Journal of Cleaner Production 254 (2020) 120035

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Climate change adaptation and carbon emissions in green urban spaces: Case study of Adelaide

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ARTICLE INFO

*Article history:*
Received 30 September 2019
Received in revised form
24 December 2019
Accepted 6 January 2020
Available online 11 January 2020

Handling Editor: Cecilia Maria Villas Bôas de Almeida

*Keywords:*
Climate change
Resilience
Adaptation
Urban greenery
Adelaide
Carbon emissions

ABSTRACT

Concentrations of building mass and insufficient greenery in cities are identified to contribute significantly to extended heat stress in the built environment, commonly known as the urban heat island (UHI) effect. This paper presents a scenario-based modelling built on climate change projections and potential alterations of urban greenery in 2030 and 2090 in Adelaide, South Australia. The model is based on regional climate change scenarios, potential urban surface cover alternatives and resulted urban microclimate variations in Adelaide. Projected energy demand variations and corresponding carbon emission are calculated in each scenario. Results indicate that an ideal urban landscape transformation scenario with 30% tree canopy can effectively decrease the surface temperature by 1 °C in winter and 3 °C in summer by 2090. It is estimated that having greener and more heat resilient public spaces could save a total carbon emission of 140,000 tone CO2e in Adelaide annually compared to a business-as-usual scenario. Urban greenery may be used as a mean of increased urban life resilience to climate change by reducing surface temperature, increasing urban resilience and decreasing the energy demand during summer.



## 1. Introduction

More than 80% of the Australian population are living in its major cities (SoAC, 2014–2015). This is already 10% above the projected worldwide urban population by 2050 (DESA, 2014). Urban areas, as the places of human agglomeration, contribute significantly to human-made climate change. Meanwhile, they are becoming more and more vulnerable to the effect of the changing climate including extended extreme weather conditions (PWC, 2011). In a majority of Australian cities, public spaces are frequently warmer than human comfort levels during summer heatwaves (BOM, 2008; Ricketts and Hennessy, 2009; Williams et al., 2012).

Summer heat stress is commonly amplified by the urban-specific heat loads in Australian cities. Outdoor heat stress pushes citizens into air-conditioned buildings, creating comfortable indoor microclimates as the cost of an ever-increasing outdoor ambient temperature (Ichinose et al., 2008); Daily travel patterns shift towards more energy-demanding modes in private air-conditioned cars in such hot urban environments (Moughtin and Shirley, 2005). The resulting increased demand for energy consumption for air-conditioning and transportation is frequently accompanied by waste heat production. This anthropogenic waste heat in urban settings is cited as a key contributor to the artificial heat load in highly-urbanised areas, commonly known as the urban heat island (UHI) effect. Consumption of energy for cooling and outdoor ambient temperature increases create a feedback loop, which can magnify heat-health consequences in cities. Here, the carbon emission reduction achieved from energy efficiency tends to be offset by the higher overall rates of energy consumption related to the demanding urban metabolism in Australian cities (SoAC, 2013).

This paper discusses low-carbon living potentials of heat resilience in greener urban spaces in Adelaide. It discusses the effect of urban greening on carbon emissions in Adelaide in 2030 and 2090 each in three different urban development scenarios. These scenarios are used to envisage energy demand variations for indoor air-conditioning and respective carbon emissions.

Urban resilience to climate change is intertwined with

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https://doi.org/10.1016/j.jclepro.2020.120035
0959-6526/

useability and comfort in outdoor spaces (Santamouris et al., 2015). To date, research indicates that frequency and quality of public life are affected by urban microclimate and outdoor thermal comfort (Bosselmann, 2008; Gehl and Svarre, 2013). Concentrations of building mass and lack of sufficient greenery in cities are identified to contribute significantly to extended heat stress in the built environment, commonly known as the urban heat island (UHI) effect (Gartland, 2008; Santamouris, 2015). Such accumulated urban heat stress affects citizens' health, especially for more physiologically or socially vulnerable population (Sivam et al., 2010; Tapper et al., 2015; Hatvani-Kovacs et al., 2016).

Previous research on heat resilience in Australian cities indicate that outdoor activities are highly sensitive to heat stress in public spaces (Gehl, 2011). Meanwhile, outdoor spaces with more tree canopy, grass cover, and shadow coverage tend to facilitate more frequent extended outdoor activities during summer (Coutts et al., 2015). Such heat resilience includes more outdoor activities during heat stress conditions associated with lower outdoor air and mean radiant temperature (MRT) compared to conventional hard urban covers such as asphalt, concrete and paving (Coutts et al., 2015). This paper is built on the findings of four previous publications by the same research group on heat resilience in Australian cities (Sharifi and Boland 2016, 2018; Sharifi et al. 2016a,b, 2017). A summary of findings of the previous research, highlighting the data that is used in the current paper is presented in the following sections.

### 1.1. Outdoor heat-activity correlations - observation

Heat-activity observations were performed in 10 selected multifunctional public spaces in Adelaide, Melbourne and Sydney. Each observation spot was observed at least 40 times between 2013 and 2014. In each observation round more than 100 participants were observed regarding their outdoor activities in a wide range of thermal environments varying between 16 °C and 44 °C. For UTCI<22−34 °C, no statistically significant decline was observed in outdoor activities, meaning that people adapted their outdoor activities, clothing and activity rate to achieve more comfortable outdoor environment. For warmer thermal environments, optional and social activities started to decline continuously, and the daily necessary activities started to get isolated. Spatial composition, supportive land uses, climate expectations, active microclimate conditioning and activity choices could extend outdoor activities by the critical zero-activity thresholds up to UTCI = 48 °C (equivalent to T = 36 °C, RH = 12%, V = 1 m/s and Δ MRT-T = 15 °C). Thereafter, outdoor prevention became the dominant adaptation strategy.

After neutral thermal thresholds are fulfilled, each 1.0 °C increase in outdoor ambient temperature causes an outdoor activity decrease rate of between 1.9% and 2.5%. Thus, for each 1.0 °C increase in outdoor heat stress, a 2.2% decrease in outdoor activities is expected (for details see: Sharifi and Boland, 2016; Sharifi et al., 2016a,b).

### 1.2. Outdoor activity and spatial preferences

A heat-activity choice survey was performed in Adelaide between 2013 and 2014. This post-activity survey of outdoor preferences highlighted that outdoor activities decrease during heat stress conditions more than any other thermal conditions (including cold, cool, slightly cool, neutral, slightly warm and warm). Outdoor activities were taken place mostly in neutral, slightly warm/cool and warm thermal environments. The most favourite urban features were tree canopy, shading (from buildings or temporary elements) and water features in Adelaide.

The heat-activity choice survey in Adelaide revealed that more than 34% of citizens had daily outdoor activities. Nearly 15% of the surveyed population expressed no willingness to attend outdoors during heat stress conditions. Such an unwillingness rate is only 2% in warm thermal conditions. Thus, the rate difference between no outdoor activity in hot and warm thermal conditions is 13%.

Heat-activity survey respondents in Adelaide expressed that tree canopies are the most attractive public space features during their outdoor attendance in heat stress conditions. Tree canopy attracted 62.9% of respondents, followed by preference rate of 49.1% for water features, 37.1% for temporary shading, 32.2% for grass coverage and 30.7% for buildings' shading. Meanwhile, 6.4% of respondents expressed that no spatial feature can attract them to attend outdoors during heat stress conditions (for details see: Sharifi et al., 2016a,b).

### 1.3. Urban surface cover temperature variations

A remote-sensing analysis of Landsat 7 ETM+, Landsat 8 and aerial thermography in Adelaide revealed that increased tree canopy cover correlates with lower heat stress in urban settings. Artificial-hard surface covers − including asphalt, concrete, and paved surfaces − gain 20 °C excess surface heat compared to urban greenery and surface water. Such excess surface heat can result in some urban precincts being up to 4 °C hotter than other adjacent precincts in the Greater Adelaide metropolitan area.

As noted in section 2.1, heat resilient urban precincts can support daily outdoor activities by UTCI = 48 °C (T = 36 °C). The minimum requirement to facilitate such heat resilience at precinct scale is to have less than 50% artificial-hard (against permeable or natural) landscape and more than 20% tree canopy in open spaces. Currently more than 70% of the total Adelaide CBD area is covered by building rooftops and paved areas. (to decrease the common ratio of artificial-hard landscapes from 70% to less than 50% in urban precincts). It is estimated that a likely 2 °C decrease in surface temperature of urban precincts is expected from a 10% increase in permeable urban covers and a 10% increase in tree canopy (for more details see: Osmond and Sharifi, 2017; Sharifi et al., 2017).

## 2. Materials and methods

This section presents the applied methods for scenario development, energy demand and carbon emission projections in Adelaide context in 2030 and 2090.

This paper uses Australian regional warming projections by Commonwealth Scientific and Industrial Research Organisation (CSIRO) in section 2.2 to extract ambient temperature variations in Adelaide by 2030 and 2090. It also, uses the secondary data from the previous studies mentioned in sections 1.1, 1.2 and 1.3 to refine these ambient temperature projections. Regional surface temperature changes are combined with potential scenarios for urban land cover change and consequent surface temperature variations in section 2.4. Energy demand are based on the temperature-demand correlation coefficient factor (K) extracted from previous study of the authors on energy demand variations in Adelaide (section 2.5). Carbon emissions in existing, improved and ideal urban greening scenarios are based on CO2-e emission factor for electricity and gas usage for Adelaide by National Greenhouse Accounts Factors (NGAF) in section 2.6.

### 2.1. Urban greening scenario development

Considering the existing 20.3% tree canopy in the City of Adelaide (Jacobs et al., 2014), an immediate tree-planting action plan is required to achieve 30% tree canopy by 2030. It worth noting that Adelaide parklands are included in this tree canopy calculation. If the City of Adelaide's surrounding parklands are taken out of the calculation, tree canopy ratio decreases to 12%.

As noted in section 2.3, the combination of increased tree canopy and soft landscapes can decrease ambient temperature in urban precincts by up to 2 °C compared to the business-as-usual scenario (a 2 °C average ambient temperature reduction is predicted based on analysed data and the literature). AS noted in section 2.1, every 1 °C decrease in heat stress is expected to result in a 4.4% increase in outdoor activities.

Two scenarios are probable in heat resilient urban precincts:

- In the case of using indoor air-conditioning, the closer the outdoor ambient temperature to the thermal neutrality zone, the lower the indoor-outdoor thermal variation. Thus, the energy demand for cooling air-conditioning decreases and people feel less thermally shocked when moving from indoors to outdoors.
- In a scenario of not using air-conditioning during uncomfortable outdoor ambient temperature, the closer outdoor ambient temperature to the human thermal neutrality zone, the healthier indoor and outdoor spaces are.

To project low-carbon benefits of heat resilience at precinct scale, these urban heat resilience scenarios are to be combined with Australian climate change projections for 2030 and 2090 to provide an overall heat stress projection.

### 2.2. Urban surface and ambient temperature projections for Adelaide in 2030 and 2090

Spatial heat resilience scenarios are to be combined with Australian climate change projections to provide overall heat stress overviews for 2030 and 2090. Australian average surface temperature for 1910–2090 scenarios was obtained from Commonwealth Scientific and Industrial Research Organisation (CSIRO) technical reports (CSIRO, 2007; CSIRO, 2014). It has to be noted that the mean surface temperature variations can lead to similar ambient temperature variations in reginal scale. However, in smaller scales of the built environment such as individual public spaces, surface temperature variations are commonly reported to be higher than ambient temperature variation.

Time series analysis of historical climate data in Australia indicates a likely 0.3 °C increase in surface temperature of Australia by 2030, and 0.5 °C increase by 2090 compared to the baseline of 1980 (0.7 °C–1.2 °C compared to 1910) (CSIRO, 2014). The basic assumption in this time series analysis is that the pattern of climate change remains constant in future (no step change or accelerating change is taken into consideration). However, the analysis of Australian mean surface temperature in 2014 shows that most of the continent – including capital cities of Sydney, Melbourne and Adelaide – has already experienced a mean surface temperature change of between 0.5 °C and 1 °C compared to 1910 (Braganza et al., 2015).

Regional climate change projections indicate more intense variations in surface temperature will be experienced by 2030 and 2090. Primary projections indicate a likely 0.4 °C–2.0 °C increase in average surface temperature in Australia by 2030 and a 1.0 °C–6.0 °C increase by 2090 relative to 1990 (Watterson et al., 2015). The variation in projections addresses uncertainties in drivers of climate change including the rate of greenhouse gas (GHG) emissions, representative concentration pathways (RCPs), and the interplay between climate regimes. Australian climate change scenarios in a CMIP5 model based on three representative concentration pathways (RCPs) of greenhouse gases (not emissions) in the earth's atmosphere indicate that annual mean surface temperature change in Australia can vary from 0.5 °C (RCP2.6) to 0.8 °C (RCP.5) by 2030 and 0.7 °C (RCP2.6) to 3.8 °C (RCP8.5) by 2090. Table 1 presents projected mean surface temperature changes in 2030 and 2090.

Surface temperature projections for 2030 have higher certainty and less variation compared to 2090. As projections go further in years, the degree of uncertainty increases. The RCP2.6 scenario predicts the least surface temperature increase among the three models. However, mean surface temperature continues to increase in other scenarios. The above regional warming scenarios are based on the A1B emission scenario of the Intergovernmental Panel on Climate Change (IPCC). Expansion of the uncertainty in GHG emissions fluctuates the range only slightly for 2030 projections. With the change in GHG emissions, mean surface temperature increase varies between 0.4 °C and 1.8 °C in Australia (CSIRO, 2007). Even though climate change projections include having a higher change in night-time surface temperature than in daytime, a simplifying assumption is made in this study to use uniform surface temperature increase projections.

The worst scenario (RCP8.5) projects a mean increase of 3.8 °C in the surface temperature of Australia compared to 2010. The projected surface temperature increase is expected to be slightly higher in the mainland and lower in coastal areas, and slightly lower in winter. To simplify the modelling process, seasonal and local changes in mean surface and ambient temperature are not taken into consideration in this chapter. The RCP4.5 scenario gives a closer match between projected and historical data (Watterson et al., 2015), and therefore, is selected as the best projection for 2030 and 2090 for this paper.

### 2.3. Heat resilience scenarios in Adelaide

The presented spatial heat resilient scenarios in this section are based on the assumption that the expected mean surface temperature changes are translated directly to equivalent hot summer conditions. Based on the findings of urban precinct surface and ambient temperatures in section 2.3, three scenarios for heat resilience are presented as follows:

- The existing or business-as-usual scenario (SC1) assumes that no improvement in the tree canopy coverage and the urban landscape take place. Thus, with the increasing urban population in Australia, urban precincts in Adelaide are expected to become similar to the existing conditions in the Adelaide CBD with limited tree canopy (15%) and soft landscape cover (20%). Public spaces in this scenario are similar to Art Centre Plaza, Blue Hive Plaza in Adelaide. No variation in the ambient temperature is expected in SC1 (the local UHI effect may increase under these conditions).
- The improved scenario (SC2) assumes that partial improvements in tree canopy coverage and the urban landscape take place. Thus, urban precincts in Adelaide are expected to become similar to the existing conditions in Adelaide CBD and Parklands with enhanced tree canopy (20%) and soft landscape cover (30%). The maximum ratio of hard surface cover will be 50% in

**Table 1**
Projected mean surface temperature change in three representative concentration pathways (RCP) scenarios in Australia for 2030 and 2090 compared to 2010.

| | 2030 (°C) | | | 2090 (°C) | | |
|---|---|---|---|---|---|---|
| | Min | Max | Mean | Min | Max | Mean |
| RCP2.6 | 0.2 | 0.9 | 0.5 | 0.3 | 1.4 | 0.7 |
| RCP4.5 | 0.3 | 1.0 | 0.6 | 1.1 | 2.4 | 1.6 |
| RCP8.5 | 0.5 | 1.2 | 0.8 | 2.5 | 4.8 | 3.8 |

the improved scenario. A likely 1.2 °C ambient temperature reduction is expected at precinct scale under hot summer conditions.

- The ideal scenario (SC3) assumes that significant improvement in tree canopy coverage and urban landscape take place. Thus, urban precincts in Adelaide are expected to become similar to existing conditions in the South East part of Adelaide CDB with an ideal tree canopy ratio of 30% and soft landscape cover of 30%. The maximum ratio of hard surface cover will be 40% in the ideal scenario. A likely 2 °C ambient temperature reduction is expected at precinct scale under hot summer conditions. Table 2 summarizes urban greening scenarios in Adelaide.

### 2.4. Combined urban ambient temperature scenarios for 2030 and 2090

The CSIRO climate change projections for 2030 and 2090 (RCP4.5) are combined with potential spatial heat resilient scenarios to calculate total urban ambient temperature variation in 2030 and 2090. Envisaged ambient temperature increase is calculated as:

**Equation 1.** Projected ambient temperature changes in future

$$\mathbf{\Delta T_{year-scenario}} = \mathbf{\Delta T_{climate\ change-year}} + \mathbf{SHR}_{\mathbf{scenario}}$$

where $\Delta T_{\text{climate change-year}}$ is the ambient temperature variation in the targeted year (2030 and 2090) from Table 1, and heat resilience scenario is based on Table 2. The combined effect of ambient temperature variation resulting from urban heat resilience scenarios and climate change reveals that Adelaide urban ambient temperatures could vary from 0.6 °C higher (SC1 summer and winter) to −2.4 °C lower (SC3 summer) in 2030 compared to 2010 (see Table 3). With lower confidence and higher variation in 2090, Adelaide urban ambient temperature could vary from 0.6 °C higher (SC1 summer and winter) to −1.4 °C lower (SC3 summer) than the 2010 average. These scenarios are used in the next section (3.2) to project potential variations in carbon emissions in 2030 and 2090 in Adelaide.

### 2.5. Energy saving for each 1.0 °C increase in urban abmient temperature

Previous research on energy consumption in Australian cities indicates that there is a strong positive (uphill) correlation between ambient temperature and electricity demand when the daily mean ambient temperature is above 22 °C (Boland, 2010). North American research confirms the high dependency of electricity demand to increased ambient temperature in California with a slightly lower threshold of 18 °C. It also reveals that slightly lower negative (downhill) correlation exists between energy demand and increased ambient temperature below 10 °C (Franco and Sanstad, 2008). European research reveals that the lower threshold of energy demand-temperature dependency varies from 15 °C in cold climates (Germany and Sweden) to 13 °C in temperate climates (Greece and Spain). The corresponding higher threshold is 22 °C in temperate climates (Moral-Carcedo and Vicéns-Otero, 2005; Bessec and Fouquau, 2008).

Adelaide has a temperate climate. The annual average of daily mean ambient temperature is 22.3 °C. Thus, the low threshold of 13 °C and a high threshold of 22 °C are applicable for temperature-electricity demand modelling.

The total regression between energy demand and the ambient temperature is non-linear in the temperate climate. However, if the regression model is divided into three segments via the break-points of 13 °C and 22 °C, each segment can be explained by a linear regression model. As Table 4 presents, In the low-temperature range ($T < 13$ °C), each 1.0 °C decrease in ambient temperature increases electricity demand by 1.1%. In the mid-temperature range (13 °C $\leq T \leq$ 22 °C) the model is mediocre and does not show any meaningful dependency. In the high-temperature range ($T > 22$ °C), each 1 °C increase in ambient temperature increases electricity demand by 2.6%. Less sensitivity of energy demand to ambient temperature variations in low ambient temperatures is explained by the lower dependency of heating on electricity (gas, oil, coal, or wood are common alternatives) compared to cooling electricity demand in the high-temperature range (Mirasgedis et al., 2006; Boland, 2010).

### 2.6. Carbon emissions in existing, improved and ideal urban greening scenarios

The presented ambient temperature change scenarios in this paper are based on the assumption that the mean ambient temperature changes (from model projections) are translated directly to equivalent hot summer conditions. Urban ambient temperature scenarios for 2030 and 2090 are combined with energy saving rate per each 1 °C in temperate climates and energy demand projections to calculate scenario-based energy demand and carbon emissions of indoor air-conditioning, influenced by outdoor spatial heat resilience. To facilitate the calculation, the following values are taken into consideration:

- Ambient temperature variation in urban heat resilient scenarios (compared to 2010)
- Correlation coefficient factor (K) between energy demand and ambient temperature
- Energy demand per capita for air-conditioning in Adelaide (ED)
- Increase in electricity and gas demand per capita in each scenario in 2030 and 2090 compared to 2010 is calculated as:

**Equation 2** Energy demand projection resulted from urban heat stress

$$\mathbf{\Delta E}_{\boldsymbol{year-scenario}} = \mathbf{\Delta T}_{\boldsymbol{year-scenario}} \times \boldsymbol{K} \times \boldsymbol{ED}_{2010}$$

- $CO_2$-e emission factor for electricity and gas usage ($f_{CO2}$) for different Australian cities is obtained from (NGAF, 2014).

**Table 2**
Heat resilient scenarios for urban surface cover transformation in Adelaide.

| Scenario | Tree canopy | Permeable landscape | Hard landscape | Precedent | Winter ambient temperature variation at urban scale (°C) | Summer ambient temperature variation at urban scale (°C) |
|---|---|---|---|---|---|---|
| SC1 (existing) | 15% | 20% | 65% | Art Centre Plaza Adelaide CBD | N/A | N/A |
| SC2 (Improved) | 20% | 30% | 50% | Adelaide CBD + Parklands | −0.8 | −1.6 |
| SC3 (Ideal) | 30% | 30% | 40% | South East of Adelaide CBD + Parklands | −1.0 | −3.0 |

**Table 3**
Combined ambient temperature projections for Adelaide in 2030 and 2090.

| | Heat resilient scenario at urban scale (°C) | | Ambient temperature variation due to climate change (°C) | | Total ambient temperature variation (°C) | | | |
|---|---|---|---|---|---|---|---|---|
| | Winter ambient temperature variation | Summer ambient temperature variation | 2030 RCP4.5 | 2090 RCP4.5 | 2030 | | 2090 | |
| | | | | | Winter | Summer | Winter | Summer |
| SC1 (existing) | N/A | N/A | 0.6 | 1.6 | 0.6 | 0.6 | 1.6 | 1.6 |
| SC2 (Improved) | −0.8 | −1.6 | | | −0.2 | −1.0 | 0.8 | 0.9 |
| SC3 (Ideal) | −1.0 | −3.0 | | | −0.4 | −2.4 | 0.6 | −1.4 |

**Table 4**
Energy demand increase resulting from 1 °C increase in ambient temperature in temperate climates.

| Temperature-demand correlation coefficient factor (K) | Ambient temperature range | | |
|---|---|---|---|
| | 5–13 °C | 13–22 °C | 22–35 °C |
| | −1.1% | 0% | +2.6% |

- $CO_2$-e emissions variation resulting from changes in energy demand in 2030 and 2090 is calculated as:

**Equation 3** Carbon emission projection resulted from urban heat stress

$$\Delta \mathbf{CO2e}_{\,year} = f_{CO2} \times \Delta \mathbf{E}_{\,year-scenario}$$

- Resulting $CO_2$-e emissions per capita are up-scaled to precinct, city, and metropolitan scales.
- An average resident population of 15,000 people is dedicated to a sample urban precinct.
- Urban population for 2030 ($P_{2030}$) and 2090 ($P_{2090}$) in the City of Adelaide local council and greater metropolitan area are obtained from forecast.id online data set available at: http://forecast.id.com.au.

## 3. Carbon emission projections for air-conditioning in 2030 and 2090

The carbon emission projection of urban greening scenarios in Adelaide is based on the findings of previous research as stated in sections 2.1–2.3 and the scenario development in this paper. Projected electricity demand and carbon emissions are based on expected ambient temperature decreases and outdoor attendance of citizens in heat resilient urban precincts. The ratio of tree canopy and permeable landscape cover are independent (predictor) parameters of the projects, whereas ambient (and surface) temperature reduction and increased outdoor attendance are dependent (predicted) variables. It worth noting that potential technological advances, improved energy efficiency of buildings, and alternative energy sources for air-conditioning appliances are not reflected in these projections. These factors are controlled to facilitate the energy demand projection without over-complication of the process and increasing uncertainty.

The targeted years are 2030 (high confidence) and 2090 (confident and worst scenarios). Carbon reduction benefits of spatial heat resilience are reflected at precinct, city, and metropolitan scales. Projected electricity demand is based on current Australian electricity demand rate per capita, the expected increase in electricity demand per each 1.0 °C (from the literature), and projected ambient temperature change in a targeted year. Resulted figures are upscaled based on urban population in targeted year, and corresponding carbon emissions are calculated.

### 3.1. Energy demand for indoor air-conditioning in Australian cities

The residential sector consumes approximately 12% of the annual energy consumption of 3621 PJ in Australia (PJ = $10^{15}$ J) (DEWHA, 2008; OCE, 2015). The rate of energy consumption is predicted to increase to 467.3 PJ in 2020, giving a twofold increase in electricity and gas consumption compared to 298.8 PJ in 1990 (see Fig. 1). Heat resilience in public space encourages more outdoor attendance. A primary assumption in this section is that an increased number of outdoor users correlates with a decreased number of indoor participants. Such an assumption is more valid for the residential sector, since commercial and industrial sectors continue their operation regardless of the number of users. Thus, residential energy demand is used in this section.

Indoor air-conditioning energy consumption is climate-sensitive in Australia and, therefore, varies between states. Space cooling consumes 3.4% of total energy and 8.7% of electricity in the residential sector of Australia. Space cooling is met entirely through electricity consumption (DEWHA, 2008). Demand for cooling energy varies across the states (see Table 5). South Australia accounted 9.7% of the demand.

Nearly 38% of the total energy in the Australian residential sector is consumed for space heating. However, the majority of this energy demand is met by mains gas. Only 3.4% of total energy and 9% of space heating energy demand is met by electricity (DEWHA, 2008). As Table 5 reveals, only 5.9% of demand belonged to South Australia.

Space cooling and heating energy demand per capita in South

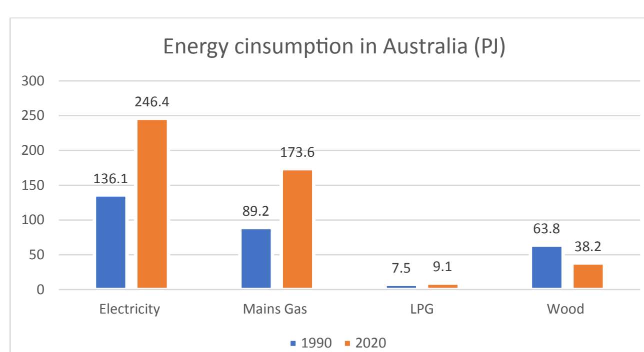


**Fig. 1.** Total energy demand projection in 2020 compared to 1990 (developed based on: DEWHA, 2008).

**Table 5**
Total heating and cooling energy consumption in the residential sector in South Australia compared with Victoria and New South Wales in 2010 (developed based on: DEWHA, 2008).

| | New South Wales | | Victoria | | South Australia | | National |
|---|---|---|---|---|---|---|---|
| | PJ | Percentage | PJ | Percentage | PJ | Percentage | PJ |
| Space cooling | 4.0 | 29.9% | 0.9 | 6.7% | 1.3 | 9.7% | 13.4 |
| Space heating | 24.9 | 16.3% | 92.3 | 60.4% | 9.0 | 5.9% | 152.9 |

**Table 6**
Annual energy demand for cooling and heating per capita (ED) in SA in 2010 (Population data: Infrastructure Australia, 2015).

| | | South Australia |
|---|---|---|
| Population in 2020 | | 1,639,000 |
| Space cooling (GJ/p) | Electricity | 0.79 |
| Space heating (GJ/p) | Electricity | 0.49 |
| | Mains Gas | 5.00 |

Australia is presented in Table 6. South Australia had the highest cooling energy demand per capita (0.79 GJ/p), followed by NSW (0.55 GJ/p) and Victoria (0.16 GJ/p) in 2010. Meanwhile, Victoria will have the highest heating energy demand per capita (16.67 GJ/p), followed by South Australia (5.49 GJ/p) and NSW (3.45 GJ/p). Changes in the sequence of the states are due to the lower residential population in South Australia compared with Victoria and NSW.

Electricity and gas demand projections in the residential sector reveal a stable demand rate since 2005 (DEWHA, 2008). Due to the low certainty of energy demand projections in the far future, a majority of predicting models provide 5–10 years forecasting. In this paper, it is assumed that electricity and gas consumption in the residential sector will be moderated by technological advances and behavioural change after 2020. If the probable energy efficiency ratio (EER) for cooling and coefficient of performance (COP) ratio for heating (facilitated by technological advances) are taken into account, the scenarios are getting too complex for this paper.

As mentioned before, space cooling relies completely on electricity, whereas only 9% of heating energy demand is met by electricity, and the remaining 91% relies mainly on wood and gas (these main sources of energy in indoor air-conditioning have very different carbon emissions, which are discussed in the following section).

The residential sector's electricity consumption rate is expected to increase from 46% in 1990 to 53% in 2020, making Australia more electricity-dependent than ever before. Considering an expected population of 24 million in Australia by 2020 (17.07 million in 1990), the annual electricity demand per capita is expected to be 10.27 Gigajoules (GJ $= 10^6$ J) in 2020 (7.69 GJ/p in 1990).

## 4. Carbon emissions in heat resilient Adelaide in 2030 and 2090

As discussed in section 3.2.1, the energy demand for indoor air-conditioning changes in low and high ambient temperature ranges (cool and warm outdoor environments). The basic assumption in this section is that the urban heat resilience scenarios will change the overall need for air-conditioning. Corresponding heating and cooling electricity and gas consumption rates in 2010 (as the reference year) are used for the calculation of energy demand in 2030 and 2090.

Electricity and carbon emissions vary among the states in Australia. This is mainly due to the variations in energy production, fuel, and energy transit networks. Carbon emissions of electricity and gas consumption in South Australia are presented in Table 7. These values are used as the $CO_2$ emission factors ($f_{CO2}$) for urban heat resilience scenarios.

Fig. 2 reveals that urban heat resilience scenarios do not have a significant effect on heating electricity demand in 2030 and 2090 in Adelaide. The decrease in heating electricity and gas demand is due to the effect of the warming climate on winter ambient temperatures. However, 91% of the resulting energy demand is reflected in heating gas consumption.

Annual cooling energy consumption, which is solely met by electricity usage, is expected to increase by 12.3 MJ/p in 2030 and 32.9 MJ/p in 2090 in the existing scenario (SC1). The ideal urban heat resilience scenario (SC3) makes a significant contribution in decreasing cooling electricity demand, which falls by 61.62 MJ/p in the ideal scenario compared to the existing scenario in 2030 and beyond.

Applying the carbon emission factors of electricity and gas consumption, Fig. 3 illustrates that, in the existing (business-as-usual) scenario (SC1), every citizen of Adelaide is expected to have an annual 17.36 kg $CO_2$-e extra carbon emission in 2030 and 46.29 kg $CO_2$-e extra carbon emission in 2090. The improved scenario (SC2) can effectively counteract the extra carbon emission resulting from climate change in 2030 with 41.94 kg $CO_2$-e/p carbon emission reduction. However, the improved scenario is not effective in 2090 (27.66 kg $CO_2$-e/p increase in carbon emissions).

The improved urban heat resilience scenario (SC2) can save 0.9 kilotons of carbon emissions (Kt $CO_2$-e) compared to the existing scenario (SC1) in a sample urban precinct, and 2.10 Kt $CO_2$-e in the City of Adelaide, and 93.98 Kt $CO_2$-e in Greater Adelaide in 2030. The ideal urban heat resilience scenario (SC3) can save 1.79 Kt $CO_2$-e compared to existing scenario (SC1) in a sample urban precinct, 4.53 Kt $CO_2$-e in the City of Adelaide, and 229.07 Kt $CO_2$-e in Greater Adelaide in 2090 (see Table 8).

## 5. Additional considerations in improved and ideal heat resilience scenarios

As noted in section 2.1, after neutral thermal thresholds, each 1.0 °C increase in outdoor heat stress results in 2.2% decrease in outdoor activities, more than 34% of citizens have daily outdoor activities, and nearly 15% of the surveyed population have no willingness to attend outdoors during heat stress conditions. Such an unwillingness rate is only 2% in warm thermal conditions. Thus, the rate difference between no outdoor activity in hot and warm thermal conditions is 13%.

As such, out of the 34% of total urban population who had daily outdoor activities, 13%, preferred not to attend outdoors during heat stress conditions, whereas they attend outdoors in warm thermal environments ($34\ \% \times 13\ \% = 4.42\%$). The resulting 4.42% variation in outdoor participants during heat stress conditions is used as an additional multiplier in the energy demand projections in the precinct, city, and metropolitan Adelaide. The primary assumption is that outdoor space participants can be excluded from indoor attendants who use air-conditioning during heat stress conditions.

**Table 7**
Carbon emissions of electricity and gas consumption in South Australia (NGAF, 2014).

| | | South Australia |
|---|---|---|
| $CO_2$ equivalent emission factor for electricity consumption | kg $CO_2$-e/kWh | 0.61 |
| | kg $CO_2$-e/MJ | 2.20 |
| $CO_2$ equivalent emission factor for gas consumption | kg $CO_2$-e/MJ | 0.08 |

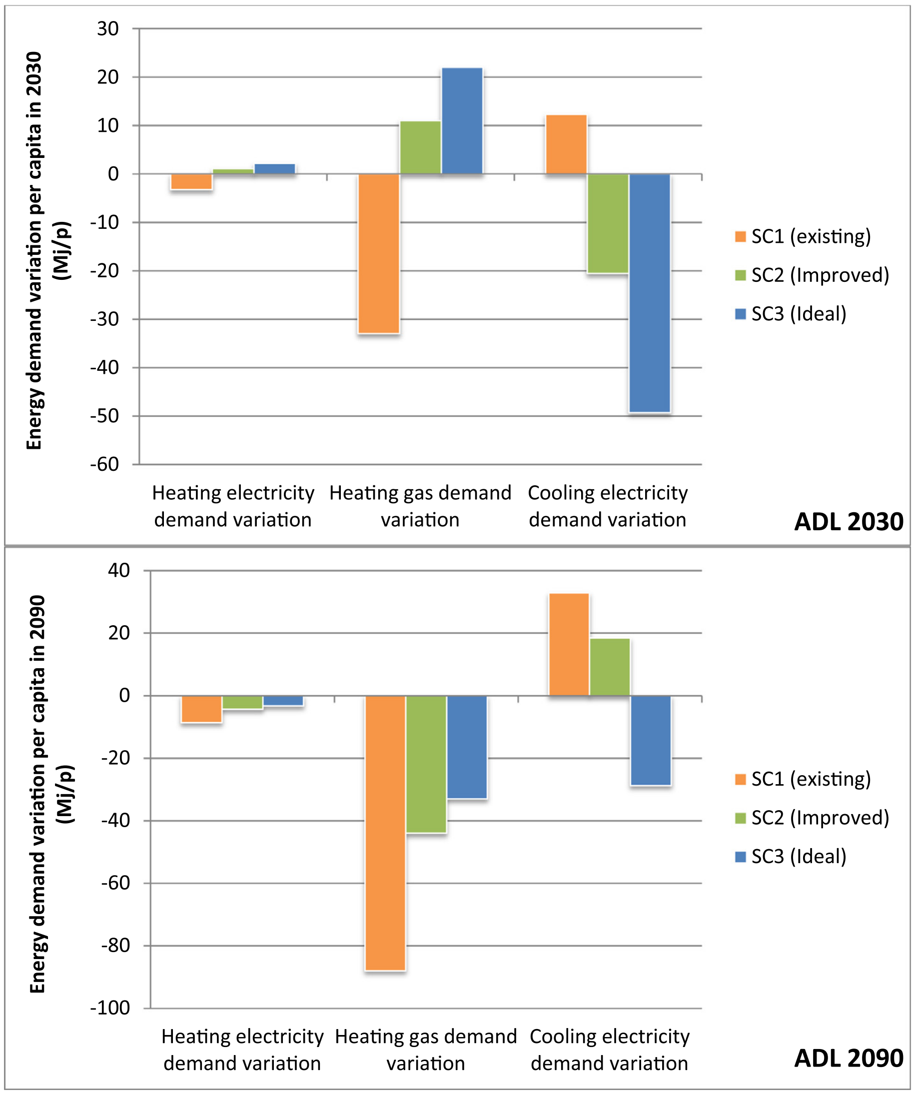


**Fig. 2.** Energy demand for indoor air-conditioning in three urban heat resilience scenarios in Adelaide (2030), 2090.

The high threshold for strong outdoor heat stress is 35–36 °C (Bröde et al., 2012). Thus, the number of days in summer 2030 and summer 2090 which have a maximum ambient temperature more than 35 °C will be influenced by the calculated 4.42% outdoor activity rejection rate. Table 9 shows the number of days with a maximum ambient temperature higher than 35 °C. In improved ideal urban heat resilience scenarios (SC2 and SC3), some part of these days will have a ambient temperature less than 35 °C and, therefore, can be ruled out as having heat stress conditions. Having 1 °C lower ambient temperature in the improved scenario, 2.4 °C lower ambient temperature in the ideal scenario in 2030, and 1.4 °C lower ambient temperature in the ideal scenario in 2090 can affect 20 days in 2030 and 33 days in 2090. This means that a 4.42% increase in the number of outdoor users on 22.2% of summer days in 2030 and 36.67% of summer days in 2090 can be expected (especially in the ideal scenario). As such, modified cooling electricity demand (and corresponding carbon emissions) can be calculated as:

**Equation 4** Modified cooling electricity demand projection resulted from urban heat stress

$$\boldsymbol{ED_{modified-year}}(\boldsymbol{elec}) = \boldsymbol{ED_{year}} \times 0.0442 \times \frac{\boldsymbol{Number\ of\ affected\ days}}{90}$$

This will be equal to a 17 kg $CO_2$-e carbon emission reduction in a sample urban precinct, 45 kg $CO_2$-e in Adelaide city and 2272 kg $CO_2$-e in the greater Adelaide area. However, to apply outdoor heat-

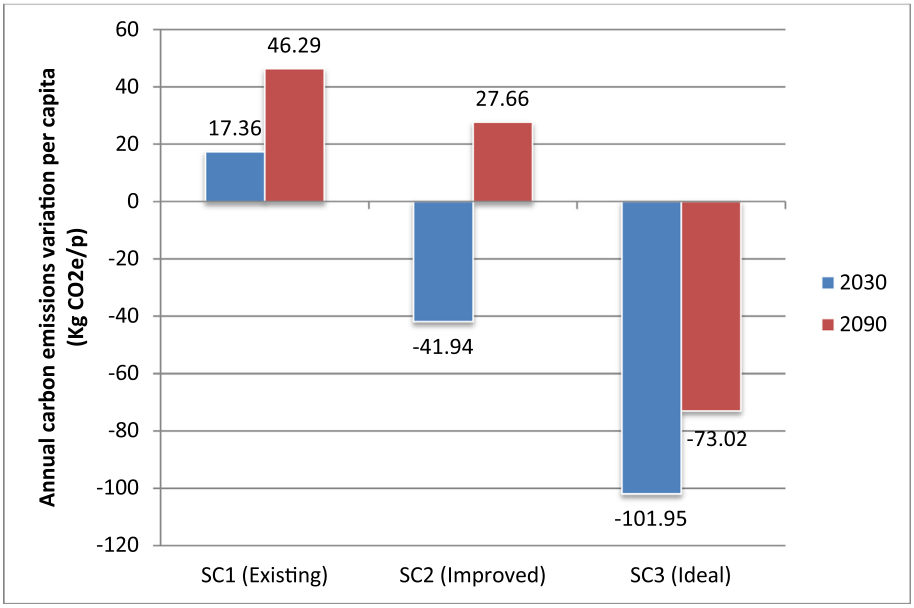


**Fig. 3.** Carbon emission variation per capita resulted from urban heat resilience scenarios in Adelaide.

**Table 8**
Annual variation in carbon emissions of indoor air-conditioning in urban heat resilience scenarios at precinct, city, and metropolitan scales of Adelaide (2030), 2090.

| | Sample urban precinct | City of Adelaide | Greater Adelaide (metropolitan area) |
|---|---|---|---|
| Population 2030 | 15,000 | 35,000 | 1,566,000 |
| Kt $CO_2$-e (SC1) | 0.26 | 0.61 | 27.18 |
| Kt $CO_2$-e (SC2) | −0.63 | −1.47 | −65.67 |
| Kt $CO_2$-e (SC3) | −1.53 | −3.57 | −159.65 |
| Population 2090 | 15,000 | 38,000 | 1,920,000 |
| Kt $CO_2$-e (SC1) | 0.69 | 1.76 | 88.87 |
| Kt $CO_2$-e (SC2) | 0.41 | 1.05 | 53.11 |
| Kt $CO_2$-e (SC3) | −1.10 | −2.77 | −140.19 |

**Table 9**
Number of days with maximum ambient temperature higher than 35 °C and 40 °C in Adelaide (Watterson et al., 2015).

| | 2030 RCP4.5 | | 2090 RCP4.5 | |
|---|---|---|---|---|
| | Days over 35 | Days over 40 | Days over 35 | Days over 40 |
| Adelaide | 26 | 6 | 32 | 9 |

activity rejection rate in Melbourne and Sydney, further research is required.

### 5.1. Margins of error and uncertainty of urban climate projections

Urban climate projections in this study are subject to uncertainty related to reginal climate projections and implementation of future urban surface covers. As shown in Table 1, the mean surface temperature in Australia may vary 0.3 °C between RCP2.6 and RCP8.5 by 2030. When projecting for 2090 the variation between different scenarios increases to 3.1 °C. In this paper, the RCP4.5 is used to decrease the error by taking the average climate change scenario. However, such average climate change scenario can have −16% margin of error to RCP2.6 and 33% error to RCP8.5 by 2030. Such error can increase to −56% compared to RCP2.6 and 137% compared to RCP8.5 with the farther extent of projection for 2090. The high margin of error for 2090 exist due to uncertain policy, technology and project implementation variations in the next 70 years. The presented urban cooling projections in greener urban settings are highly sensitive to such urban policy and landscape project implementations.

The urban cover-temperature regression model has $p < 0.05$ and $R^2 > 0.7$ which adds additional 5% error to the projections. The electricity demand regression model has $p < 0.05$ and $R^2 > 0.5$ which adds further 5% error, and outdoor living behavioral change model has $p < 0.05$ and $R^2 > 0.5$ which adds another 5% error to the projections.

## 6. Conclusions

Both time series analysis and modelled climate data in Australia indicate that a warming climate is inevitable, and climate change mitigation strategies only can decrease the intensity of this climate warming. Thus, adaptation to climate change is an emerging agenda for Australian cities.

This paper discusses the application of spatial heat resilience at precinct scale in low-carbon cities. The generalisation criteria for heat-activity observation, choice survey spatial preferences, and surface cover measurement in Adelaide are discussed. Projected climate change scenarios are combined with spatial heat resilience scenarios for the calculation of probable variations in energy demand and corresponding carbon emissions in 2030 and 2090.

Australian ambient temperature is expected to increase between 0.3 °C and 1.0 °C in 2030 compared to 2010 (RCP4.5 scenario). The ambient temperature increase could reach 2.4 °C in

2090. An ideal urban transformation towards having 30% tree canopy, 30% soft and natural landscape cover, and 40% hard surface cover could decrease the ambient temperature in urban scale up to 1.0 °C in winter and 3.0 °C in summer in Adelaide. Mean summer ambient temperature in Adelaide is expected to increase 0.6 °C in the existing scenario, decrease by 1.0 °C in the improved scenario and decrease by 2.4 °C in the ideal scenario in 2030. Increases of 1.6 °C in the existing scenario, 0.9 °C (improved scenario) and a decrease of 1.4 °C in the ideal scenario are expected in 2090.

Each 1.0 °C increase in summer ambient temperature increases cooling electricity demand by 2.6% in Adelaide. Each 1.0 °C increase in winter ambient temperature decreases heating energy (electricity and gas) demand by 1.1%. Heat resilient urban precincts could save 140 Kt $CO_2$-e in Adelaide metropolitan area. In addition, public life and heath will be better supported in heat resilient urban precincts.

Urban greenery may be used as a mean of increased urban life resilience to climate change by reducing ambient temperature, increasing urban population resilience to heat and decreasing the energy demand for air conditioning during summer.

## Declaration of competing interest

There is no known conflict of interest associated with this manuscript.

## Acknowledgements

This study is linked to the Urban Microclimates project (RP 2005), facilitated by the CRC for Low Carbon Living. It is supported by the CRC LCL's partners including the City of Adelaide. Methods compliance with Australian Code for the Responsible Conduct of Research is approved by UniSA's Human Research Ethics Committee in 2013 (PR 31464).

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