Build Simul
https://doi.org/10.1007/s12273-024-1140-7

Assessing the impact of heat mitigation measures on thermal performance and energy demand at the community level: A pathway toward designing net-zero energy communities

Khan Rahmat Ullah[1] (✉), Veljko Prodanovic[2,3,4], Gloria Pignatta[1], Ana Deletic[2,5], Mattheos Santamouris[1]

1. School of Built Environment, Faculty of Arts, Design & Architecture, University of New South Wales, Sydney, 2052 NSW, Australia
2. School of Civil and Environmental Engineering, University of New South Wales, Sydney, 2052 NSW, Australia
3. Institute for Artificial Intelligence Research and Development of Serbia, 21000 Novi Sad, Serbia
4. Institute for Multidisciplinary Research, University of Belgrade, Kneza Višeslava 1, 11000 Belgrade, Serbia
5. School of Civil and Environmental Engineering, Engineering Faculty, Queensland University of Technology, QLD 4001, Australia

Abstract

In the context of escalating global energy demands, urban areas, specifically the building sector, contribute to the largest energy consumption, with urban overheating exacerbating this issue. Utilizing urban modelling for heat-mitigation and reduction of energy demand is crucial steps towards a sustainable built-environment, complementing onsite energy generation in the design and development of Net-zero Energy (NZE) Settlement, especially in the context of Australian weather conditions. Addressing a significant gap in existing literature, this study offers empirical analysis on the climate and energy efficacy of integrated heat mitigation strategies applied in 14 neighbourhood typologies located in Sydney, Australia. Examining the application of cool materials on roads, pavements, and rooftops, alongside urban vegetation enhancement, the analysis demonstrates scenario effectiveness on heat mitigation that leads to reduce ambient temperature and energy demands along with CO_2 emissions within the neighbourhoods. Considering building arrangement, built-area ratio, building height, and locations, ENVI-met and CitySim are utilized to assess the heat-mitigation and the energy demand of neighbourhoods, respectively. Results indicate that mitigation measures can lead up to a 2.71 °C reduction in ambient temperature and over 25% reduction in Cooling Degree Hours, with a 34.34% reduction in cooling energy demand and overall energy savings of up to 12.49%. In addition, the annual energy-saving yields a CO_2 reduction of approximately 141.12 tonnes, where additional vegetation further amplifies these reductions by enhancing CO_2 absorption. This study showcases the pathway towards achieving NZE goals in climates similar to that of Australia, highlighting significant benefits in heat-mitigation, environmental impact, and energy-savings.

Keywords

urban overheating
cool materials
vegetation, heat mitigation
energy savings
CO_2 reduction

Article History

Received: 13 March 2024
Revised: 09 April 2024
Accepted: 25 April 2024

Research Article

Architecture and Human Behavior

1 Introduction

Urban areas constitute one of the primary cohorts with the largest energy demands and major contributions to worldwide greenhouse gas emissions, where the building sector serves as a pivotal contributor to the substantial levels of energy consumption and concurrent emission of pollutants (Hu et al. 2022). For example, buildings contribute to more than one-third of the total energy consumption (Hong et al. 2018) and are responsible for 40% of CO_2 emissions, where urban overheating is one of the leading factors underlying this incident (Asif et al. 2017). With the expansion of urban areas, agricultural lands are being converted into urban spaces, leading to an increase in anthropogenic activities and urban populations which is accompanied by the term *Urban Overheating* (Mondal et al. 2024), that leads to temperature surges of 5–10°C, affecting over 400 cities globally (Santamouris 2015). Apart from

E-mail: k.ullah@unsw.edu.au

natural sources, urban environments are significantly impacted by numerous sources of such anthropogenic heat, such as industrial equipment, vehicles, and systems for heating and air conditioning (Alhazmi et al. 2022; Bonifacio-Bautista et al. 2022). The temporal variation of urban overheating yields Urban Heat Island (UHI) effects that can be derived through specific indicators considering a range of climates and building types (Singh and Sharston 2023). The UHI impact exacerbates energy use, increasing it by approximately 0.73 ± 0.64 kWh/(m^2·°C) (Santamouris 2014), and peaks electricity demand by up to 12.3% (Santamouris et al. 2015) for each degree Celsius increase, influenced by local building and energy infrastructure characteristics. The phenomenon also impacts public health, with a 6% higher heat-related mortality in warmer areas and significant threats during heatwaves (Schinasi et al. 2018). Communities in Australia (and regions of the world with similar climates) are especially prone to heat-related health issues. Sydney (located in south-eastern Australia) experiences a humid subtropical climate, marked by warm summers and mild winters. The warmest month is January with a record high of 45.8 °C in 2016 (Santamouris et al. 2017). The trend of increasing ambient temperatures beyond the human body's tolerance threshold has led to heatwaves not just in Sydney but also in other Australian major cities such as Adelaide (Nitschke et al. 2011) and Brisbane (Tong et al. 2010), resulting in heat-related fatalities. In 2011, the Hunter Valley region on outskirts of Sydney experienced six consecutive days of heatwaves with maximum temperatures soaring above 39 °C (Schaffer et al. 2012). Such heatwaves highly threatened the public health and energy demand of the community (Schaffer et al. 2012; Santamouris 2020). For example, Santamouris et al. (2017) investigated the urban heat island and overheating phenomena in Sydney, discovering that Cooling Degree Days in western Sydney are approximately three times greater than in the Eastern coastal area due to the pronounced development of the UHI. In addition, such higher ambient temperature adversely impacts on both the supply and demand of electricity for cooling (Santamouris 2020) that leads to create a surge in peak electricity demand during warmer seasons, necessitating the construction of additional power plants. Additionally, it diminishes the generation capacity and constrains the efficiency of transmission and distribution systems of electrical power (Chandramowli and Felder 2014; Dirks et al. 2015; Bartos et al. 2016). These studies appeal to enhance the design and execution of urban mitigation strategies to offset the effects of the urban heat island within the communities.

Urban heat-mitigation technologies encompass various strategies designed to diminish the heat sources and augment heat-sink mechanisms in cities. In recent years, many studies aimed at developing and scaling up effective urban heat mitigation solutions that have predominantly focused on the use of reflective materials to minimize solar heat absorption by urban infrastructure along with the urban greenery and their optimum incorporation in urban planning (Akbari et al. 2016). Heat-mitigation strategies significantly reduce the peak-ambient temperature (Akbari et al. 2016) which leads to benefit for energy consumption (Santamouris et al. 2018), lessen heat-related mortality (Susca 2012), and reduce pollution those have separately been assessed in several case studies. Cool materials are the pioneer among the recently developed mitigation measures that have higher thermal emissivity as well as reflectance for visible and near-infrared wavelength range (Santamouris et al. 2011). These materials can be applied on roads, pavements, as well as building exteriors, including facades and rooftops to significantly lower ambient temperatures, thereby reducing the energy demand within neighbourhoods. The orientation of building facades plays a crucial role in energy savings during summer, although it may lead to considerable heat loss in winter (Xu et al. 2024). Beyond the employment of materials with high albedo, incorporating greenery represents an effective strategy to counteract UHI effects. This involves the integration of vegetation in the areas surrounding settlements as well as on building rooftops (Fahmy et al. 2018; Cascone et al. 2019). Greenery can yield cooling impacts via evapotranspiration along with shading as well as airflow control depending on the precinct type and geographic location (Santamouris et al. 2020). In addition to rooftops and surrounding areas of buildings, integrating greenery on building walls is an effective approach to significantly lower cooling energy demand (Anwar et al. 2021). Besides, the impact of cool materials and green surfaces on temperature reduction is time-dependent, with distinct effectiveness observed during daytime versus night-time periods (Herath Mudiyanselage 2023).

In Sydney, this overheating phenomenon along with heat-mitigation potential has been extensively investigated (Santamouris et al. 2017; Santamouris et al. 2018; Yun et al. 2020; Bartesaghi-Koc et al. 2020). The substantial magnitude of the urban heat island effect can be attributed to the influence of two synoptic meteorological systems on the local climate (Bartesaghi-Koc et al. 2021), specifically the sea-breeze plays a key role in reducing the ambient temperature in the eastern coastal part of the city, whereas warm western winds originating from the desert contribute to heating the western part of the city (Khan et al. 2021a; Khan et al. 2021b). For example, Santamouris et al. (2018) studied a case study located in the Sydney, observing a peak intensity of UHI up to 6 °C. They implemented high solar reflective materials and greenery on outdoor and roof surfaces that achieved up to 3 °C reduction in peak ambient temperatures. Simulating 10 summer days revealed a 20% decrease in residential cooling energy demand. However, the study's 10-day summer focus indicates that broader seasonal or annual analyses could offer more comprehensive insights into the enduring effects of these strategies. Another study (Santamouris et al. 2020) in Paramatta City, western Sydney, assessed the effects of heat mitigation on energy use, indoor comfort, and heat-related mortality and morbidity through 8 heat-mitigation scenarios combining reflective surfaces and greenery, reducing peak ambient temperatures by up to 2.5 °C and annual cooling loads by 1.5 TWh. Besides, CO_2 emissions and indoor overheating were reduced by up to 1.21 MT and 80%, respectively. Despite utilizing multi-year weather data, the study's focus was limited to the effects of mitigation strategies during a typical summer, expanding its scope to include all seasons could offer a fuller view of the strategies' year-round effectiveness. Garshasbi et al. (2020) forecasted the 2050 cooling energy demand for a settlement in South Creek, western Sydney, projecting a 0.8°C rise in peak summer temperatures and a 1.6 °C increase in average daily temperatures. Using mitigation strategies like cool materials, greenery, and irrigation, they managed to lower the average temperature by up to 1.6 °C and cut residential cooling loads by approximately 70%. Although the study prominently assessed long-term cooling energy needs for buildings, further detailed analysis is needed on how building design and layout affect energy consumption, especially during winter season. Khan et al. (2022) used simulated urban building energy scenarios in Greater Sydney, assessing thermal and energy performance through adaptive measures over two summers. Results showed that buildings' adaptive strategies significantly lowered indoor temperatures by up to 2.3 °C and reduced cooling energy demand by as much as 97%. The study showed improved energy efficiency in summer but highlighted the need to explore the effects in winter, aiming for a comprehensive view of adaptive strategies' performance throughout the year. Santamouris et al. (2019) comprehensively examined 14 typologies of neighbourhoods within Sydney urban areas considering the phenomenon of urban overheating by developing mesoscale climatic models to evaluate Sydney's current and projected 2050 climatic and land use conditions, alongside simulating the impact of mitigation measures over a summer month. Results showed a potential reduction in peak ambient temperatures by up to 2.5 °C along with noting up to 6% cooling energy demand variation. However, the study mainly focused on summer cooling energy demand, omitting the effects of mitigation on annual energy needs, particularly winter heating requirements. Kolokosta et al. (2022) further analyzed these 14 neighbourhood typologies to understand the role of urban planning and city typologies in mitigating the urban heat island effect. They found that aspect and built-area ratios adversely impact settlements' cooling potential. While the study shed light on thermal comfort, it left the year-round energy demand unexplored.

From above discussion it is revealed that the studies consisted of heat-mitigation measures within Sydney climate zone (and applicable to other areas with similar climate) are often confined to shorter periods (Santamouris et al. 2018), mainly in summer (Santamouris et al. 2020), leaving the winter season less examined. Additionally, the influence of architectural design and urban planning on energy consumption throughout the year is insufficiently studied (Khan et al. 2022). Moreover, the effects of mitigation measures on heat-mitigation and annual energy needs are not discussed simultaneously (Santamouris et al. 2019; Khan et al. 2022; Kolokotsa et al. 2022), where heating penalty are yet to be discussed (Khan et al. 2022). According to the best of the author's knowledge, there has been a notable absence of studies exploring such combined impacts of mitigation measures throughout a year-round from the perspective of Australian weather conditions. This study, therefore, targets to lead the way in designing and assessing the viability of integrating mitigation measures into neighbourhoods, with a particular emphasis on heat, energy, and environmental aspects, through software simulations drawing insights from 14 typologies of neighbourhoods comprising the impact of settlement types and geographic locations to set a precedent for future research and development in climates similar to Australia's. This paper aims to address the research question on what is the thermal and energy-saving benefit of introducing heat-mitigation measures across 14 different types of settlements in the Australian climate. To provide an answer, work will address two sub-questions:

(i) How do cool materials on roofs, roads, and pavements along with vegetation impact on heat-mitigation, and
(ii) What are the impacts of heat-mitigation measures on energy and carbon perspective?

2 Research methods

This research involved a software-based simulation of heat and energy perspective at 14 existing residential communities in Sydney, Australia. The overall approach of this study is illustrated in Figure 1, which outlines the overall approach of the study, starting with the selection of neighbourhoods in Sydney's urban areas for analysis. The next steps involve developing models using ENVI-met and CitySim software, incorporating specific parameters and real-world weather data from 2017, obtained from Sydney's Bureau of Meteorology (BOM). ENVI-met is used to simulate microclimatic conditions over 10 consecutive days in summer

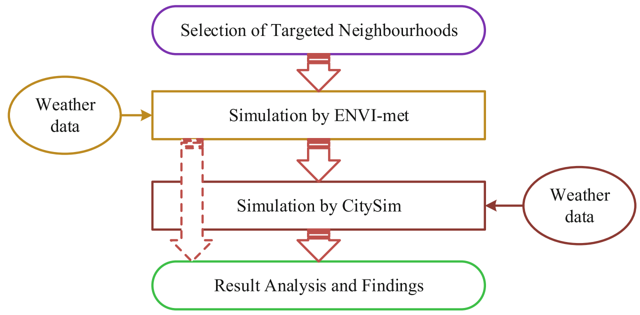


Fig. 1 Overall approach of the study

and 3 consecutive days in winter, while CitySim assesses the annual energy demands of the communities. Simulations for two scenarios are conducted: the base case (BC), representing current conditions, and the mitigated case (MC), showing potential improvements. A detailed analysis of results from both ENVI-met and CitySim simulations follows, highlighting key findings. This approach aims to provide a comprehensive understanding of both microclimatic effects for heat mitigation and the energy consumption implications for the neighbourhoods studied.

The processes and modelling, along with the specification of related parameters, are detailed in subsections 2.1 to 2.5.

2.1 Description of targeted neighbourhoods

Based on building height as per building typologies defined by the Department of Planning and Environment New South Wales and suggested by the Urban Taskforce Australia, there are 7 housing types described in the reference (Santamouris et al. 2019). Each of the seven housing types is further distinguished into two specific typologies: (1) Open Type (OT) and (2) Compact Type (CT). While OT typologies likely emphasize buildings with more open spaces, possibly featuring larger setbacks, more green areas, and potentially less density, CT typologies focus on more densely constructed buildings with maximizing the use of available space, with smaller setbacks, higher density, and possibly a greater emphasis on verticality. Therefore, there are 14 residential building typologies identified in New South Wales, particularly for Sydney's urban area, which correspond to existing settlements within the climatic zones of Sydney that are listed in Table 1. Table 2 shows detailed parameters of 14 settlements, including building height, size and stories, street width, and built-area ratio.

Above mentioned 14 residential typologies have been modelled and microclimatic simulation is done by ENVI-met and, CitySim is employed to calculate the energy demand of these settlements for both BCs and MCs. Figure 2 illustrates an overview of simulation process of the study.

Figure 2 illustrates that ENVI-met and CitySim are employed to model the settlements and run the simulation for BCs and MCs. Since, the historical meteorological data from 2017 is used for the BC of ENVI-met simulation, considering the extrapolation and distance of the neighbourhoods, correlated weather data is used for the MCs of ENVI-met along with both BCs and MCs of CitySim simulation. As mitigation measures, cool materials are considered for roads, pavements, and buildings' rooftops along with some additional vegetation within the settlements. Hence, ambient temperature and CO_2 emissions are obtained from the output file of ENVI-met, while CitySim provides cooling and heating energy demand as outputs of the simulation. From outputs of ENVI-met, the impacts of

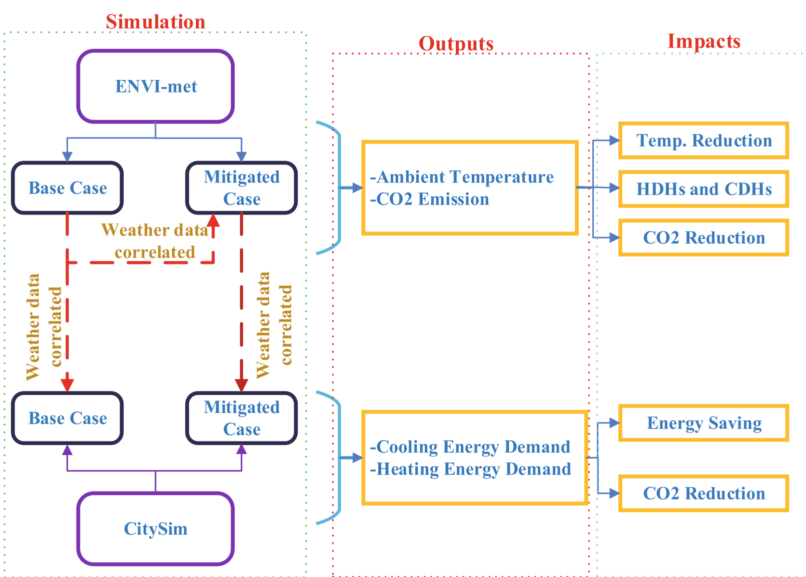


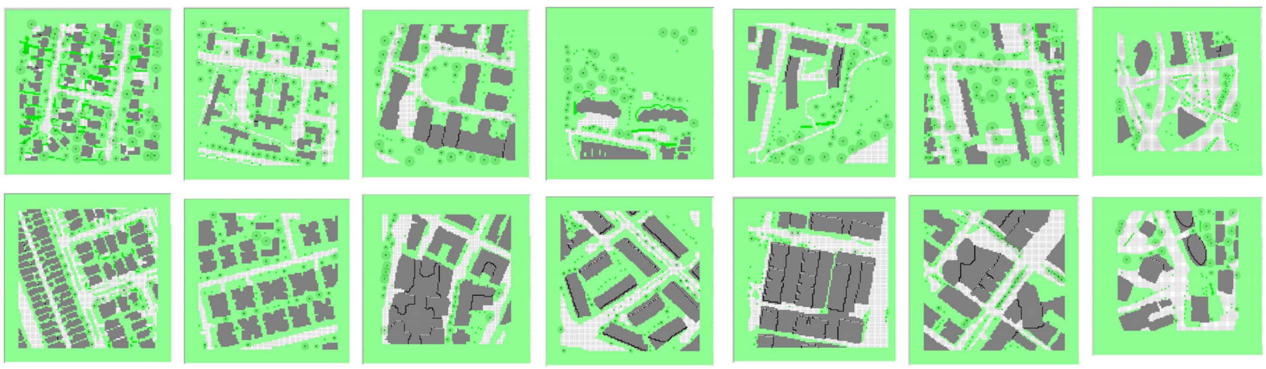
Fig. 2 Overview of simulation process

Table 1 Overview of the 14 targeted residential typologies in Sydney, featuring locations and corresponding models by ENVI-met and CitySim

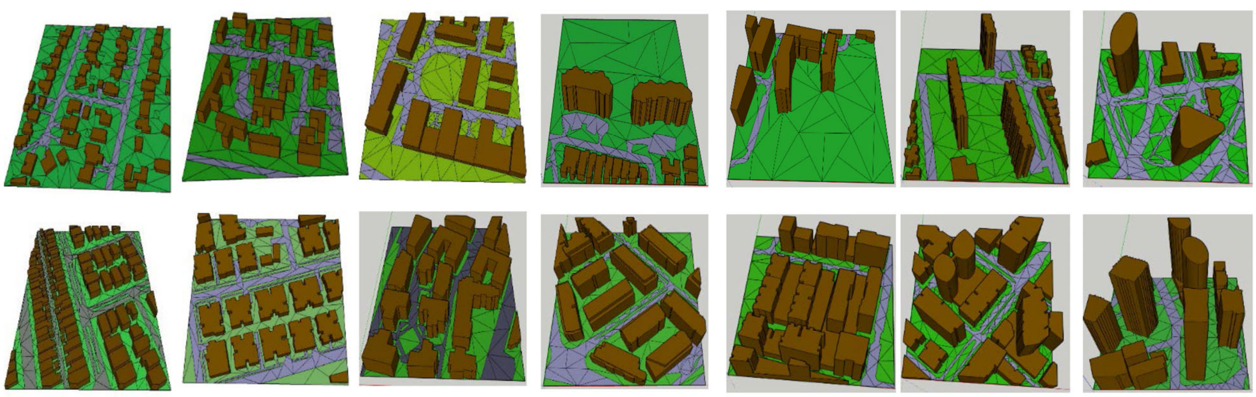
Overview of neighbourhoods and their models							
Typologies and location	OT1: Normanhurst https://goo.gl/maps/vd3Bj6sDgUD2 - CT1: Kellyville https://goo.gl/maps/ULKg6dEeV2y	OT2: Kooloora https://goo.gl/maps/ee9sSLxS9zu - CT2: Epping https://goo.gl/maps/GJFKv2N5fF72	OT3: Rosebery https://goo.gl/maps/ovzfXEPqW7D2 - CT3: Meadowbank https://goo.gl/maps/Rr4JqhhhLBJ2	OT4: Raleigh Park https://goo.gl/maps/Jbma3iGfcdK2 - CT4: Harold Park https://goo.gl/maps/sNsaw8UMFm22	OT5: Parramatta https://goo.gl/maps/Jt7fwke7oW62 - CT5: Mascot https://goo.gl/maps/y8Rnqy2sfEL2	OT6: Waterloo https://goo.gl/maps/X6FXdEPiieT2 - CT6: Wentworth Point https://goo.gl/maps/xw2DoREU5712	OT7: Sydney Olympic Park https://goo.gl/maps/HBjK9Mu4LWL2 - CT7: Chatswood https://goo.gl/maps/mTHdULfhEyF2

Bitmap (from Nearmap)

Model (ENVI-met)



Model (CitySim)



mitigation measures on temperature, cooling degree hours (CDHs) and heating degree hours (HDHs), and emission of CO_2 are calculated. Similarly, amount of energy savings and corresponding CO_2 reduction are calculated from the output data of CitySim.

2.2 Weather data

The weather data for these simulations, crucial for accurate microclimatic and energy demand assessments, was sourced from the year 2017 and obtained from the BOM in Australia.

Table 2 Overview of 14 settlements with various parameters (e.g., building height, size, and stories as well as street width and built-area ratio, etc) (Santamouris et al. 2019)

Various parameters of targeted settlement typologies														
Typologies	OT1	CT1	OT2	CT2	OT3	CT3	OT4	CT4	OT5	CT5	OT6	CT6	OT7	CT7
No. of stories	1	2	3	4	6	6	8	8	10	12	18	22	35	40
Building height (m)	4	8	10	12	18	18	30	30	40	40	60	70	130	145
Street width (m)	25–35	25–30	25–30	15–30	15–20	15–20	35–45	20–25	20–30	25–30	45–55	25–30	35–70	20–40
Building size (m^2)	150–300	150–300	250–500	650–1000	1000–2000	1000–2000	1000–1500	1000–1500	1000–1500	4000–6000	1000	1500–2000	1000–1500	1000–1500
Built-area ratio	22%	37%	16%	37%	30%	55%	13%	38%	15%	55%	14%	48%	15%	30%
Road & pavement (%)	15.9	19.5	21.6	20.1	21.8	28.2	8.3	18	11.3	10.2	22.3	20.6	32.3	18.6
Greenery (%)	62.1	43.5	62.4	42.9	48.2	16.8	78.7	44	73.7	34.8	63.7	31.4	52.7	51.4

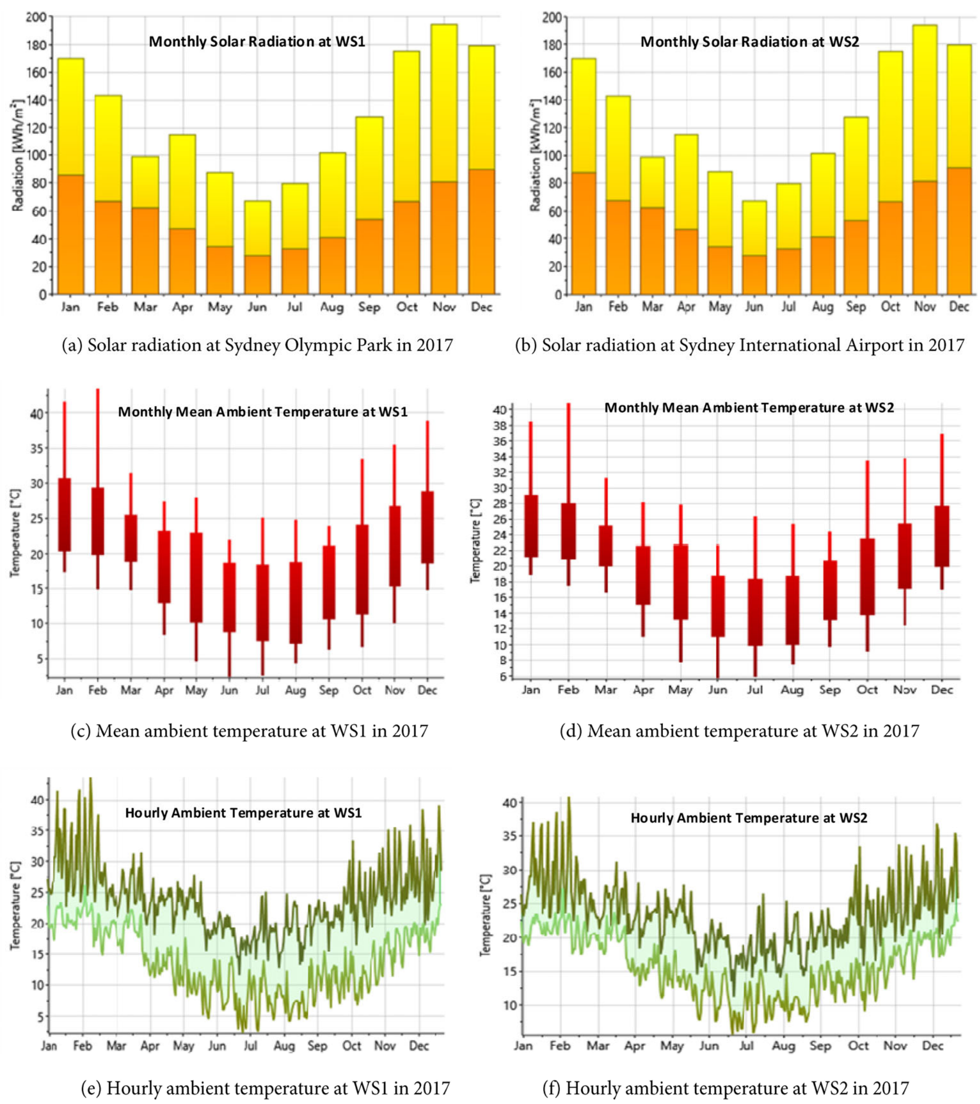


Fig. 3 The solar radiation and temperature at WS1 and WS2 in 2017

The locations of these neighbourhoods are strategically near two primary weather stations: (i) WS1 - the Sydney Olympic Park (having latitude and longitude of 33°85′ S and 151°06′ E, respectively with an elevation of 15 m above the sea level) and (ii) WS2 - the Sydney International Airport (having latitude and longitude of 33.93°S and 151.17°E, respectively with an elevation of 9 m above the sea level). Both are situated within Sydney that have a temperate climate with a mild winter (zone 5) and has about 122 sunny and cloud-free days per year. The monthly solar radiation and temperature along with hourly temperature are shown in Figure 3.

The weather data illustrated in Figure 3 were generated from Meteonorm 8.0 software with the help of the historical meteorological data from 2017 brought from the BOM, Australia. From Figures 3(a) and (b), it is seen that the solar radiation was higher during October to mid-March. The maximum radiation was obtained in November 2017 which was 194 kWh/m^2 and 196 kWh/m^2, where the radiation went minimum in June reaching about 68 kWh/m^2 and 64 kWh/m^2 for WS1 and WS2 respectively. Besides, Figures 3(c) and 3(d) illustrate that the mean minimum temperature in the winter months of June through August is approximately 9 °C. The summer season is considered from October through to mid-March with a mean maximum temperature of 25 °C. Besides, from Figures 3(e) and (f) it is seen that the daily maximum ambient temperature remained over 30 °C from October to mid of March. It crossed 40 °C multiple times during January and February for WS1, and once in February for WS2 in 2017. The city has warm, sometimes hot summers, and mild winters with no extreme seasonal differences as the weather is moderated by proximity to the ocean. For our simulations, we utilized historical meteorological data from 2017, sourced from the BOM, Australia. For compatibility with ENVI-met, this data was used as .epw format. Conversely, CitySim required the weather data in .cli and .hor formats, necessitating conversion through Meteonorm software to ensure precision and software compatibility. It is important to note that while converting weather data with Meteonorm, the parameters' values remained unchanged; however, the quantity of parameters was reduced (from the 33 parameters found in .epw files to just 12 in .cli files), adapting to the specific input requirements of CitySim.

2.3 Simulation by ENVI-met

In the present investigation, the ENVI-met V5.0.3 software suite was utilized to conduct simulations under both BC and MC conditions, leveraging real-time meteorological data from the year 2017. ENVI-met is equipped with a three-dimensional microclimatic model that is specifically engineered to replicate the interactions between surfaces, vegetation, and the atmosphere within urban locales. This tool stands out for its precision in modelling the spatial distribution of key climatic variables within urban settings. ENVI-met incorporates a comprehensive three-dimensional Computational Fluid Dynamics (CFD) framework, which employs the Reynolds-averaged Navier-Stokes equations in a non-hydrostatic form, applying these equations across each spatial grid and temporal interval (Santamouris et al. 2019).

In this study, the full forcing method is used for both BCs and MCs, where the simulations were forced for the air temperature, relative humidity, and solar radiation. Implantation of additional vegetation and using cool materials on roads and pavements are the mitigation measures taken by the ENVI-met mitigated models. The key steps and settings are as follows:

a) For BCs and MCs, the simulation is run for all 14 typologies of neighbourhoods located within Sydney's climate. Bitmap (photo obtained from Nearmap) is used to identify the buildings, roads, grasses, and trees within the community. The spatial resolution used in the simulations is 2 m horizontally. The area has been rendered with 120 × 120 × 60 (x-y-z) cells, with the following size: dx = 2.0 m, dy = 2.0 m, and base dz = 2.0 m. The number of cells along z-axis varies with the height of the buildings. The grid at the z-axis is telescopic with a thicker cell near the ground, allowing a better accuracy for edge effects. The actual size of the settlement is considered for 200 m × 200 m, where additional 20 cells are added around the model to avoid the instability error of ENVI-met simulations.
b) As additional vegetation for MCs, at least one 01CLDM [cylindric, large trunk, dense, medium (15 m)] is considered for 20 m × 20 m free space outside the building in the community.
c) For the BC, the albedo of asphalt road (ST), pavement-lite (PL), pavement grey (PG) and pavement dark (PD) are used as 0.2, 0.8, 0.5 and 0.2, respectively. The values are the standard by-default setup of ENVI-met which are also used in reference literature (Santamouris et al. 2019). Then the CDHs, HDHs, and ambient temperature are calculated with the help of the BOM weather file for 2017. For the MC, the material of asphalt road is replaced by Q5 (a modified material with an albedo of 0.5), and all PGs and PDs are replaced by Q3 which has an albedo of 0.55. These values are chosen from reference literature (Santamouris et al. 2019). Then, the CDHs, HDHs, and ambient temperature are calculated for MCs and compared with BCs.
d) In full forcing method, the initial wind speed and direction were taken as a fixed value to avoid the instability errors of the simulations which were 2.5 m/s and 250°, respectively. Other parameters are supplied through an EPW weather file (as discussed in subsection 2.3.1).

In addition, the materials used in the default wall having with 3 layers [i.e., outside layer - 0100PL (1 cm), first layer – 0100IN (11 cm) and second layer – 0100CO (6 cm)] have also been considered for the roofs of all the buildings during the simulation of ENVI-met (Santamouris et al. 2019). Besides, the urban surface properties and vegetation types used in all neighbourhoods are provided in Table 3 and Table 4, respectively.

2.3.1 *Weather data for ENVI-met*

For ENVI-met simulation, we have 2 subsets of weather data for summer and winter to determine the impacts of mitigation measures during those seasons. It is known that ENVI-met takes many days to give the output depending on the size of the model, therefore, it is recommended running the simulation for 2–5 days (Ambrosini et al. 2014). Alternatively, for long-term analysis, a clustering method to yearly weather files proposed and demonstrated by Acero et al. (2020) can be recommended. However, considering the determination of the energy demand for

Table 3 Urban surfaces albedo and emissivity for the BC and MC of 14 neighbourhoods (Santamouris et al. 2019)

Code	Name	Albedo	Emissivity	OT1	OT2	OT3	OT4	OT5	OT6	OT7	CT1	CT2	CT3	CT4	CT5	CT6	CT7
0100PD	Concrete pavement dark	0.20	0.90	√	√	—	—	√	√	√	√	—	√	√	—	—	—
0100PG	Concrete pavement gray	0.50	0.90	√	√	√	√	√	√	√	√	√	√	—	√	√	√
0100PL	Concrete pavement light	0.80	0.90	√	—	√	√	√	—	√	√	√	√	—	√	—	√
0100ST	Asphalt road	0.20	0.90	√	√	√	√	√	√	√	√	√	√	√	√	√	√
0100WW	Deep water (swimming pools)	0.00	0.96	√	—	—	√	—	—	—	√	—	—	—	—	—	—
0100KK	Brick road (red stones)	0.30	0.90	—	—	—	—	—	—	—	—	√	√	—	—	—	√
0100Q3	Cool pavement	0.55	0.90	√	√	√	√	√	√	√	√	√	√	√	√	√	√
0100Q5	Cool asphalt road	0.50	0.90	√	√	√	√	√	√	√	√	√	√	√	√	√	√

Table 4 The vegetation characteristics used in the 14 neighbourhoods (Santamouris et al. 2019)

Code - Name	OT1	OT2	OT3	OT4	OT5	OT6	OT7	CT1	CT2	CT3	CT4	CT5	CT6	CT7
0100XX - Grass 25cm aver. dense	√	√	√	√	√	√	√	√	√	√	√	√	√	√
0100H2 - Hedge dense, 2m	√	—	√	√	√	√	—	—	—	—	—	—	—	√
0100H4 - Hedge dense, 4m	√	—	—	—	—	—	—	—	—	—	—	—	—	—
01PLDS - Palm, large trunk, dense, small (5m)	—	√	—	√	—	√	—	—	—	—	—	—	√	√
01PLDM - Palm, large trunk, dense, medium (15m)	—	√	—	√	—	√	—	—	—	—	—	—	√	√
01PLDL - Palm, large trunk, dense, large (25m)	√	√	—	√	—	√	—	—	—	√	—	—	√	√
01OLDS - Cylindric, large trunk, dense, small (5m)	—	√	—	—	—	—	—	—	—	—	—	—	√	—
01OLDM - Cylindric, large trunk, dense, medium (15m)	—	√	—	—	—	—	—	—	—	—	—	—	√	—
01CLDL - Cylindric, large trunk, dense, large (25m)	—	—	—	√	√	√	—	—	—	—	√	—	—	—
01OLDL - Cylindric, large trunk, dense, large (25m)	√	√	—	—	—	√	—	—	—	—		—	√	—
01CSDS - Cylindric, small trunk, dense, small (5m)	√	—	√	√	√	√	√	√	—	—	—	—		√
01CSDM - Cylindric, small trunk, dense, medium (15m)	√	—	√	√	√	√	√	√	—	√	—	√		√
01CSDL - Cylindric, small trunk, dense, large (25m)	√	—	√	√	—	√	√	√	√	√	—	√		√
01CLDS - Cylindric, large trunk, dense, small (5m)	√	—	√	√	—	√	√	√	√	√	√	√	√	√
01CLDM - Cylindric, large trunk, dense, medium (15m)	√	—	√	√	√	√	√	√	√	√	√	√	√	√
01SMDS - Spherical, medium trunk, dense, small (5m)	—	—	—	—	√	√	—	—	—	—	—	—	—	—
01SMDM - Spherical, medium trunk, dense, medium (15m)	—	—	—	—	√	√	—	—	—	—	—	—	—	—
01SMDL - Spherical, medium trunk, dense, large (25m)	—	—	—	—	—	√	—	—	—	—	—	—	—	—
01CMDS - Cylindric, medium trunk, dense, small (5m)	√	—	—	—		—	√	—	—	—	—	—	—	√
01CMDM - Cylindric, medium trunk, dense, medium (15m)	√	—	—	—		—	√	—	—	—	—	—	—	√
01CMDL - Cylindric, medium trunk, dense, large (25m)	√	—	—	—	—	—	√	—	—	—	—	—	—	√
01HLDL - Heart-shaped, large trunk, dense, large (25m)	—	—	—	—	—	—	—	—	√	—	—	—	—	—
01ALDS - Conic, large trunk, dense, small (5m)	—	—	—	—	—	—	—	—		—	√	—	—	—
01ALDM - Conic, large trunk, dense, medium (15m)	—	—	—	—	—	—	—	—	—	—	√	—	—	—
01ALDL - Conic, large trunk, dense, large (25m)	—	—	—	—	—	—	—	—		—	√	—	—	—

the whole year by CitySim, which is dependent on the output of ENVI-met simulations, we tried to take the duration of ENVI-met simulation as much as we could. Therefore, we considered 10 consecutive days (starting at 05:00 AM on 21/01/2017 and ending at 04:59 AM on 31/01/2017) considering the highest ambient temperature in summer to observe the impact of the mitigation scenario. However, cool materials are likely to show an adverse impact in winter which is obvious and must be counted in our study. As, ENVI-met responds with instability errors if the temperature is near zero or negative which yields challenges for long-run simulation during winter, 3 consecutive days (starting at 05:00 AM on 21/07/2017 and ending at 04:59 AM on 24/07/2017) are chosen for winter which is just after six months of summer simulation.

In our study, although we focus on 14 neighbourhoods, the weather data utilized comes from only two weather stations (WS1 and WS2), which are closest to our study areas. To account for the discrepancies caused by distance and data extrapolation, establishing correlations is crucial. This approach is particularly important since ENVI-met simulations cover selected days, necessitating correlations to project impacts over an entire year. We specifically correlate ambient temperature data to assess heat mitigation effectiveness. For both sets of correlations, we ensure a coefficient of determination (R^2) exceeding 0.95, enabling the derivation of accurate equations to adjust the 2017 weather data comprehensively. Given the structure of our simulations—running both BC and MC scenarios for each neighbourhood across summer and winter—this process results in four correlation equations per settlement, enhancing the precision of our annual climate impact analysis.

The processing of weather data sourced from the BOM for this study involves several key steps to ensure accuracy and relevance for both BC and MC simulations:

1. BOM weather data is initially used to simulate BCs in ENVI-met for both the summer and winter seasons, covering all targeted neighbourhoods.
2. A correlation analysis is performed between the ENVI-met BC output data and the original BOM weather data. This step accounts for factors like data extrapolation and the geographic distance of the settlements. A correlation equation, derived for both summer and winter seasons, is then applied to generate a revised weather data file. This adjusted file serves as the new input for the MC simulations in ENVI-met, encompassing the entire year.
3. A subsequent correlation is conducted between the output data from the ENVI-met MC simulations and the corresponding input weather data used for MC. This correlation specifically considers the extrapolated effects of implemented mitigation strategies, such as the addition of vegetation and the application of cool materials on roads and pavements, on the weather data.

Summer simulations using ENVI-met were conducted successfully for all 14 targeted neighbourhoods. However, during the winter phase, only 6 neighbourhoods (OT2, CT2, CT3, CT4, CT5, and CT6) completed simulations without encountering instability errors, a common occurrence often observed in ENVI-met running at lower ambient temperatures. To address this challenge for the remaining neighbourhoods, we implemented a strategy of using the same correlation equations, categorizing them based on similarities in building typologies and heights. Consequently, groups such as OT1 with OT2, CT1 with CT2, CT3 with OT3, CT4 with OT4, CT5 with OT5, and a collective grouping of CT6, OT6, CT7, and OT7 were assigned the same correlation equations for the winter simulations. The specific equations employed for correlating the weather data across these simulations are detailed in Appendix A.

2.4 Simulation by CitySim

In the present study, the latest version of CitySim Pro has been employed to perform detailed energy simulations at the community scale. CitySim is a C++ based graphical user interface that uses the physics-based model to perform detailed dynamic simulations based on an electrical circuit analogy (resistor–capacitor network) (Robinson et al. 2009). Hourly models of urban radiation, building thermal, occupant behaviour, energy conversion system, and heating, ventilation, and air-conditioning equipment models are utilized to perform the simulation (Khan et al. 2022). Table 5 contains some key parameters used for this simulation.

The CitySim is employed to calculate the annual heating and cooling energy demand for all settlements for both BC and MC. While Table 5 details the energy demand areas for the buildings within each settlement, the annual energy demand calculation was performed on a per square meter basis of these specified areas, expressed in kWh/m². While we considered mitigation measures by ENVI-met for outdoor heat sources, in addition, we used cool materials on rooftops of the buildings during CitySim simulations as a part of the adaptation of the building's scenario. For roofs, albedo is considered as 0.2 and 0.8 for the BC and MC cases respectively, where the roads are considered as asphalt road (albedo = 0.2 and kfactor = 0), the other parts (excluding buildings) are considered as green surface (albedo = 0.3 and kfactor = 0.4) neglecting the shading effects of trees. Therefore, the collective impacts of mitigation measures along with cool roofs on energy demand have been calculated through CitySim simulation. For modelling of the

Table 5 Input parameters for CitySim simulations

Typologies of settlements		Area of energy demand by buildings (m^2)	Occupant density (m^2/p)	Internal gains		Ventilation system
				Sensible loads (W/p)	Latent loads (W/p)	
OT	OT1	9374.00	50	90	45	The ideal mechanical ventilation system is considered
	OT2	18789.00	25			
	OT3	64981.23				
	OT4	25893.73				
	OT5	53276.32				
	OT6	54032.13				
	OT7	109429.99				
CT	CT1	26338.45	50			
	CT2	59508.64	25			
	CT3	91056.24				
	CT4	104450.73				
	CT5	181201.24				
	CT6	262511.58				
	CT7	228402.80				

neighbourhoods, a 200 m × 200 m area is chosen for each settlement (same number of buildings and area used in ENVI-met). SketchUp Pro-2017 is used to develop the building models for both cases of all settlements as shown in Table 1. These models are used by CitySim to specify the parameters (detailed archetypes are listed in Table 5) and perform the simulations. All geometrical parameters including types, height, no. of stories and footprint area of the buildings, width of the street, window spacing etc., are obtained from the archetypes (Santamouris et al. 2019). The thermophysical properties of the buildings including building envelope, heating, ventilation, and air-conditioning (HVAC) systems, internal loads, etc., are defined in accordance with the National Construction Code (NCC) (NatHERS 2019). Other parameters are selected from default values of CitySim, where windows are considered as single glazing. The *U*-value and *g*-value of the building envelope (including wall and roof) are considered about 5.80 W/(m^2·K) and 0.85, respectively. The infiltration, the shading device (λ) and the cut-off irradiance are taken as 0.50 h^{-1}, 0.20, and 100, respectively. To define the occupancy profile, the simulation considered 25 m^2 and 50 m^2 for an occupant living in the apartment and in the house, respectively, where the sensible heat, radiant part, and latent heat are chosen as 90 W/p, 0.60 and 45.0 W/p, respectively. Besides, the CitySim considered an ideal mechanical ventilation system for residential buildings, where this simulation takes the default values of some parameters (e.g., Φ = 20, ρ = 1000, Cp = 4180, η_th = 0.95 and η_tech = 0.3) used in Heat-Tank and Cool-Tank of HVAC system. Nationwide House Energy Rating Scheme (NatHERS) standard is used to determine the internal loads. Total sensible heat loads are considered with the summation of daily usage of appliances and lighting loads to be aligned with ASHRAE standards (ASHRAE 2017; Khan et al. 2022). Besides, the summer period is taken from the beginning of October to the end of March, considering the average daytime temperature is about 25 °C and above; where rest of the 6 months are considered as winter to calculate the heating and cooling energy demand for all the year round in 2017.

2.4.1 *Weather data for CitySim*

In conducting CitySim simulations, two distinct types of weather files were essential: climate (.cli) and horizon (.hor) files, both generated via Meteonorm 8.0 software (Remund et al. 2017). This software adapted the 2017 weather data to create hourly .cli files for the entire year, requiring additional parameters such as precipitation (mm), cloud-cover fraction (Octas), and surface temperature (°C) for accurate building energy modelling. Meteonorm also generated cloud-cover and precipitation data based on radiation time series from input files (.epw) and filled in any missing parameters. Horizon files (.hor) were created for each weather station referenced in our study (Khan et al. 2022). For the BC simulations in CitySim, we utilized a weather file modified with data correlated from ENVI-met's MC simulation inputs to assess the 2017 energy demand. Conversely, for CitySim's MC simulations, the input was a weather file adjusted based on data correlated from the ENVI-met MC simulation outputs, allowing us to explore the potential improvements in energy demand scenarios for all settlements under consideration.

2.5 Data analysis process

The output data obtained through the simulation by ENVI-met and CitySim are analyzed through various steps. The collective impact of vegetation and cool materials used on roads and pavements influence temperature and energy consumption of the settlements. The impacts on ambient temperature are determined by comparing the data obtained from BC and MC of ENVI-met simulation. The correlated output data of the BC and the MC of ENVI-met is used to calculate the yearly Cooling Degree Hours (CDHs) and Heating Degree Hours (HDHs). Heating and cooling degree hours are defined as the sum of the differences between the hourly average temperature and the base temperature and calculated using Equations (1) and (2).

$$\mathrm{CDH} = \sum_{k=1}^{k=N} (T_{\mathrm{out}} - T_{\mathrm{cool}}) \tag{1}$$

$$\mathrm{HDH} = \sum_{k=1}^{k=N} (T_{\mathrm{heat}} - T_{\mathrm{out}}) \tag{2}$$

where, T_{out} is the outdoor ambient temperature (°C) and T_{cool} is the temperature of start cooling ($T_{\mathrm{cool}} \geq 26$ °C) and T_{heat} is the temperature of start heating ($T_{\mathrm{heat}} \leq 16$ °C). During the summer months, the average daytime temperature was consistently observed to exceed 25 °C at each weather station. Conversely, during winter, temperatures were recorded to range between 15 and 16 °C. Based on these observations, the threshold temperatures for cooling (T_{cool}) and heating (T_{heat}) were established at 26 °C and 16 °C, respectively. These set points are corroborated by existing literature, confirming their appropriateness for studies within the Australian weather perspective (Santamouris et al. 2021; Livada et al. 2021).

The annual heating energy demand (HED) and cooling energy demand (CED) are calculated by analysing the output data obtained from both BCs and MCs of CitySim simulation. To calculate the HED and CED, Equations (3) and (4) are used.

$$\mathrm{HED} = \frac{\sum_{N=1}^{N=k} \mathrm{HHED}/1000}{A} \tag{3}$$

$$\mathrm{CED} = \frac{\sum_{N=1}^{N=k} \mathrm{HCED}/1000}{A} \tag{4}$$

where, HHED = hourly heating energy demand (Wh), HCED = hourly cooling energy demand (Wh), k = number of hours in a year, A = No. of floors ×∑ total floor area (m^2) of all buildings at the settlement. The HED and CED are determined on a per square meter basis, with results reported in kWh/m^2.

Subsequently, the HED and CED values for each settlement are multiplied by the respective energy demand area of the buildings within that settlement to calculate the total energy demand. Comparison of energy demand between BCs and MCs facilitated the determination of energy savings for each settlement. These energy savings are then used to assess their impact on CO_2 emissions, utilizing Equation (5).

$$\mathrm{CO2}_{\mathrm{reduction}} = \mathrm{ES} \times 7.09 \times 10^{-4} \tag{5}$$

where, ES denotes annual energy savings (kWh)

The impact of vegetation on CO_2 emission is determined by comparing the output CO_2 data obtained for BCs and MCs through ENVI-met simulation. The amount of CO_2 emissions (mg/(m^3·hour)) for both BC and MC are to be found from the output file of ENVI-met, which is used to calculate the CO_2 emissions during summer and winter of the settlements. Equation (6) is employed to find the daily CO_2 emissions (DCE, in g/(m^3·day)) in summer and winter.

$$\mathrm{DCE} = \sum_{t=0}^{t=24} \mathrm{HCE}/1000 \tag{6}$$

where, HCE = hourly CO_2 emissions (mg/(m^3·hour)) obtained in ENVI-met output file.

2.6 Validation of models

To ensure the robustness of our methodology, we anchored the development of our models in ENVI-met and CitySim on established research findings. We utilized the research outcomes from Santamouris et al. (2019) to shape our ENVI-met models for both the base cases and mitigated cases scenarios. This alignment was due to the congruence of our study areas with the neighbourhoods examined in their work, adopting similar parameter values for consistency. Additionally, for constructing our CitySim models, we leveraged insights from Khan et al. (2022), particularly for modelling the base case scenarios that simulate the Sydney climate's impact on residential buildings. For the mitigated case scenarios within CitySim, modifications were made to refine the models based on their framework, ensuring our methodology was grounded in and validated by prior empirical research.

3 Result analysis

The effects of implementing mitigation measures such as the integration of vegetation within urban areas, and the application of cool materials on roads, pavements, and building rooftops, have been evaluated using the ENVI-met and CitySim software platforms. This assessment encompasses all 14 typologies of neighbourhoods. A comprehensive analysis of the results and a subsequent discussion are presented in the subsections 3.1 to 3.3.

3.1 Impacts on heat-mitigation within the community

To assess the effectiveness of mitigation strategies on heat-mitigation within urban settlements, an initial step involves analysing variations in ambient temperature. This analysis is facilitated by examining the outputs from the BC and MC simulations conducted using ENVI-met. A notable decrease in ambient temperature was observed during the winter simulation scenarios. As a method to illustrate this effect, one reference temperature was chosen from each weather station to illustrate this scenario. For WS1 and WS2, the maximum ambient temperatures were recorded about 36.4 °C and 37.2 °C respectively on 24th of January. Depending on these 2 values, all settlements were observed where the outcomes are illustrated in Figure 4.

From Figure 4(a), it is seen that the maximum ambient temperature was around 38.5 °C for the settlements CT2, CT3 and CT6. The drop of ambient temperature lies between 1 and 2 °C where about 2.07 °C was dropped for the settlement of CT6. On the other hand, Figure 4(b) shows that up to 2.57 °C temperature could be reduced by employing mitigation measures within the community. The built-area ratio exerts a significant influence on ambient temperatures within urban settlements, with its effect becoming more pronounced when mitigation measures are applied. A higher built-area ratio is associated with elevated ambient temperatures due to the increased density of built surfaces that absorb and retain heat. However, these densely built areas also exhibit a greater potential for temperature reduction when targeted mitigation strategies are implemented. For instance, in the neighbourhoods proximal to WS1, settlements CT2, CT3, and CT6, which have built-area ratios of 37%, 55%, and 48% respectively, recorded higher baseline ambient temperatures. Moreover, among these, CT3 and CT6 demonstrated the most significant temperature reductions of 1.76 °C and 2.07 °C respectively after the application of mitigation measures. A similar pattern was observed in the neighbourhoods near WS2, where CT4, with a built-area ratio of 38%, showed the highest ambient temperature increase. Additionally, the settlements around WS2 experienced a more substantial decrease in ambient temperatures compared to those near WS1. This discrepancy can be attributed to the fact that mitigation measures tend to be more effective in areas with higher initial temperatures.

For further assessment of the impacts of mitigation strategies on heat-mitigation performance of the settlements, yearly CDHs and HDHs were calculated by using Equations (1) and (2). Although the simulations conducted with ENVI-met are limited to 10 selected days during the summer and 3 days in the winter, the extrapolation of these short-term data points to generate annual CDHs and HDHs was facilitated through the application of correlation data for the year 2017. Figures 5(a) and (b) illustrate the results of CDHs for OT and CT settlements, respectively.

From Figures 5(a) and (b), it becomes evident that CT settlements consistently register higher CDHs in comparison to those in the OT settlements regardless of their geographical location, prevailing weather conditions, and built-area ratio. The maximum CDHs were found about 3300 hours and 4000 hours for OT and CT settlements, respectively. Depending on the built-area ration, the settlements show similar trends on CDHs like ambient temperature. For example, settlements CT2, CT3, and CT6, which have built-area ratios of 37%, 55%, and 48% respectively, recorded higher CDHs. Besides, we can see that up to 25.98% CDHs could be reduced for OT typologies, while around 20.34% CDHs could be reduced for CT settlements. This observation implies that CT settlements, due to specific aspects of their design, structure, or the density of their built environment, are more susceptible to heat accumulation. As a result, there is a greater need for cooling interventions to achieve a comfortable indoor climate.

The utilization of cool materials, while beneficial for reducing CDHs, has been observed to inadvertently increase

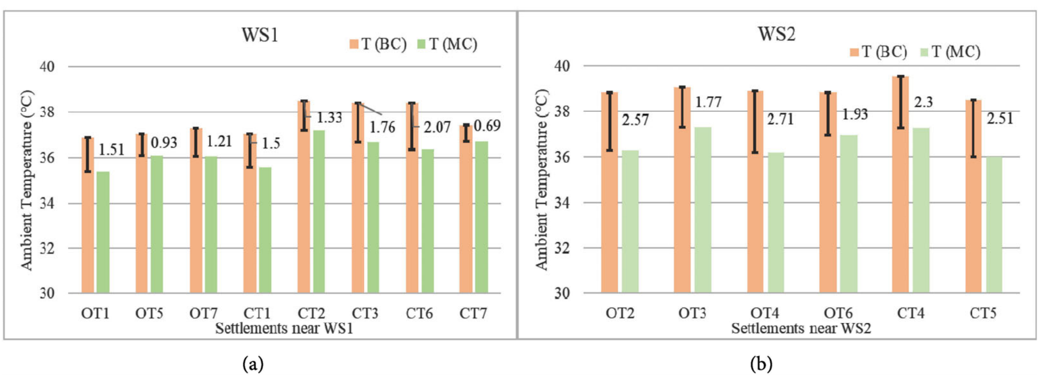
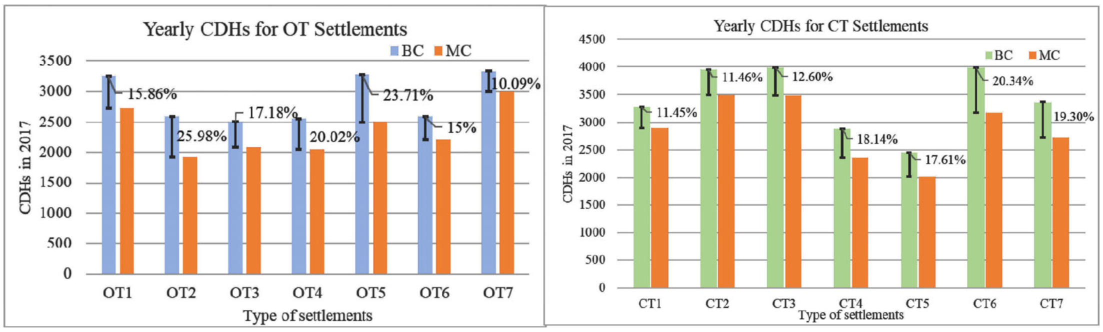


Fig. 4 Ambient temperature of various settlements located near to (a) the WS1at 12:00 PM and (b) the WS2 at 10:00 AM on 24th January 2017



(a) CDHs of OT settlements (b) CDHs of CT settlements

Fig. 5 Yearly CDHs of all typologies of neighbourhoods

HDHs, a phenomenon often referred to as the heating penalty. This effect is detailed in Table 6.

From Table 6, it is noted that the increase in HDHs, attributable to the adoption of cool materials, generally ranges between 2% and 6%. However, exceptions are found in the settlements of OT5 and CT7, where the heating penalties are notably higher, at approximately 12.18% and 10.03%, respectively. Despite this, such increases in HDHs are considered to be within acceptable limits when weighed against the benefits derived from the significant reduction in CDHs.

3.2 Impacts on energy demand of settlements

The effects of mitigation measures on energy demand are quantitatively assessed by examining annual heating and cooling energy loads. Utilizing the outputs from CitySim, the demands for heating and cooling energy are determined through the application of Equations (3) and (4), respectively. The outcomes of this analysis are systematically presented in Table 7, which details the heating and cooling energy demand scenarios for all 14 typologies of neighbourhoods under review.

Table 6 Scenario of yearly heating degree hours for BCs and MCs of all settlements

Settlement typologies	OT1	OT2	OT3	OT4	OT5	OT6	OT7	CT1	CT2	CT3	CT4	CT5	CT6	CT7
BC (hrs)	10401	6111	6756	6299	10548	9988	10751	10548	10898	10662	6150	6127	10662	10860
MC (hrs)	10620	6330	6998	6529	11833	10204	10988	11187	11142	10895	6369	6346	10895	11950
Increment (hrs)	219	219	242	230	1285	216	237	639	244	233	219	219	233	1090
% Change	2.11	3.59	3.6	3.65	12.18	2.16	2.2	6.06	2.25	2.19	3.56	3.58	2.19	10.03

Table 7 Impact of mitigation measures on annual heating and cooling energy demand at OT and CT settlements

Settlement typologies		Cooling energy demand			Heating energy demand		
		BC (kWh/(m²·y))	MC (kWh/(m²·y))	% Change	BC (kWh/(m²·y))	MC (kWh/(m²·y))	% Change
OT settlements	OT1	12.8	9.7	24.22	15.59	18.4	18.02
	OT2	9.75	7.52	22.88	6.45	6.66	3.21
	OT3	3.95	3.13	20.82	3.39	3.93	16.08
	OT4	5.99	5.27	12.02	5.48	5.8	5.84
	OT5	6.12	4.24	30.81	10.40	11.71	12.63
	OT6	7.62	7.13	6.42	6.22	6.38	2.57
	OT7	5.64	5.26	6.74	10.27	10.49	2.14
CT settlements	CT1	13.92	9.14	34.34	16.56	18.89	14.07
	CT2	7.11	6.06	14.78	18.39	19.38	5.38
	CT3	6.06	5.34	11.88	7.75	8.3	7.10
	CT4	5.62	4.91	12.66	5.02	5.22	3.95
	CT5	3.57	3.24	9.24	4.19	4.28	1.84
	CT6	5.36	4.35	18.71	8.87	9.11	2.76
	CT7	5.99	4.52	24.64	11.51	12.55	9.04

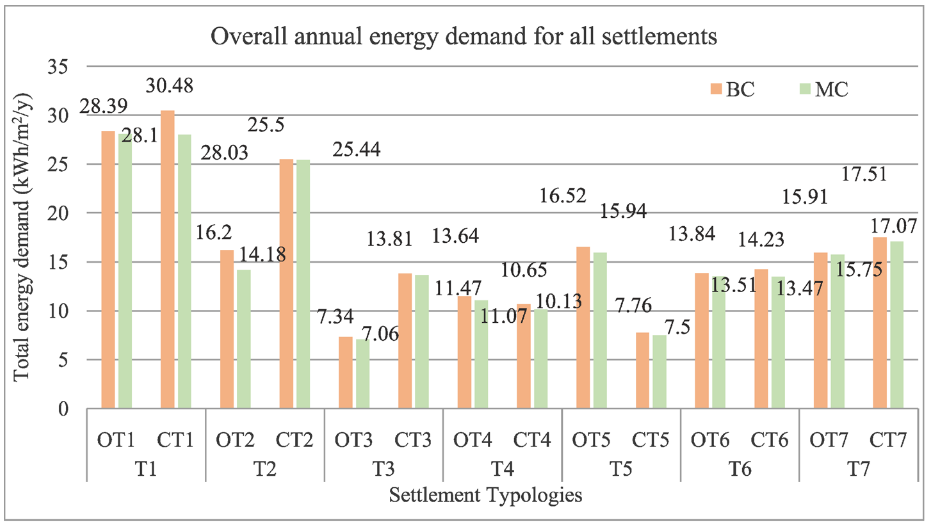
Table 7 provides a comprehensive overview of how mitigation strategies have effectively reduced cooling energy demand across various urban typologies. Specifically, within the OT typologies, the OT5 settlement exhibited the most significant reduction in cooling energy demand, amounting to approximately 30.81%. In contrast, among the CT typologies, the CT1 neighbourhood demonstrated the highest energy savings, achieving a reduction of about 34.34%. Irrespective to ambient temperature and CDHs, the geographic positioning of the neighbourhoods, particularly their location in the western region of Sydney, far from the coast, plays a critical role in the observed outcomes related to energy savings and thermal comfort improvements. This inland area is typically subject to higher ambient temperatures compared to coastal regions, due to factors such as reduced sea breezes and increased urban heat island effects. Consequently, the implementation of mitigation strategies, especially the use of cool materials in these locales, has been shown to be more effective, leading to significant reductions in cooling energy demand.

The comparison of energy demand and savings among different settlements within the OT and CT typologies reveals nuanced insights into the impact of building height, built area ratio, and overall energy consumption area on the effectiveness of mitigation strategies. For instance, OT4 and CT4, both featuring 8-story buildings, exhibit similar energy demands and achieve comparable energy savings of around 12%. This similarity suggests that buildings of equal height and presumably similar design and occupancy characteristics can respond similarly to energy efficiency interventions, regardless of their OT or CT classification. In contrast, despite having the same building height of 6 stories, OT3 and CT3 demonstrate a notable difference in energy savings, with OT3 achieving a higher reduction of about 20.83% compared to CT3, this is because of having less greenery but more asphalt roads those have been replaced with cool materials for MC. This discrepancy may further be attributed to variations in other factors such as building orientation, thermal insulation, or the specific nature and implementation of mitigation measures, highlighting the complex interplay of factors that influence energy performance. Furthermore, the comparison between CT7 and OT7, which are the tallest buildings in their respective typologies with 40 and 35 stories, respectively, illustrates a significant difference in energy demand reduction. CT7 exhibits a markedly higher efficiency in reducing energy demand—73% more than OT7. This superior performance is likely due to CT7's higher built area ratio and a larger energy consumption area, which is almost double that of OT7. The higher built area ratio of CT7 could increase the potential for heat absorption and retention, necessitating more aggressive or effective energy reduction strategies that can yield substantial savings.

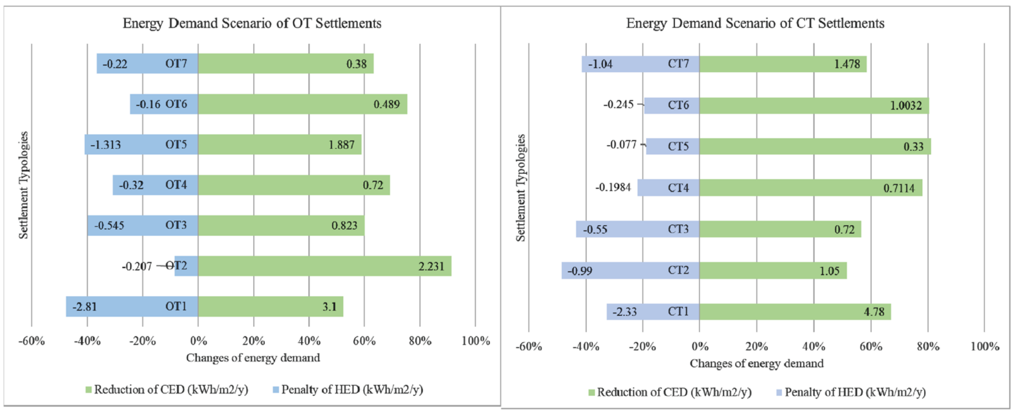
The adoption of cool materials, while beneficial for decreasing ambient temperatures during warmer months, consequently, has a counterproductive effect in the winter season by increasing the demand for heating energy. This phenomenon is clearly documented in Table 7, where an uptick in heating energy requirements is observed as a direct consequence of the lowered ambient temperatures attributable to cool materials. Despite this, it is important to note that the increase in heating loads during the colder months is generally less significant than the reduction in cooling loads during warmer periods. This differential effect results in a net decrease in the overall energy demand for settlements when considering the entire year. Such outcomes are illustrated in Figure 6 which compares the overall energy demands of the settlements under study to their respective BCs.

Figure 6 provides a comprehensive overview of overall energy savings achieved through the implementation of various mitigation strategies across different urban settlement typologies. The data reveal that though there is a heating penalty during winter, the reduction of CED is always higher compared to corresponding HED which results an overall positive energy demand reduction throughout a year. Figure 6(a) illustrates that, among the neighbourhoods, OT2 typology exhibits the highest energy savings, approximately 12.49%, underscoring the significant impact of targeted interventions. This is followed by savings of 8.04%, 5.34%, and 4.82% for the CT1, CT6, and CT4 settlements, respectively. These figures highlight the variable effectiveness of mitigation measures across different contexts, with certain settlements achieving more pronounced energy savings than others. On the other hand, Figures 6(b) and (c) illustrate the energy demand scenario depending on the typologies (OT and CT). Specifically, the right side of each bar chart in these figures indicates the reduction in cooling energy demand for the respective neighbourhood, attributable to the implementation of mitigation measures. Conversely, the left side of the bar charts reveals an increase in heating energy demand, representing a heating penalty associated with the adoption of these mitigation measures. Irrespective to the results of OT2 typology, Figures 6(b) and (c) suggest that CT typologies tend to demonstrate a more positive trend in energy savings percentages. This is attributed to their larger built area ratios and greater proportions of roads and pavements, which afford more opportunities to apply cool materials over a wider area compared to OT typologies.

This analysis reveals a critical insight: while the implementation of cool materials can indeed lead to higher



(a) Overall energy demand scenario of all settlements



(b) Energy savings scenario for OT typologies (c) Energy savings scenario for CT typologies

Fig. 6 Overall energy demand and energy savings scenario for all neighbourhoods

energy demands for heating in cooler seasons, the magnitude of energy savings achieved during hot seasons outweighs this drawback. Consequently, the strategic use of cool materials contributes to a net reduction in annual energy consumption for heating and cooling combined. This underscores the importance of adopting a holistic perspective when evaluating the efficacy of mitigation strategies, taking into account the varying impacts across different seasons to assess their overall benefit in reducing the energy footprint of urban settlements.

3.3 Impacts on CO_2 emissions

The reduction in energy demand by mitigation measures directly contributes to a decrease in emissions, notably CO_2, which is primarily released through the burning of fossil fuels in energy production. The dual approach of not only reducing energy consumption but also enhancing the carbon absorption capacity of urban areas through increased vegetation significantly amplifies the environmental benefits of these strategies.

3.3.1 *Reduction in CO_2 emissions through energy savings*

In subsection 3.2, it is documented how the adoption of mitigation strategies significantly diminished the energy demand across the urban settlements that correlates to a decreased reliance on fossil fuels, which are a primary source of CO_2 emissions when burned for energy production. The quantification of this reduction in CO_2 emissions is achieved through the application of Equation (5) and the results are illustrated in Figure 7.

Figure 7 elucidates the substantial reductions in CO_2 emissions achievable through the implementation of mitigation strategies within urban settlements, delineating the impact of these strategies on both OT and CT typologies. For OT settlements, OT5 stands out with the highest

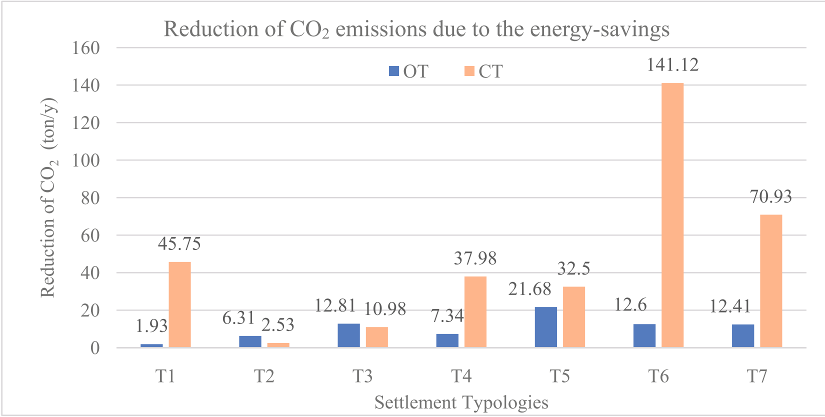


Fig. 7 Reduction of CO_2 emissions by all settlements

reduction in CO_2 emissions, amounting to approximately 21.68 ton per annum. This significant reduction is attributed to the maximal energy savings realized through mitigation measures. The results highlight that CT settlements experience even greater reductions in CO_2 emissions compared to OT typologies. This difference is largely due to the higher built-area ratios characteristic of CT settlements, which facilitate the extensive application of cool materials on roads, pavements, and rooftops. Moreover, the proportion of roads and pavements relative to green spaces within a settlement impacts its energy demand; areas with more extensive road and pavement coverage can significantly benefit from cool materials in reducing ambient temperatures and, consequently, energy demand. This reduction in energy demand directly translates to lower CO_2 emissions. For instance, the CT6 settlement, with a built area ratio of 48%—the second highest among CT typologies—and the largest area covered by roads and pavements, achieves the maximum reduction in CO_2 emissions, totalling about 141.12 ton per year. Meanwhile, despite CT1 showcasing the highest energy savings, its CO_2 emissions reduction is less pronounced due to a lower built-area ratio and the smallest area designated for energy consumption.

3.3.2 *Enhancement of CO_2 absorption through increased vegetation*

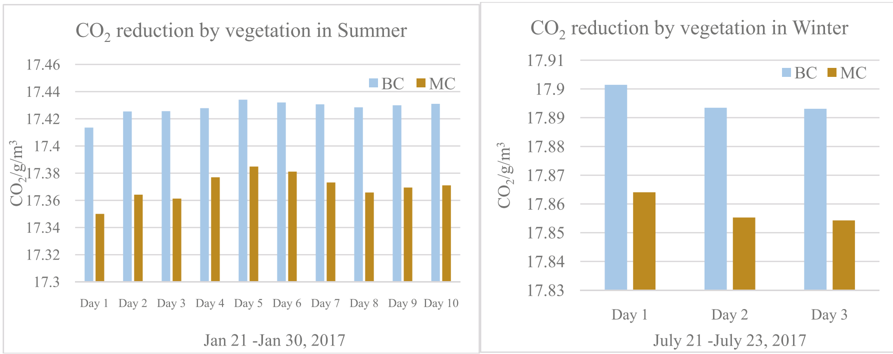
Increased vegetation within urban green spaces as a complementary strategy for reducing CO_2 levels. Trees and plants absorb CO_2 from the atmosphere during the process of photosynthesis, serving as natural carbon sinks. By expanding green spaces and integrating more vegetation into urban planning, the neighbourhood areas have effectively increased their capacity to absorb CO_2. This not only contributes to further reductions in atmospheric CO_2 levels but also enhances biodiversity, improves air quality, and supports the well-being of urban residents. In our study, vegetation has moderately reduced the CO_2 emission in various settlements. Table 8 listed the daily CO_2 reduction by vegetation for various settlements those care calculated by using Equation (6).

From Table 8 it is seen that the emission of CO_2 is reasonably reduced for all typologies. It is discussed earlier that the models consider for extra vegetation if there are no trees located within a space of 20 m × 20 m. Therefore, having more greenery areas in OT settlements, CT typologies are frequently considered for additional vegetation which causes more reduction of CO_2 emissions compared to the OT typologies. Furthermore, CO_2 emissions fluctuate between summer and winter within the same neighbourhood. Supporting this observation, Figure 8 displays the reduction in CO_2 emissions attributed to vegetation in the Kooloora settlement (OT2).

Figure 8 illustrates the impact of vegetation on CO_2 reduction, highlighting a differential absorption rate of up to 0.06 g/(m^3·day) during the summer and 0.04 g/(m^3·day) in the winter. The lower absorption rate in winter (as shown in Figure 8(b)) correlates with the reduced availability of sunlight, a key driver of photosynthetic processes in plants.

Table 8 CO_2 reduction by vegetation during summer 2017

	T1		T2		T3		T4		T5		T6		T7	
Typologies	OT1	CT1	OT2	CT2	OT3	CT3	OT4	CT4	OT5	CT5	OT6	CT6	OT7	CT7
BC (g/(m^3·day))	17.46	17.52	17.43	17.48	17.52	17.44	17.44	17.45	17.385	17.45	17.6	17.42	17.49	17.49
MC (g/(m^3·day))	17.42	17.46	17.37	17.41	17.46	17.39	17.43	17.385	17.42	17.37	17.56	17.38	17.42	17.42
Reduction	0.04	0.06	0.06	0.07	0.06	0.05	0.01	0.07	0.05	0.08	0.04	0.04	0.07	0.07



(a) (b)

Fig. 8 The amount of CO_2 reduction due to the vegetation in (a) summer and (b) winter for OT2 in the year 2017

Such a comparable pattern was observed in other settlements, as depicted in Figure 9.

Figure 9 delineates the comparison of daily CO_2 emissions reduction of various settlements between summer and winter, providing a visual representation of the seasonal dynamics affecting CO_2 reduction through vegetation. Results indicate that the absorption of CO_2 emissions is higher in summer than in winter that reinforce the concept that while vegetation plays a crucial role in reducing urban CO_2 levels, its effectiveness is subject to seasonal variations that influence plant growth and photosynthetic activity.

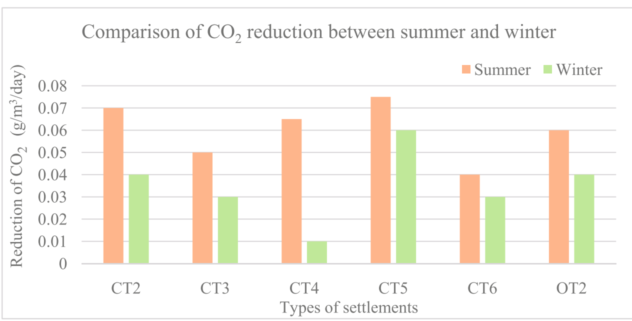


Fig. 9 Variation of CO_2 emission between summer and winter

4 Discussions

This study provides an in-depth examination of the wide-ranging effects of mitigation strategies on urban settlements, including heat-mitigation, reductions in energy demand, and decreased CO_2 emissions. By synthesizing key findings across different sections, this discussion aims to contextualize these results within the broader landscape of existing research, offering a comparative analysis to highlight the study's contributions and distinctions.

Our research considered reducing ambient temperature as a fundamental measure for mitigating heat within settlements, by employing cool materials on roads and pavements and incorporating vegetation. This approach was validated against existing research, particularly for the Australian climate. For instance, a Sydney case study (Santamouris et al. 2018) increased global albedo from 0.1 to 0.7, achieving up to a 3 °C drop in peak ambient temperature and a 20% reduction in CED, while our findings showed a temperature decrease of up to 2.71 °C at the community level and a potential CED reduction of up to 30.81%. Despite similar albedo adjustments, our temperature reduction was slightly lower as cool materials were not considered on rooftop in the ENVI-met simulation, while energy savings were greater, attributed to their inclusion in the CitySim simulation. Besides, in the Paramatta City case study (Santamouris et al. 2020), a combination of mitigation strategies led to a peak ambient temperature decrease of up to 2.5 °C and a reduction in annual cooling loads by 1.5 TWh, achieving significant reductions in CO_2 emissions and indoor overheating by as much as 1.21 MT and 80%, respectively. Our research, however, reports a slightly greater decrease in ambient temperature and a CO_2 emission reduction of approximately 141.12 tonnes annually. The difference in temperature reduction between the two studies may stem from their approach of adjusting albedo values from 0.08–0.15 to 0.4–0.6 for roofs and pavements, while extensive tree-plantation accounts for the substantial CO_2 emission reduction. In addition, the South Creek study (Garshasbi et al. 2020) showed that considering future climate and urban growth, mitigation efforts significantly lower temperatures and CED by up to 2.2 °C and 70%, respectively, using strategies like cool materials, greenery, and irrigation. This marked decrease in CED, exceeding our results, is due to the introduction of 5 million irrigated trees across Sydney and enhanced albedo of urban surfaces, coupled with extensive landscape watering. Furthermore, applying supercool materials with high albedo on building rooftops significantly decreases CED, achieving reductions of up to 97% in the Greater Sydney case study (Khan et al. 2022). This reduction surpasses our findings, as it involves using materials with an albedo of 0.96 and 97% emissivity along with incorporating additional adaptation strategies within buildings. Beyond that, the research by Santamouris et al. (2019), focusing on same neighbourhood typologies, demonstrated reductions in ambient temperature and CED of up to 2.5 °C and 6%, respectively. Our findings generally surpass these, likely due to our higher roof albedo along with the use of a different energy simulation tool, despite both studies applying similar albedo values for roads and pavements.

Contrasting our results with global research, such as a notable Italian case study (Cardinali et al. 2018; Castaldo et al. 2020; Piselli et al. 2020), provides a compelling perspective on the effectiveness of various mitigation strategies. In Italy, mitigation strategies like deciduous trees, cool gravels, reflective roads, and roofs led to a 2 °C drop in ambient temperature, 4%–5% energy savings, and 5% less CO_2 emissions. Additionally, cool materials for roofs and pavements resulted in a 22% drop in energy consumption and ambient temperature decreased of 1.5 °C and 1.8 °C at the building and community levels, respectively (Cardinali et al. 2020). In contrast, our study showcases even more promising outcomes, with 5 settlements achieving ambient temperature reductions exceeding 2 °C, and the most notable case reaching a decrease of up to 2.71 °C. This led to an impressive reduction in overall energy demand by approximately 12.49%, resulting in up to 141.12 tonnes of CO_2 reduction per year, excluding the additional benefits derived from CO_2 absorption due to the increase in vegetation. Another case study in Italy (Boccalatte et al. 2020), illustrates the effectiveness of reflective and cool materials in urban design for enhancing energy efficiency. By using reflective materials on roads with increased albedo from 0.05 to 0.2, cool materials on roof with raised albedo from 0.1 to 0.7, the albedo enhancement of non-green ground surfaces from 0.05 to 0.23, and cladding to buildings collectively led to an 8% reduction in annual energy demand, where our research demonstrates even higher efficiency gains for at least 2 settlements beyond the ambient temperature reductions along with substantial CO_2 emission reductions in certain neighbourhoods. In addition, despite a growing focus on sustainable urban development, existing studies often overlook the broad spectrum of mitigation and adaptation measures within communities. A notable contrast is found in the Sustainable Urban District of Vauban in Germany (Coates 2013) which achieves energy efficiency through building-specific adaptations rather than addressing external heat sources. Vauban's use of extensive insulation, modern windows, and ventilation systems resulted in up to 79% energy savings, exceeding the outcomes of our study that focused on high-albedo materials to mitigate the urban heat island effect and cool buildings indirectly. While our approach aimed at reducing the urban heat island effect by mitigating outdoor heat-sources that directly impacts on energy demand, Vauban's success underscores the potential for even greater savings through direct building interventions.

In summary, this study evaluates urban heat mitigation potential, focusing on their impact on temperature, energy savings, and CO_2 emissions reduction, particularly within the Australian context. It compares our approaches and results with both local and global case studies, showcasing significant achievements in ambient temperature reduction and energy demand. Therefore, our research not only underscores the potential of such measures in the Australian setting but also sets a precedent for future studies in sustainable urban development and potential pathways towards achieving the NZE goals in the community level within diverse climatic scenarios.

5 Conclusion

The cumulative effect of climatic conditions at local, regional, and global scales on the thermal efficiency of built structures and human health represents a significant concern worldwide. In scrutinizing the influence of local and regional climatic phenomena on architectural constructs, it is imperative to extend our focus beyond thermal efficiency to also encompass the energy requirements of communities situated within the temperate climate zone like Sydney. In the current research, our objective was to elucidate the existing state of mitigation of outdoor heat-sources along with the energy performance of buildings at the community level. To this end, we implemented various mitigation strategies consisting of cool materials on roads, pavements, and rooftop of the buildings along with additional vegetation within the settlements that aimed at enhancing both the heat-mitigation and energy savings of these structures. Consequently, the dual goals of augmenting heat-mitigation and diminishing energy consumption were realized, thereby paving the way for the conceptualization and design of NZES drawing insights from 14 typologies of neighbourhoods under the context of weather conditions like Australia which is still missing in the literature. Addressing the absence of such targeted research in the literature, this study contributes a valuable perspective on:

- **Heat-mitigation of the settlements:** Mitigation measures significantly reduced the ambient temperature and CDHs up to 2.71 °C (for OT4) and 25.98% (for OT2) respectively. Notably, five settlements among the 14 typologies analyzed—OT2, OT4, CT4, CT5, and CT6—recorded a reduction in ambient temperature exceeding 2.0 °C during a specific day in summer. This demonstrates the potential of targeted mitigation measures to substantially lower the cooling demand within urban environments. Furthermore, these strategies can reduce up to 810 hours of CDHs, underscoring the tangible benefits of implementing such measures in mitigating the urban heat island effect and reducing energy consumption for cooling.

- **Energy savings:** Among 14 typologies of neighbourhoods, half of them demonstrated a reduction in CED of near or more than 20%, showcasing the effectiveness of the implemented mitigation measures. Notably, within this group, two settlements stood out by exhibiting energy savings in CED of more than 30%. The most significant reduction was observed in the CT1 settlement, where energy savings reached approximately 34.34%, highlighting the exceptional impact of targeted mitigation strategies on cooling energy requirements. Furthermore, the overall energy demand across the settlements saw a notable decrease, with the OT2 settlement achieving a reduction of up to 12.49%. This reduction in overall energy demand underscores the broader implications of implementing energy-efficient measures, not only in terms of cooling energy in summer but also the heating penalty in winter within urban settlements.
- **CO_2 reduction:** The energy savings achieved through the mitigation strategies served to a noteworthy reduction in CO_2 emissions, with the CT6 settlement demonstrating a remarkable reduction of up to 141,116.7 kg/year. This underscores the environmental benefits of energy efficiency measures, highlighting their role in contributing to emission reductions and combating climate change. Besides, additional vegetation in the settlement further enhanced the environmental impact by achieving the CO_2 absorption rate which was up to 0.075g/(m^3·day) for the CT5 settlement. This illustrates the dual benefit of combining energy-saving measures with green infrastructure to maximize the CO_2 reduction potential. The absorption of CO_2 by vegetation is a crucial complementary strategy, enhancing the sustainability of urban settlements by offsetting emissions through natural processes.

Finally, this work not only enriches the academic discourse on sustainable urban development but also provides a practical guide for cities aiming to navigate the complexities of climate change heat-mitigation and energy efficiency. The Australian context, characterized by its diverse climates ranging from the arid interior to the temperate coastal regions, offers a broad spectrum of insights that apply to a wide range of global contexts. By highlighting the gap in the literature and addressing it with concrete data and analysis, the study contributes significantly to the ongoing global conversation on sustainable urban living. It underscores the necessity of localized, climate-responsive planning and the potential for urban areas worldwide to reduce their environmental impact while improving the quality of life for their inhabitants.

However, there are some areas that remain ripe for further investigations to enhance the sustainability and efficiency of urban environments:

- Investigating the specific impact of vegetation on thermal comfort could be advanced by employing multiple climate models. These models would separately incorporate additional vegetation, and then assess it in conjunction with the application of cool materials for roads and pavements. Such an approach allows for a nuanced understanding of how green infrastructure and reflective surfaces contribute to urban cooling and thermal comfort separately as well as collectively.
- The economic feasibility of implementing new materials for urban infrastructure could be evaluated through the calculation of payback periods. This analysis would consider the initial costs associated with the introduction of innovative materials and technologies against the backdrop of anticipated energy savings and potential environmental benefits. Such economic assessments are crucial for justifying investments in sustainable urban development projects.
- Energy performance in urban settlements could be further improved by incorporating additional adaptation measures within the buildings themselves. This approach enhances the buildings' ability to maintain thermal comfort with minimal energy use.
- To achieve the NZES goal, onsite energy generation is an essential task. The development of renewable energy technologies and systems tailored for onsite energy generation presents a critical avenue for research. This involves exploring innovative design solutions that integrate seamlessly into urban buildings and landscapes, potentially leveraging solar, wind, and other renewable sources to meet energy demands sustainably.

These areas offer promising pathways for advancing urban sustainability, energy efficiency, and the realization and further steps towards of NZE goals at the community level.

Appendix A

It may be noted that for the summer phase, ENVI-met simulations were successfully executed for all 14 designated neighbourhoods. In contrast, winter simulations were successful without instability errors for only 6 neighbourhoods (OT2, CT2, CT3, CT4, CT5, and CT6), an issue often arising from lower ambient temperatures. To accommodate the other neighbourhoods, we applied same correlation equations, grouping them by building typologies and heights. As a result, groups—such as OT1 with OT2, CT1 with CT2, CT3 with OT3, CT4 with OT4, CT5 with OT5, and a combined

Table A1 Equations used for correlation of weather data for at 14 targeted neighbourhoods

Neighbourhood typologies		Equations for summer	Equations for winter
OT1	BC	$T_{OT1\_BC}=T_{WS1}\times1.08-2.35$	$T_{OT1\_BCW}=T_{WS1\_W}\times1.06-1.57$
	MC	$T_{OT1\_MC}=T_{OT1\_BC}\times0.87+3.10$	$T_{OT1\_MCW}=T_{OT1\_BCW}\times1.01-0.28$
OT2	BC	$T_{OT2\_BC}=T_{WS2}\times1.15-3.99$	$T_{OT2\_BCW}=T_{WS2\_W}\times1.06-1.57$
	MC	$T_{OT2\_MC}=T_{OT2\_BC}\times0.83+4.20$	$T_{OT2\_MCW}=T_{OT2\_BCW}\times1.01-0.28$
OT3	BC	$T_{OT3\_BC}=T_{WS2}\times1.19-5.35$	$T_{OT3\_BCW}=T_{WS2\_W}\times0.74+4.14$
	MC	$T_{OT3\_MC}=T_{OT3\_BC}\times 0.88+2.92$	$T_{OT3\_MCW}=T_{OT3\_BCW}\times0.94+1.64$
OT4	BC	$T_{OT4\_BC}=T_{WS2}\times1.16-4.43$	$T_{OT4\_BCW}=T_{WS2\_W}\times1.05-1.31$
	MC	$T_{OT4\_MC}=T_{OT4\_BC}\times0.79+5.61$	$T_{OT4\_MCW}=T_{OT4\_BCW}\times0.99+0.09$
OT5	BC	$T_{OT5\_BC}=T_{WS1}\times1.10-2.96$	$T_{OT5\_BCW}=T_{WS1\_W}\times1.03-0.46$
	MC	$T_{OT5\_MC}=T_{OT5\_BC}\times1.04-2.30$	$T_{OT5\_MCW}=T_{OT5\_BCW}\times0.97+0.43$
OT6	BC	$T_{OT6\_BC}=T_{WS2}\times1.15-3.99$	$T_{OT6\_BCW}=T_{WS2\_W}\times1.26-6.62$
	MC	$T_{OT6\_MC}=T_{OT6\_BC}\times0.85+3.90$	$T_{OT6\_MCW}=T_{OT6\_BCW}\times0.98+0.21$
OT7	BC	$T_{OT7\_BC}=T_{WS1}\times1.13-3.70$	$T_{OT7\_BCW}=T_{WS1\_W}\times1.26-6.62$
	MC	$T_{OT7\_MC}=T_{OT7\_BC}\times0.89+2.90$	$T_{OT7\_MCW}=T_{OT7\_BCW}\times0.98+0.21$
CT1	BC	$T_{CT1\_BC}=T_{WS1}\times1.10-2.96$	$T_{CT1\_BCW}=T_{WS1\_W}\times0.94+1.64$
	MC	$T_{CT1\_MC}=T_{CT1\_BC}\times0.85+3.99$	$T_{CT1\_MCW}=T_{CT1\_BCW}\times0.74+4.14$
CT2	BC	$T_{CT2\_BC}=T_{WS1}\times1.20-5.10$	$T_{CT2\_BCW}=T_{WS1\_W}\times0.94+1.64$
	MC	$T_{CT2\_MC}=T_{CT2\_BC}\times0.90+2.53$	$T_{CT2\_MCW}=T_{CT2\_BCW}\times0.74+4.14$
CT3	BC	$T_{CT3\_BC}=T_{WS1}\times1.18-4.45$	$T_{CT3\_BCW}=T_{WS1\_W}\times0.94+1.64$
	MC	$T_{CT3\_MC}=T_{CT3\_BC}\times0.85+4.01$	$T_{CT3\_MCW}=T_{CT3\_BCW}\times0.99+0.05$
CT4	BC	$T_{CT4\_BC}=T_{WS2}\times1.19-4.64$	$T_{CT4\_BCW}=T_{WS2\_W}\times1.05-1.31$
	MC	$T_{CT4\_MC}=T_{CT4\_BC}\times0.84+4.23$	$T_{CT4\_MCW}=T_{CT4\_BCW}\times0.99+0.09$
CT5	BC	$T_{CT5\_BC}=T_{WS2}\times1.14-3.77$	$T_{CT5\_BCW}=T_{WS2\_W}\times1.03-0.46$
	MC	$T_{CT5\_MC}=T_{CT5\_BC}\times0.79+5.58$	$T_{CT5\_MCW}=T_{CT5\_BCW}\times0.97+0.43$
CT6	BC	$T_{CT6\_BC}=T_{WS1}\times1.18-4.45$	$T_{CT6\_BCW}=T_{WS1\_W}\times1.2636-6.62$
	MC	$T_{CT6\_MC}=T_{CT6\_BC}\times0.86+3.42$	$T_{CT6\_MCW}=T_{CT6\_BCW}\times0.9829+0.21$
CT7	BC	$T_{CT7\_BC}=T_{WS1}\times1.14-4.07$	$T_{CT7\_BCW}=T_{WS1\_W}\times1.2636-6.62$
	MC	$T_{CT7\_MC}=T_{CT7\_BC}\times1.04-2.19$	$T_{CT7\_MCW}=T_{CT7\_BCW}\times0.9829+0.21$

set of CT6, OT6, CT7, and OT7—utilized identical correlation equations for winter.

Acknowledgements

This research was supported by the 2020 UNSW Scientia PhD Scholarship Scheme and carried out under the UNSW Scientia Project entitled "Energy Poverty in NSW. Characteristics, Impact and Solutions". The authors acknowledge the Australian Bureau of Meteorology for providing the weather data, KAEMCO for providing access to CitySim Pro, and Dr. Jérôme Henri Kämpf for providing technical support on the software.

Funding note: Open access funding provided through UNSW Library.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article. Mattheos Santamouris is an Editorial Board member of *Building Simulation*.

Author contribution statement

The conception and design of the study were collaboratively developed by all the authors. Model preparation, data collection and analysis were performed by Khan Rahmat Ullah. The first draft of the manuscript was written by Khan Rahmat Ullah and all authors subsequently reviewed and critiqued it through successive iterations. The final version of the manuscript has been read and approved by all contributing authors.

References

Acero JA, Koh EJK, Pignatta G, et al. (2020). Clustering weather types for urban outdoor thermal comfort evaluation in a tropical area. *Theoretical and Applied Climatology*, 139: 659–675.

Akbari H, Cartalis C, Kolokotsa D, et al. (2016). Local climate change and urban heat island mitigation techniques—The state of the art. *Journal of Civil Engineering and Management*, 22: 1–16.

Alhazmi M, Sailor DJ, Anand J (2022). A new perspective for understanding actual anthropogenic heat emissions from buildings. *Energy and Buildings*, 258: 111860.

Ambrosini D, Galli G, Mancini B, et al. (2014). Evaluating mitigation effects of urban heat islands in a historical small center with the ENVI-met® climate model. *Sustainability*, 6: 7013–7029.

Anwar MW, Ali Z, Javed A, et al. (2021). Analysis of the effect of passive measures on the energy consumption and zero-energy prospects of residential buildings in Pakistan. *Building Simulation*, 14: 1325–1342.

ASHRAE (2017). ASHRAE Handbook—Fundamentals: Nonresidential Cooling and Heating Load Calculations. Atlanta, GA, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Asif M, Dehwah AHA, Ashraf F, et al. (2017). Life cycle assessment of a three-bedroom house in Saudi Arabia. *Environments*, 4: 52.

Bartesaghi-Koc C, Osmond P, Peters A (2020). Quantifying the seasonal cooling capacity of 'green infrastructure types' (GITs): An approach to assess and mitigate surface urban heat island in Sydney, Australia. *Landscape and Urban Planning*, 203: 103893.

Bartesaghi-Koc C, Haddad S, Pignatta G, et al. (2021). Can urban heat be mitigated in a single urban street? Monitoring, strategies, and performance results from a real scale redevelopment project. *Solar Energy*, 216: 564–588.

Bartos M, Chester M, Johnson N, et al. (2016). Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States. *Environmental Research Letters*, 11: 114008.

Boccalatte A, Fossa M, Ménézo C (2020). Best arrangement of BIPV surfaces for future NZEB districts while considering urban heat island effects and the reduction of reflected radiation from solar façades. *Renewable Energy*, 160: 686–697.

Bonifacio-Bautista M, Ballinas M, Jazcilevich A, et al. (2022). Estimation of anthropogenic heat release in Mexico City. *Urban Climate*, 43: 101158.

Cardinali M, Pisello AL, Piselli C, et al. (2020). Microclimate mitigation for enhancing energy and environmental performance of Near Zero Energy Settlements in Italy. *Sustainable Cities and Society*, 53: 101964.

Cascone S, Gagliano A, Poli T, et al. (2019). Thermal performance assessment of extensive green roofs investigating realistic vegetation-substrate configurations. *Building Simulation*, 12: 379–393.

Castaldo VL, Pisello AL, Piselli C, et al. (2018). How outdoor microclimate mitigation affects building thermal-energy performance: A new design-stage method for energy saving in residential near-zero energy settlements in Italy. *Renewable Energy*, 127: 920–935.

Chandramowli SN, Felder FA (2014). Impact of climate change on electricity systems and markets—A review of models and forecasts. *Sustainable Energy Technologies and Assessments*, 5: 62–74.

Coates GJ (2013). The sustainable urban district of Vauban in Freiburg, Germany. *International Journal of Design & Nature and Ecodynamics*, 8: 265–286.

Dirks JA, Gorrissen WJ, Hathaway JH, et al. (2015). Impacts of climate change on energy consumption and peak demand in buildings: A detailed regional approach. *Energy*, 79: 20–32.

Fahmy M, Ibrahim Y, Hanafi E, et al. (2018). Would LEED-UHI greenery and high albedo strategies mitigate climate change at neighborhood scale in Cairo, Egypt? *Building Simulation*, 11: 1273–1288.

Garshasbi S, Haddad S, Paolini R, et al. (2020). Urban mitigation and building adaptation to minimize the future cooling energy needs. *Solar Energy*, 204: 708–719.

Herath Mudiyanselage P (2023). The effectiveness of Urban Green Infrastructure for urban heat regulation. PhD Thesis, The Australian National University, Australia.

Hong T, Langevin J, Sun K (2018). Building simulation: Ten challenges. *Building Simulation*, 11: 871–898.

Hu S, Zhang Y, Yang Z, et al. (2022). Challenges and opportunities for carbon neutrality in China's building sector—Modelling and data. *Building Simulation*, 15: 1899–1921.

Khan HS, Santamouris M, Kassomenos P, et al. (2021a). Spatiotemporal variation in urban overheating magnitude and its association with synoptic air-masses in a coastal city. *Scientific Reports*, 11: 6762.

Khan HS, Santamouris M, Paolini R, et al. (2021b). Analyzing the local and climatic conditions affecting the urban overheating magnitude during the Heatwaves (HWs) in a coastal city: A case study of the greater Sydney region. *Science of the Total Environment*, 755: 142515.

Khan HS, Paolini R, Caccetta P, et al. (2022). On the combined impact of local, regional, and global climatic changes on the urban energy performance and indoor thermal comfort—The energy potential of adaptation measures. *Energy and Buildings*, 267: 112152.

Kolokotsa D, Lilli K, Gobakis K, et al. (2022) Analyzing the impact of urban planning and building typologies in urban heat island mitigation. *Buildings* 12(5): 537.

Livada I, Pyrgou A, Haddad S, et al. (2021). Recent climatic trends and analysis of monthly heating and cooling degree hours in Sydney. *Climate*, 9: 114.

Mondal N, Anand P, Khan A, et al. (2024). Systematic review of the efficacy of data-driven urban building energy models during extreme heat in cities: Current trends and future outlook. *Building Simulation*, 17: 695–722.

NatHERS (2019). Software Accreditation Protocol. Nationwide House Energy Rating Scheme (NatHERS).

Nitschke M, Tucker GR, Hansen AL, et al. (2011). Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis. *Environmental Health* 10: 42.

Piselli C, Di Grazia M, Pisello AL (2020). Combined effect of outdoor microclimate boundary conditions on air conditioning system's efficiency and building energy demand in net zero energy settlements. *Sustainability*, 12: 6056.

Remund J, Müller S, Kunz S, et al. (2017). Meteonorm Handbook part I: Software, Global Meteorological Database Version 7 Software and Data for Engineers, Planers and Education, METEOTEST, Fabrikstrasse 14 CH-3012, Bern, Switzerland.

Robinson D, Haldi F, Kämpf J, et al. (2009). Citysim: Comprehensive micro-simulation of resource flows for sustainable urban planning. In: Proceedings of the 11th International IBPSA Building Simulation Conference.

Santamouris M, Synnefa A, Karlessi T (2011). Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Solar Energy*, 85: 3085–3102.

Santamouris M (2014). On the energy impact of urban heat island and global warming on buildings. *Energy and Buildings*, 82: 100–113.

Santamouris M (2015). Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *Science of the Total Environment*, 512–513: 582–598.

Santamouris M, Cartalis C, Synnefa A, et al. (2015). On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review. *Energy and Buildings*, 98: 119–124.

Santamouris M, Haddad S, Fiorito F, et al. (2017). Urban heat island and overheating characteristics in Sydney, Australia: An analysis of multiyear measurements. *Sustainability*, 9: 712.

Santamouris M, Haddad S, Saliari M, et al. (2018). On the energy impact of urban heat island in Sydney: Climate and energy potential of mitigation technologies. *Energy and Buildings*, 166: 154–164.

Santamouris M, Haddad S, Garshasbi S, et al. (2019) Sydney's third city – final report. CRC for Low Carbon Living.

Santamouris M (2020). Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. *Energy and Buildings*, 207: 109482.

Santamouris M, Paolini R, Haddad S, et al. (2020). Heat mitigation technologies can improve sustainability in cities. An holistic experimental and numerical impact assessment of urban overheating and related heat mitigation strategies on energy consumption, indoor comfort, vulnerability and heat-related mortality and morbidity in cities. *Energy and Buildings*, 217: 110002.

Santamouris M, Papadopoulos AM, Paolini R, et al. (2021). Cool roofs cost benefit analysis. Research Plan and Progress Report. School of Built ENVIRONMENT, UNSW Sydney, Australia.

Schaffer A, Muscatello D, Broome R, et al. (2012). Emergency department visits, ambulance calls, and mortality associated with an exceptional heat wave in Sydney, Australia, 2011: a time-series analysis. *Environmental Health*, 11: 3.

Schinasi LH, Benmarhnia T, De Roos AJ (2018). Modification of the association between high ambient temperature and health by urban microclimate indicators: A systematic review and meta-analysis. *Environmental Research*, 161: 168–180.

Singh M, Sharston R (2023). Normalized urban heat island (UHI) indicators: Classifying the temporal variation of UHI for building energy simulation (BES) applications. *Building Simulation*, 16: 1645–1658.

Susca T (2012). Multiscale approach to life cycle assessment. *Journal of Industrial Ecology*, 16: 951–962.

Tong S, Ren C, Becker N (2010). Excess deaths during the 2004 heatwave in Brisbane, Australia. *International Journal of Biometeorology*, 54: 393–400.

Xu F, Tian D, Gao Z, et al. (2024). The effects of cool materials, façade orientation, and morphological parameters on energy consumption at the residential neighborhood scale. *Building Simulation*, 17: 525–542.

Yun GY, Ngarambe J, Duhirwe PN, et al. (2020). Predicting the magnitude and the characteristics of the urban heat island in coastal cities in the proximity of desert landforms. The case of Sydney. *Science of the Total Environment*, 709: 136068.