use and are responsible for a large proportion of GHG emissions [14]. According to the International Energy Agency (IAE), energy use for buildings space cooling has doubled since 2000 and may double again from current levels by 2040 [14, 15]. It is estimated that space cooling will become the single largest building electricity user, accounting for approximately 16% of global electricity demand in 2050 [15]. It is, therefore, necessary to identify energy-efficient alternatives for energy-consuming mechanical systems. Nowadays, new technologies in building design [16], air-conditioning system [17], and/or application of artificial intelligent method [18-20] are widely employed to increase the energy performance of buildings. While effective, these methods are often associated with some additional costs. To minimise these costs, nature-based opportunities should be considered first.

Natural Ventilation (NV) is an alternative cooling source that can be utilised to reduce energy usage for cooling and ventilation in buildings [21, 22]. With concerns for energy, climate change and indoor air quality, the NV strategies have become one of the key elements in the design of sustainable buildings. NV is to bring fresh air from outside to indoor areas using natural driving forces such as wind and buoyancy [23]. The cooling potential of NV depends on many parameters, including outdoor climate conditions and building characteristics such as window and balcony types [24-30]. However, the first step in an NV strategy in buildings is to identify the availability and usability of NV in each climate. Quantifying NV potential for a specific climate can assist architects in employing appropriate passive and/or low-energy NV strategies and improve the energy demand of buildings [31]. The following section reviews the indices developed for evaluating the NV potential and states the research objectives.

1.1. Natural ventilation evaluation indices

The outdoor environment is one of the most influential factors in assessing Natural Ventilation Potential (NVP) in buildings. Generally, NVP can be assessed on three main scales, including Climate, Site and Building. Fig. 1 depicts this classification. NVP in the climate scale depends on climatic parameters such as air temperature and humidity of a specific location [27, 32, 33]. Several indices in this category are introduced later in this section. In the site scale, which refers to buildings' surrounding here, some other parameters such as urban morphology and planning strategies [34, 35], noise and atmospheric pollution [36] are considered along with meteorological parameters. The building scale often includes more sophisticated evaluation metrics for NVP estimation. These metrics are useful in the buildings' design phase allowing designers to find the interactive effect of building parameters on NVP, such as thermal properties of the building envelope, openings configuration, solar and internal heat gain, etc. The impact of these parameters is usually investigated using numerical [25, 37] and/or experimental methods [38-41]. For example, field measurements were conducted to evaluate cooling potential of different NV strategies in office buildings in Cyprus [40]. The results showed that the night-time cross ventilation strategy is more effective in reduction of cooling energy in office buildings. Another study evaluated the impact of NV on indoor thermal environment in educational buildings. The results demonstrated that natural ventilation can improve both energy performance and indoor air quality in buildings [41]. Some indices have also been developed considering building parameters such as Natural Ventilation Effectiveness (NVE) [24], Ventilation Performance Indicator (VPI) [42], Satisfied Natural

Ventilation Hour (SNVH) [43], Natural Ventilation Cooling Effectiveness (NVCE) and Climate Potential Utilization Ratio (CPUR) [26]. All metrics are informative and can be employed during different building phases to estimate the cooling potential of NV. However; understanding the potential of a climate for natural ventilation should be the first step. A comprehensive review of NVP metrics has been presented in the study by Yoon et al [26].

NVP in the climate scale is evaluated without interfering with (specific) building characteristics. Indices such as natural ventilation hours (NVh) [28, 44-46], Climatic Cooling Potential (CCP) [32], Climatic Potential for Natural Ventilation (CPNV) [27], enthalpy-based climatic cooling potential [47], are used in the climate scale. Artmann et al. [32] introduced the CCP index to estimate the night-time cooling potential of NV based on building and outdoor temperature differences where building temperature is assumed to oscillate harmonically within a range. CPNV is an index that is defined as "the number of hours in a year when natural ventilation could be performed, divided by the total number of hours in a year" [27]. This index includes ambient temperature and humidity ratio constraints in the comfort range. The upper band of temperature is determined by the adaptive thermal comfort model, and for the relative humidity, the constraints of 30% and 70% are considered. NV hours index is defined as the number of hours in a year when outdoor weather conditions (e.g. temperature, humidity, wind speed, air quality) are suitable for using NV. Typical Meteorological Year (TMY) weather files are used to evaluate NV hours. The upper thresholds of the adaptive thermal comfort model are considered for NV hours calculation, and the maximum allowable indoor air speed can be estimated using an empirical equation [28].

These indices indicate the (nearly) maximum potential of NV that can be exploited in a climate. Factors such as wind directions, window discharge coefficients, building geometry, local pollution levels, urban obstructions, and external noise ultimately affect the number of hours when natural ventilation is utilised in buildings. The actual number is often lower than the actual number of CPNV. It is worth noting that some strategies can be implemented in buildings (e.g. benefiting from buildings' thermal mass) so that the actual NV hours can exceed CPNV [26]. An index proposed here is the Climatic Potential of Extended Natural Ventilation (CPENV), which is based on the effect of elevated airspeed. In some climates, thermal comfort can be met simply by increasing indoor air speed using low-energy devices instead of cooling down the air using air conditioning systems [48-53]. An example of a low-energy device is ceiling fans, which are frequently used in many warm and hot regions [48, 50, 54, 55]. Windcatchers [56], a double-skin façade building with strategic openings [57], and a well-design building with cross ventilation are examples of zero energy strategies for utilising the Climatic Potential of Extended Natural Ventilation (CPENV). According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the upper limit of the adaptive thermal comfort model can be extended with the elevated airspeed and thus, the number of hours that a building benefits from natural ventilation can be extended. This extension, indeed, depends on the climate characteristics and varies from one climate to another. Importantly, this potential may change over time due to global warming. Erba et al. [58] studied the potential of natural night ventilation under future weather climates in Milan and found that NV potential would reduce during the hottest months in the future. Heracleous et al [59] assessed the climate change impacts on natural ventilation in educational buildings in Southern Europe. It was found that the educational buildings cannot satisfy the thermal comfort requirements of the future. Bamdad et al. [48] demonstrated that ceiling fan energy saving potential in mixed-mode buildings varies in different climates and would also change in the future for each specific climate, that necessitate evaluation of NV strategies under various climate change scenarios. According to IPCC, the impact of climate change is different around the globe, and some regions are likely more affected by global warming and may experience greater temperature rises. Thus, climatic potentials of both NV and ENV may vary over time in different regions in the future.

The majority of studies conducted so far have only focused on NV potential under present climate conditions, and future changes of CPNV have not been fully studied. Accordingly, this research aims to 1) quantify CPNV under present climate conditions and explore how this potential may change over time in the future in different Australian climate zones, 2) propose new indices called Climatic Potential of Extended Natural Ventilation (CPENV) which identifies to what extent the climatic potential of NV can be exploited in a given if elevated airspeed requirements are met, and Total Climatic Potential of Extended Natural Ventilation (TPENV), 3) evaluate the sensitivity of these new indices to global warming based on emissions scenarios introduced in IPCC AR5 [7]. Furthermore, in this research climatic potential of NV is studied under two-time schedules: when NV is desired only during office hours and for all the time (24 h). The rest of the paper is structured as follows: Section 2 describes the paper's methodology. Section 3 presents the results and discusses the main findings. Finally, conclusions are drawn, and future research directions are stated in Section 5.

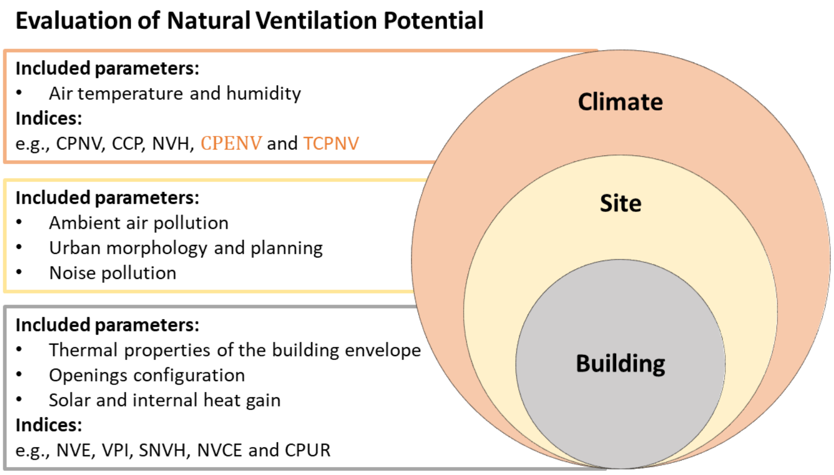


Figure 1: Identified scopes for evaluation of NVP in the literature and corresponding indices including the proposed indices (in colour).

2. Methodology

2.1. Climatic Potential of NV and ENV

The first step in designing natural ventilation strategies in buildings is to identify whether (or to what extent) a climate is suitable for utilising natural ventilation. The suitability of a climate for natural ventilation depends on different parameters such as temperature, humidity, and outdoor air quality. The CPNV index [27] quantifies a climate's suitability for natural ventilation using temperature and humidity. This index, discussed earlier, is calculated by the hours when natural ventilation can be performed divided by the total number of hours in a year. In this research, in order to examine the suitability of a climate for NV in a specific time interval of a day (for example, if NV is desired only during office hours) for a given period (e.g. only in summer), the original formula for CPNV index [27] was re-formulated with some changes, and also presented as a percentage. The modified formula allows users to better customise the duration of interest and evaluate CPNV for a specific time period. The modified formula for CPNV index is written as follows:

$$CPNV = \left(\frac{1}{h_{tot}} \sum_{d=d_s}^{d_f} \sum_{i=i_s}^{i_f} h_{NV,d,i} \right) \times 100 \quad (1)$$

$$h_{NV,d,i} = \begin{cases} 1, & if \quad T_{l,j} \leq T_{o,d,i} \leq T_{u,j} \text{ , and } W_l \leq W_{o,d,i} \leq W_u \\ 0, & otherwise \end{cases}$$

where $h_{NV,d,i}$ represents the i-th hour of the d-th day in a typical year and is equal to 1 when outdoor conditions meet the thermal comfort criteria, i_s is the start time, i_f is the final time, d_s is the start day, and d_s is the final day of natural ventilation. h_{tot} is the total number of hours in the desired duration (e.g. $i_s = 1$, $i_f = 24$, $d_s = 1$, $d_f = 365$, and $h_{tot} = 8760$ if NV is sought 24hr per day for a whole year), T is the temperature, W is the humidity ratio, and subscripts l, u and o refer to lower, upper and outdoor, respectively. The lower and the upper temperature limits can be determined by the adaptive thermal comfort model introduced by ASHRAE Standard 55 or EN 16798-1:2019. According to the ASHRAE [60], the upper and lower temperatures of the adaptive comfort model with 80% acceptability can be identified as follows:

$T_{u,j} = 0.31(T_{m,j}) + 21.3$	(2)
$T_{l,j} = 0.31(T_{m,j}) + 14.3$	(3)

Where $T_{m,j}$ can be calculated using the mean monthly outdoor dry bulb temperature, and $j = 1, 2, \ldots, 12$ refers to the calendar months. The prevailing mean outdoor air temperature can also be used for the calculation of T_m [60]. It should be noted that lower values for T_l can be utilised based on other references [27, 30]. In [27] humidity constraints were considered for CPNV calculations, and the suggested lower and upper bounds are 30% and 70%, which are often assumed to guarantee thermal comfort conditions. It should also be noted that ANSI/ASHRAE Standard 55 discusses that humidity has been considered in the adaptive thermal comfort model, and there is no need to consider humidity as a separate constraint. Some other studies also disregarded this constraint [26]. However, if humidity is a concern, appropriate values for W_l and W_u (or RH_l and RH_u) can be considered in the above equation.

Climatic potential of Extended Natural Ventilation (CPENV): ASHRAE standard 55 [60] allows an increase in the upper acceptability limit of adaptive thermal comfort related to airspeed if the operative temperature is greater than 25˚C. The upper acceptability limit can be increased up to 2.2 ˚C when the average airspeed in buildings is 1.2 m/s. This increase can extend the climatic potential of natural ventilation. With the use of some low energy devices such as ceiling fans or passive strategies, indoor airspeed can reach the required level, and NV can still be used for cooling purposes. It should be noted that some studies have shown higher temperature offsets as a result of elevated airspeed (e.g., ceiling fans) [49], which can also be used to calculate CPENV; however, in this study, the ASHRAE recommendation is followed. The index below quantifies the climatic potential of extended natural ventilation (CPENV):

$$CPENV = \left(\frac{1}{h_{tot}} \sum_{d=d_s}^{d_f} \sum_{i=i_s}^{i_f} h_{ENV,d,i}\right) \times 100 \tag{4}$$

$$h_{ENV,d,i} = \begin{cases} 1, & if \quad T_{u,j} \leq T_{o,d,i} \leq (T_{u,j} + \Delta T) \;, \quad and \quad W_l \leq W_{o,d,i} \leq W_u \\ 0, & otherwise \end{cases}$$

where $h_{ENV,i}$ is the *i*-th hour in a typical year and is equal to 1 when outdoor conditions meet the above criteria. In this research delta T is set to 2.2 ℃ [60]. Total Climatic Potential of Natural Ventilation (TCPNV) is also defined as follows:

$$TCPNV = CPNV + CPENV \tag{5}$$

2.2. Future climate data

The IPCC in the Fifth Assessment Report (AR5) introduced four scenarios, called Representative Concentration Pathways (RCPs), to predict how concentrations of GHG in the atmosphere will change in the future. These pathways are based on a different approach than the previous (SRES) scenarios introduced in the third and fourth Assessment Reports. RCPs introduce a range of possible climate change scenarios as a result of different levels of radiative forcing (RF), which quantifies changes in energy flux (W/m^2) in the atmosphere caused by anthropogenic GHG emissions relative to a reference year (pre-industrial period). These four pathways include RCP 2.6, which represents a mitigation scenario leading to a low RF level of 2.6 (W/m2) and a global temperature increase in the range of (0.3 to 1.7 ˚C), RCPs 4.5 and 6 representing two medium stabilisation pathways in which RF is stabilised at

4.5 and 6 (W/m^2) after 2100, and RCP 8.5 reflects a very high emission pathway with a projected global temperature increase of in the range of (2.6 to 4.8˚C). It should be noted that the geographical distribution of the temperature increase would be different in different regions around the globe.

To predict future climate conditions, Global Climate Models (GCMs) are used. These numerical models simulate the earth systems such as physical processes in the atmosphere, oceans, and land surface under different emission scenarios to predict future climate conditions. However, the spatial resolution of these models is quite coarse (in the range of 100-300 km^2) and cannot be directly used for building simulation studies [61]. To convert GCMs data to suitable temporal and spatial resolutions, downscaling techniques are applied. There are two commonly used downscaling techniques: dynamical and statistical methods. The dynamical downscaling method uses Regional Climate Models (RCMs) and generates information with finer resolutions from GCMs outputs; however, it is computationally intensive [62]. In contrast, statistical downscaling such as the morphing method is based on accepted statistical procedures and creates statistical links between observed local climate variables and larger-scale climate variables. Both techniques have been widely used by many researchers to understand the impact of climate change on buildings. Of all statistical methods, morphing is the well-established and the most commonly used statistical method [61, 63]. In this study, future weather files developed by Commonwealth Scientific and Industrial Research Organisation (CSIRO) were used. The morphing method was applied to the typical meteorological year (TMY) weather data of each climate to predict future climate conditions under two RCP2.6 and RCP8.5 scenarios in eight different Australian climate zones, specified in Table 1. CSIRO TMY files are based on historical weather data drawn from the years 1990 to 2015. These files are also used in the Australian accredited energy rating tools [64]. More details about CSIRO’s future weather files are available here [65].

Table 1: Specification of climate zones in Australia

Climate Zone (CZ)	Climate Specification	City	Köppen climate classification
1	Hot humid summer, and warm winter	Darwin	Tropical Savanna Climate (Aw)
2	Warm humid summer and mild winter	Brisbane	Humid subtropical climate (Cfa)
3	Hot dry summer and warm winter	Alice Spring	Hot desert (BWh)
4	Hot dry summer and cool winter	Wagga Wagga	Humid subtropical (Cfa)
5	Warm temperate	Perth, and Adelaide, Sydney (East)	Mediterranean climate (Csa), Humid subtropical (Cfa)
6	Mild temperate	Sydney (West), Melbourne	Humid subtropical (Cfa), Temperate oceanic climate (Cfb)
7	Cool temperate	Canberra & Hobart	Mild temperate oceanic climate (Cfb)
8	Very cold winter & warm to hot dry summer	Alpine regions	Subpolar oceanic (Cfc)

3. Results

In this study, to investigate the impact of global warming on NV and ENV, high and low emissions pathways: RCP 2.6 and RCP 8.5 were selected and used to project future weather conditions for two time periods, the 2050s and 2090s, in ten major cities located in different climate zones in Australia. These two scenarios represent the possible minimum and maximum changes in the future climate according to IPCC. In this section, the projected weather data is first analysed, then both CPNV and CPENV are quantified, and the impact of climate change on these indices is discussed for two schedules: a full day (24 h) schedule for NV, as opposed to office hours. For NV during office hours, it is assumed that NV is desired only during office hours. This study uses the occupancy schedule between 07:00 and 18:00 for office buildings recommended by National Australian Built Environment Rating System (NABERS) [66]. It should be noted that CPNV and CPENV values are extracted based on typical meteorological year weather data developed by CSIRO; however, other TMY files or measured data can also be utilised to calculate these indices.

3.1. Future weather

Table 2 shows the annual mean and projected temperatures for 2050 and 2090 for ten Australian cities. The Climate Zone (CZ) associated with each city is also presented in this table. These climate zones are defined by the national construction code of Australia, ranging from CZ1 (hot, humid summer, warm winter) to CZ 8 (Alpine). As can be seen, the average yearly temperature rise varies in different cities. It is predicted that by 2050 Hobart and Wagga Wagga will experience the minimum and maximum temperature rises under the low emission scenario (RCP2.6), respectively. Considering the RCP 8.5, it is estimated that Sydney will experience the maximum temperature rise of 2.4 ℃ by 2050. These temperature rises will be intensified by 2090 with a maximum of 4.5 ℃ in Brisbane, followed by 4.2 ℃ for Wagga Wagga, Canberra and Alice Springs under the high emission scenario.

Table 2: Projections of the temperature change under the two RCP scenarios (2.6 and 8.5) in 2050 and 2090

Climate Zone	**Annual average temperature (℃)**	**ΔT (2050)**		**ΔT (2090)**	
	Present	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
Darwin (CZ1)	27.3	0.8	2.1	0.7	3.7
Brisbane (CZ2)	20.1	1.1	2.1	0.7	**4.5**
Alice Springs (CZ3)	21.6	0.9	2.1	0.8	4.2
Wagga Wagga (CZ4)	15.8	1.6	1.9	0.8	4.2
Perth (CZ5)	18.4	1.0	1.7	0.5	3.7
Adelaide (CZ5)	17.0	1.0	1.4	0.8	3.7
Sydney (CZ5&6)	18.1	1.3	**2.4**	1.1	4.1
Melbourne (CZ6)	15.8	0.9	1.5	0.8	4.1
Canberra (CZ7)	13.3	1.2	1.9	1.1	4.2
Hobart (CZ7)	12.7	0.7	1.6	0.5	4.1

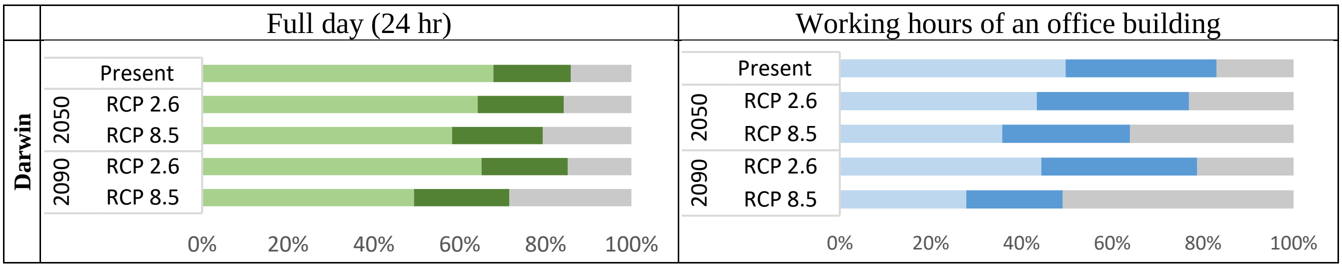
3.2. Climatic potential of NV and ENV

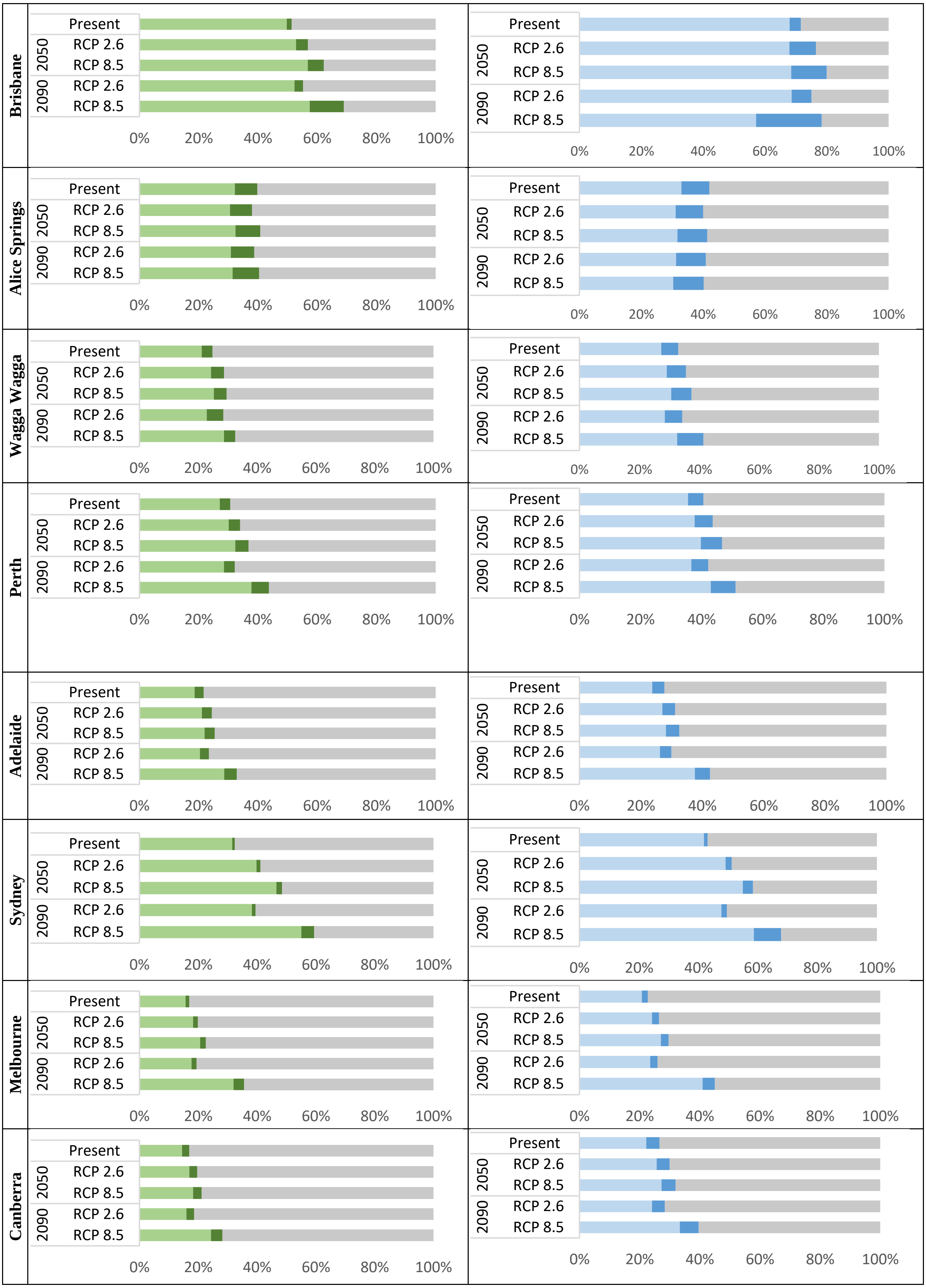
Figure 2 shows the climatic potential of CPNV and CPENV for ten cities under present and future climate conditions. As can be seen, both CPNV and CPENV are a function of climate characteristics and climate change scenarios. Figure 2 shows that Darwin and Brisbane have a significant potential to use NV, followed by Sydney and Perth. For all cities, CPNV during office hours increases except for Darwin, which experiences a reduction of 18%. Brisbane, however, significantly benefits from an increase in NV availability during office hours. Importantly, CPNV in all cities, except Darwin, increases (or remain almost constant) in the future, underlining the role of this strategy in designing low-energy buildings and mitigating GHG emissions.

In Hobart with a cold climate, the CPNV value is less than 10%, and CPENV is negligible. Under future climate conditions, neither CPNV nor CPENV changes significantly. The only exception is the RCP8.5 scenario by 2090, in which CPNV reaches approximately 22%. However, this climate shows higher potential for NV during office hours, with about 15% under present climate conditions and around 33% under RCP 8.5 by 2090.

CPENV in Darwin is remarkably higher than in other climates under both present and future climate conditions. Although climate change reduces the CPNV in Darwin, particularly during office hours, this climate has a significant potential to benefit from ENV under both present and future climate conditions, and the TCPNV value is still very high. In Brisbane, buildings targeting to employ NV during office hours (e.g., mixed-mode buildings) can benefit significantly from both CPNV and CPENV, leading to TCPNV between 70 to 80%. However, CPENV in Brisbane (CZ2) is not a constant trend over time and increases under climate change, reaching 11% by 2090. CPENV in other studied cities shows a max of 4% under the worst climate change scenario.

Regarding the CPENV during office hours, the same trend is observed. However, the CPENV value is higher during this time interval, particularly for Darwin that reaches up to 34% under RCP 2.6 by 2090. Overall, warmer climates in Australia can benefit more from CPENV than colder Australian climates, even under climate change effects.




Brisbane
Alice Springs
Wagga Wagga
Perth
Adelaide
Sydney
Melbourne
Canberra
Present
2050
RCP 2.6
RCP 8.5
2090
RCP 2.6
RCP 8.5
0%
20%
40%
60%
80%
100%

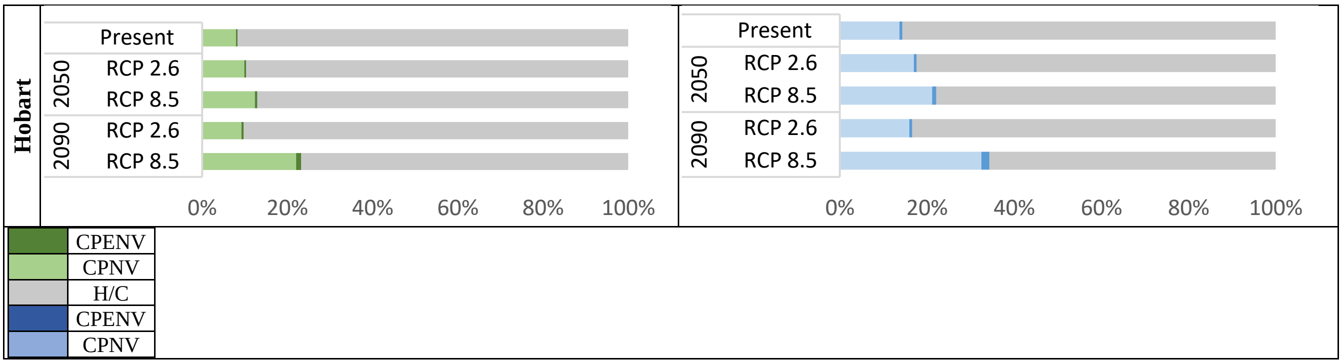


Figure 2: CPNV and CPENV under two-time intervals: 24 hr and office working hours (7 am to 6 pm)

Table 3: CPNV and TCPNV changes under climate change for the full day (24 h)

City	CPNV	CPNV changes in the future				TCPNV	TCPNV changes in the future			
	Present	2050 (RCP 2.6)	2090 (RCP 2.6)	2050 (RCP 8.5)	2090 (RCP 8.5)	Present	2050 (RCP 2.6)	2090 (RCP 2.6)	2050 (RCP 8.5)	2090 (RCP 8.5)
Darwin (CZ1)	67.9	-3.7	-2.8	-9.6	-18.5	85.9	-1.6	-0.8	-6.5	-14.3
Brisbane (CZ2)	49.7	3.1	2.6	0.3	-0.7	51.4	5.5	3.9	10.9	17.6
Alice Springs (CZ3)	32.2	-1.6	-1.3	0.3	-0.7	39.8	-1.8	-1.1	1.0	0.6
Wagga Wagga (CZ4)	21.2	3.2	1.8	4.2	7.6	24.8	3.9	3.7	4.8	7.8
Perth (CZ5)	27.1	3.0	1.5	5.3	10.7	30.6	3.4	1.6	6.2	13.1
Adelaide (CZ5)	18.6	2.5	1.8	3.4	10.0	21.7	2.8	1.8	3.7	11.2
Sydney (CZ5,6)	31.5	8.2	6.7	15.0	23.5	32.4	8.7	7.1	16.1	27.0
Melbourne (CZ6)	15.7	2.6	2.0	5.0	16.3	17.0	2.9	2.4	5.6	18.6
Canberra (CZ7)	14.5	2.5	1.5	3.8	9.9	17.0	2.7	1.7	4.2	11.3
Hobart (CZ7)	7.8	2.0	2.0	4.4	14.1	8.3	1.5	1.2	4.6	14.6

Table 3 shows the changes of CPNV and TCPNV in 2050 and 2090 under two climate change scenarios for ten cities across Australia. The prediction results reveal that climate change can significantly affect both CPNV and CPENV when NV is pursued for the whole day. The maximum CPNV under the present climate is seen in tropical climate of Darwin with roughly 68%, followed by Brisbane with approximately 50% throughout the year. This table also reveals that although Sydney (CZ6) and Alice Springs (CZ3) are located in different climate zones, both climates offer approximately the same CPNV, around 32%. In other cities, CPNV ranges between nearly 15% (Canberra and Melbourne) and 27% (Perth) except for Hobart. This city has the lowest CPNV in Australia, reaching around 8% annually. The predicted results under different climate change scenarios reveal Darwin's most prominent change in CPNV under RCP 8.5 with approximately 10% and 18.5% in 2050 and 2090. In contrast, climate change will affect CPNV in Brisbane and Alice Springs less than in other cities. Table 2 also predicts that CPNV will increase in the future in other cities, recommending the implementation of NV strategies in buildings. For example, Sydney is expected to experience the highest increase in CPNV from 6.7%

(under RCP 2.6, 2090) to 23.5% (under RCP 8.5, 2090). In other cities located in CZ 4 to 7, the predicted rise in CPNV ranges from 7.6% in Wagga Wagga (CZ4) to 16.3% in Melbourne (CZ6) under RCP 8.5 by 2090.

Under present climate conditions, implementing ENV strategies can increase the potential of NV in all studied cities. However, the magnitude of this increase is different and depends on the climate zone. Table 3 shows a remarkable rise in CPNV in hot and humid tropical climate of Darwin (Koppen: Aw) by 18% (67.9% to 85.9%). The second-highest increase is Alice spring (Koppen: BWh) by 7.6% (32.2% to 39.8%). In other cities, the CPENV is between approximately 3.5% in Wagga Wagga and 0.5% in Hobart. The impact of climate change on the CPENV in most cities and climates across Australia is similar to its effect on CPNV, described in the previous paragraph, except for Brisbane with a humid subtropical climate, showing a good potential for employing ENV strategies in the future, in particular under the worst-case climate change scenario. Elevating airspeed allows more hours to fall in the acceptable temperature range for NV purposes in the future in Brisbane. Under the RCP 8.5 scenario, TCPNV potential will increase by about 17.6% by 2090.

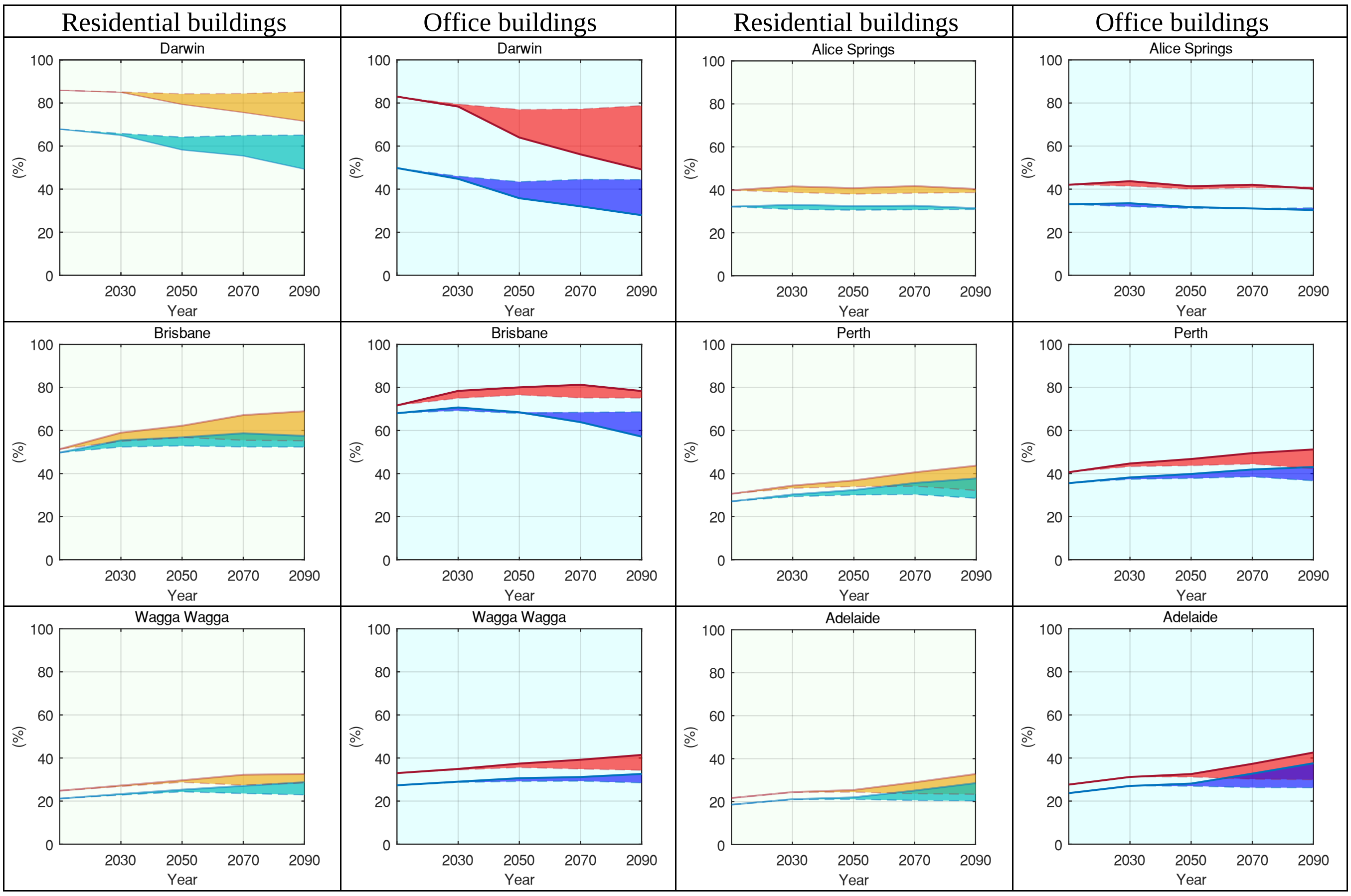
Table 4: CPNV and TCPNV changes under climate change for office working hours (from7 am to 6 pm)

City	CPNV	CPNV changes in the future				TCPNV	TCPNV changes in the future			
	Present	2050 (RCP 2.6)	2090 (RCP 2.6)	2050 (RCP 8.5)	2090 (RCP 8.5)	Present	2050 (RCP 2.6)	2090 (RCP 2.6)	2050 (RCP 8.5)	2090 (RCP 8.5)
Darwin (CZ1)	49.8	-6.4	-5.4	-14.0	-21.9	83.0	-6.0	-4.2	-19.0	-33.8
Brisbane (CZ2)	68.0	-0.1	0.6	0.5	-10.9	71.6	4.9	3.4	8.4	6.7
Alice Springs (CZ3)	33.0	-1.9	-1.7	-1.3	-2.7	42.0	-2.0	-1.1	-0.7	-1.8
Wagga Wagga (CZ4)	27.3	1.8	1.1	3.3	5.3	33.0	2.6	1.3	4.4	8.4
Perth (CZ5)	35.6	2.2	1.1	4.3	7.5	40.6	3.0	1.6	6.1	10.6
Adelaide (CZ5)	23.7	3.3	2.5	4.4	13.9	27.7	3.5	2.3	4.9	14.9
Sydney (CZ5,6)	41.8	7.3	5.9	13.1	16.8	43.1	8.2	6.5	15.3	24.7
Melbourne (CZ6)	20.7	3.4	2.8	6.3	20.2	22.7	3.7	3.2	6.9	22.3
Canberra (CZ7)	22.4	3.4	1.8	5.0	11.1	26.6	3.4	1.7	5.3	13.0
Hobart (CZ7)	13.7	3.3	2.2	7.4	18.8	14.4	3.3	2.8	7.6	20.0

Table 4 indicates the present and future CPNV and TCPNV values when NV is desired only during office hours (07:00 am-18:00 pm). In all studied climates, CPNV values are greater than its values for the full-day schedule except for Darwin with an 18% reduction (67.9% to 49.8%). This difference is due to the high daily temperature in Darwin. CPNV reaches the highest value in Brisbane, 68%, and the lowest in Hobart, 13.7%. In other cities, CPNV ranges between 20.7% in Melbourne and 41.8% in Sydney. The predicted results under the effect of climate change show that CPNV declines in three cities in climate zone 1-3 (Darwin, Brisbane, and Alice Springs), with the highest reduction of 22% in Darwin. In other cities (CZ 4 to 7), CPNV shows higher potential in the future than present climate. This opportunity results from increasing temperature and having a greater number of hours in the thermal comfort range throughout the year, which is suitable for applying NV strategies. Similar to Table 3 (top), Table 4 (bottom) shows that ENV strategies have an increasing effect on the CPNV; however, with different magnitudes across Australia. Darwin offers a remarkable potential for both NV and ENV strategies, with approximately 83% under present climate conditions. Climate change, however, has a considerable decreasing effect on TCPNV in Darwin. On the other hand, Alice Springs is expected to face a negligible reduction in TCPNV (2%). It is predicted that in all other cities, CPENV will increase in the future, with a more pronounced increase in Sydney and Melbourne by 24.7% and 22.3%, respectively.

Overall, Tables 3 and 4 show that the impact of climate change on CPNV and CPENV is different and depends on the climate change scenario. The results indicate that CPNV and CPENV will increase under the RCP 8.5 scenario by 2090 for both full-day and office hours schedules in all cities, except for Darwin, Alice Springs, and Brisbane (office hours), which all have (very) warm climates. Although global warming will affect CPNV and CPENV values, TCPNV is still significant in these climates. In more detail, CPNV and CPENV would not change identically due to climate change during the full day and office hours schedules as shown in Figure 2. It is expected that in cold/mild climates (e.g., Hobart, Canberra, Melbourne), buildings seeking NV during office hours have higher potential to save energy in the future compared to buildings with a full-day NV time schedule. On the contrary, CPNV and CPENV would significantly drop in warmer climates such as Darwin, particularly during office hours. In such climates, climate change will lead to warmer days (overheating risk). Therefore, the number of hours that air temperature exceeds the upper acceptability limit increases, and consequently, the NV potential will decrease.

Figure 3 illustrates trends of changes in CPNV and TCPNV (CPNV + CPENV) from the present climate to 2090 under low and high emission scenarios. Dash and solid lines in these figures represent the RCP 2.6 and RCP 8.5 scenarios, respectively. Therefore, the larger shaded area between the two lines represents the higher sensitivity of these indices to the climate change scenarios. For example, a comparison between Alice Springs and Darwin shows that the shaded area in Darwin grows considerably from the present conditions to 2090, meaning that CPNV and TCPNV in Darwin are very sensitive and can be remarkably affected by climate change. Therefore, given the lifetime of buildings, heavy reliance on NV alone in buildings is not recommended in Darwin to meet thermal comfort conditions. On the other hand, Alice Springs is almost not sensitive to climate change, meaning that in the future, with either low or high emission scenarios, CPNV and TCPNV would remain almost unchanged. Notably, the minimum and maximum potentials of CPNV and TCPNV in the future can be seen in these figures, setting the constraints for architects and/or building designers on how much they can rely on NV.



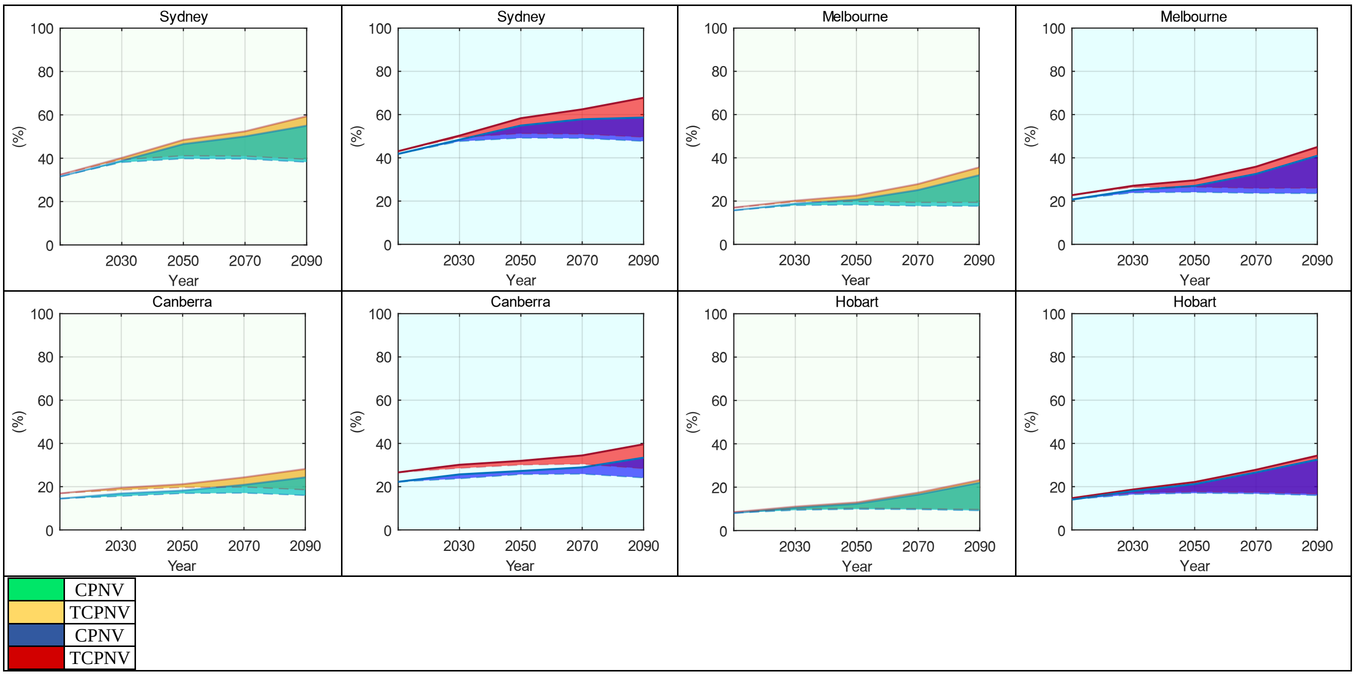


Figure 3: Sensitivity of CPNV and TCPNV to climate change scenarios in studied cities.

4. Future work

The indices introduced in this study are suitable during the conceptual design stage of a building when the potential application of natural ventilation in a given climate is desired. Since the proposed indices do not take into consideration architectural elements and/or the site characteristics, further analyses are necessary during the detailed design phase to determine the actual performance of different natural ventilation strategies in a given building. Field measurements, airflow models and/or computational fluid dynamics are among the widely used methods in literature. The proposed indices can be used as benchmarks to evaluate different NV strategies in buildings. Moreover, quantification of climatic potential of NV in different climates under both present and future climate change are important to develop a set of guidelines to define climates where natural ventilation is more appropriate, and to design sustainable NV strategies.

In the current research, the lower limit introduced by the adaptive thermal comfort model was applied for the CPNV calculation; however, this low limit can be lowered as stated in the literature [27], leading to higher CPNV values, especially for cold and mild climates. Also, two schedules were considered in this research; however, the start and end time of NV in buildings can vary depending on occupancy schedules, buildings class (e.g., school), and ventilation strategy. Moreover, the high and low emissions pathways were considered to evaluate the impact of climate change on the proposed indices. Further research is suggested to investigate the impact of other climate change scenarios on natural ventilation.

5. Conclusion

This study analyses the climatic potential of natural ventilation (CPNV) based on the ASHRAE adaptive thermal comfort model in different climates of Australia. A new index called the climatic potential of extended natural ventilation or CPENV was also introduced. CPENV indicates to what extent CPNV can be extended in a specific climate when airspeed is elevated. The sensitivity of both CPNV and CPENV indices were evaluated under the present and projected climate conditions since the CPNV may change over time due to global warming. Two different time schedules for utilising NV strategies were investigated: a whole day and only during office hours. To demonstrate the applicability of the new index and the methodology, ten Australian cities with different climate conditions were investigated. It was found that the CPNV varies significantly in diverse climates across Australia. It was shown that some climates such as Darwin have a great potential for NV under present climate conditions; however, this potential may significantly drop in the future. On the contrary, in some climates such as Sydney, CPNV will increase in the future, encouraging the implementation of NV strategies in buildings in these climates. It was also found that climate change has the minimal impact on NV in some climates such as Alice Springs, and CPNV in this climate is not sensitive to global warming. The results showed that CPNV and CPENV values calculated during office hours are greater than the full day schedule in all climates except Darwin. In cold climates such as Hobart, although the CPNV is low for the full day schedule, it is increased moderately during office hours schedule.

The results showed that CPNV could be extended up to 18% and 33% for the full day and office hours schedules, respectively, highlighting a significant cooling potential embedded in mild to warm climates, which can be exploited if the required elevated airspeed criteria are met with the use of NV passive strategies or low energy devices (e.g., ceiling fans). Importantly, CPNV and CPENV may not necessarily follow a similar trend, meaning that one may increase while another may decrease in the future. CPENV increases in mild climates and decreases in very hot climates in the future due to global warming. These indices are helpful during the conceptual design stage to identify how much climatic cooling potential of NV is available in a specific climate under present climate conditions, and how much of this potential would remain available in the future. It is suggested that the proposed equations are incorporated into building simulation tools to provide valuable insights into the NV potential of a given location.

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Appendix A. Humidity impact on NV Potential

In this section, the effect of the Relative Humidity (RH%) constraint on the defined indices , CPNV and TCPNV are discussed. Tables 1.A and 2.A present the effect of RH constraint on CPNV and TCPNV for the present and the climate change scenarios. As can be seen in these tables a 70% RH constraint can have a remarkable effect on CPNV and TCPNV in three cities: Darwin, Brisbane and Sydney. These climates are characterised by noticeable hours in a year with a relative humidity of more than 70%. The impact of considering the humidity constraint on CPNV estimation reaches the maximum level in Darwin with more than 50% reduction when NV is desired for the whole day. The impact of climate change on CPNV with 70% RH limit follows a similar trend as the full relative humidity range presented in section 3.2.

Overall, in situations where humidity is a concern, CPNV and CPENV are affected by humidty in Darwin, Brisbane and Sydney, under both present and future climates. In other studied cities, the 70% humidity constrain can be ignored for the present climate due to less than 2% effect on the CPNV throughout the year.

Table A.1: CPNV and TCPNV for the full day (24 h) considering relative humidity constraint (<70%) in the present and future climates.

City	CPNV (%), RH≤70%	CPNV reduction (%) compared to RH≤100%	CPNV (%) (climate change impact)				TCPNV (%), RH≤70%	TCPNV reduction (%) compared to RH≤100%	TCPNV (%) (climate change impact)			
	Present		2050 (RCP 2.6)	2090 (RCP 2.6)	2050 (RCP 8.5)	2090 (RCP 8.5)	Present		2050 (RCP 2.6)	2090 (RCP 2.6)	2050 (RCP 8.5)	2090 (RCP 8.5)
Darwin (CZ1)	15.7	-52.2	13.8	13.2	10.9	9.8	31.7	-54.2	29.9	29.6	23.9	18.4
Brisbane (CZ2)	26.9	-22.9	29.9	27.5	31.3	28.4	28.0	-23.4	32.8	29.5	32.8	36.9
Alice Springs (CZ3)	30.8	-1.4	29.4	29.4	30.3	29.1	38.4	-1.4	36.8	37.2	38.6	29.1
Wagga Wagga (CZ4)	20.4	-0.8	22.8	21.8	23.4	24.6	24.1	-0.8	27.2	25.6	27.7	30.1
Perth (CZ5)	25.1	-2.0	27.0	26.0	28.6	31.9	28.6	-2.0	30.8	29.6	33.0	37.9
Adelaide (CZ5)	17.3	-1.3	19.3	19.2	20.1	25.0	20.4	-1.3	22.7	22.2	23.5	29.3
Sydney (CZ5,6)	18.8	-12.8	23.0	22.5	24.1	28.3	19.6	-12.8	24.3	23.8	25.8	32.0
Melbourne (CZ6)	14.2	-1.5	16.4	16.2	18.1	26.3	15.5	-1.5	18.0	18.0	20.0	30.0
Canberra (CZ7)	14.4	-0.8	16.0	15.8	16.4	17.8	16.8	-0.8	18.7	18.4	19.3	21.6
Hobart (CZ7)	7.4	-0.7	9.0	8.4	11.3	18.4	7.8	-0.7	9.4	9.0	11.9	19.6

Table A.2: CPNV and TCPNV for office working hours (from 7 am to 6 pm) considering relative humidity constrain (<70%) in the present and future climates.

City	CPNV (%), RH≤70%	CPNV reduction (%) compared to RH≤100%	CPNV (%) (climate change impact)				TCPNV (%), RH≤70%	TCPNV reduction (%) compared to RH≤100%	TCPNV (%) (climate change impact)			
	Present		2050 (RCP 2.6)	2090 (RCP 2.6)	2050 (RCP 8.5)	2090 (RCP 8.5)	Present		2050 (RCP 2.6)	2090 (RCP 2.6)	2050 (RCP 8.5)	2090 (RCP 8.5)
Darwin (CZ1)	17.6	-32.2	13.8	13.9	10.0	7.1	46.7	-36.3	41.3	42.3	28.8	17.2
Brisbane (CZ2)	50.0	-18.0	52.7	50.0	52.5	41.1	52.5	-19.1	50.0	54.3	61.8	59.3
Alice Springs (CZ3)	32.4	-0.6	30.5	30.3	30.2	28.8	41.4	-0.6	39.5	40.0	39.9	38.7
Wagga Wagga (CZ4)	27.0	-0.3	28.2	27.8	29.5	29.6	32.7	-0.3	34.7	33.7	36.3	38.4
Perth (CZ5)	33.9	-1.7	35.6	34.7	37.2	38.8	39.0	-1.7	41.5	40.3	44.1	46.9
Adelaide (CZ5)	22.2	-1.5	25.1	24.7	26.1	34.0	26.2	-1.5	29.3	28.5	30.6	39.0
Sydney (CZ5,6)	32.2	-9.6	37.9	37.1	39.1	40.8	33.5	-9.6	39.9	38.9	42.2	49.0
Melbourne (CZ6)	19.7	-1.1	23.0	22.8	25.2	36.9	21.7	-1.1	25.3	25.3	27.8	40.9
Canberra (CZ7)	22.8	-0.9	25.1	24.9	25.6	27.3	27.2	-0.9	29.5	29.2	30.3	33.5
Hobart (CZ7)	13.5	-0.5	16.2	15.3	20.2	29.8	14.2	-0.5	16.8	16.0	21.1	31.6