Renewable and Sustainable Energy Reviews 186 (2023) 113668

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Beating urban heat: Multimeasure-centric solution sets and a complementary framework for decision-making

Yongling Zhao [a,*], Sushobhan Sen [b,c], Tiziana Susca [d], Jacopo Iaria [e], Aytaç Kubilay [a], Kanchane Gunawardena [f], Xiaohai Zhou [a], Yuya Takane [g], Yujin Park [h], Xiaolin Wang [i], Andreas Rubin [a], Yifan Fan [j], Chao Yuan [k,l], Ronita Bardhan [m], Dominique Derome [n], Diana Ürge-Vorsatz [o], Jan Carmeliet [a]

[a] Department of Mechanical and Process Engineering, ETH Zurich, Switzerland
[b] Department of Civil & Environmental Engineering, University of Pittsburgh, USA
[c] Department of Civil Engineering, Indian Institute of Technology Gandhinagar, India
[d] Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Italy
[e] Department of Biological, Geological, Environmental Sciences, University of Bologna, Italy
[f] The Martin Centre for Architectural and Urban Studies, University of Cambridge, UK
[g] Environmental Management Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Japan
[h] Department of Urban Planning and Real Estate, Chung-Ang University, South Korea
[i] School of Engineering, Australian National University, Canberra, Australia
[j] College of Civil Engineering and Architecture, Zhejiang University, China
[k] College of Design and Engineering, National University of Singapore, Singapore
[l] NUS Cities, National University of Singapore, Singapore
[m] Department of Architecture, University of Cambridge, UK
[n] Department of Civil Engineering, Sherbrooke University, Canada
[o] Department of Environmental Sciences and Policy, Central European University, Austria

A R T I C L E I N F O

Keywords:
Urban climate
Urban heat mitigation
Decision-making for heat mitigation
Multidimensional ITE index
Ranking of solution sets

A B S T R A C T

Urban areas are experiencing excessive heating. Addressing the heat is a challenging but essential task where not only engineering and climatic knowledge matters but also a deep understanding of social and economic dimensions. We synthesize the state of the art in heat mitigation technologies and develop an 'ITE index' framework that evaluates the **i**nvestment (**I**), **t**ime for implementation (**T**), and **e**ffectiveness (**E**) of candidate heat mitigation measures. Using this framework, we assess 247 multimeasure-centric solution sets composed of all possible combinations of 8 individual measures. The multidimensional ITE index is quantified for heat mitigation effectiveness based on different urban scales, investment levels, the impact of local climate zones (LCZs), and professionals' perceptions using the analytical hierarchy process. The top 50 unique solution sets consist of 4–7 individual measures across all LCZs, with the use of thermally efficient buildings and high-efficiency indoor cooling being the two recurrent measures contributing to the best solution sets. While every city varies in terms of its ideal solution sets, we provide a multimeasure-centric framework for decision-making in which different dimensions can be integrated, understood, and quantified.

1. Introduction

Population growth [1,2], the warming of the local background climate [3,4], the densification of urban settlements [5,6], and a reduction in evaporation capability [7,8] are known to be some of the factors leading to the development of urban heat islands. While these factors are complex at different scales and in different climate zones, as highlighted in the 2021 United Nations Environment Programme (UNEP) report 'Beating the heat: A sustainable cooling handbook for cities' [9], intercity and intercountry disparities in social and economic characteristics add tremendous difficulty to decision-making on heat mitigation solutions. This perspective builds on the handbook, aiming to enable future decision-making on heat mitigation solutions where not

* Corresponding author.
E-mail address: yozhao@ethz.ch (Y. Zhao).

https://doi.org/10.1016/j.rser.2023.113668
Received 19 April 2023; Received in revised form 6 August 2023; Accepted 20 August 2023
Available online 4 September 2023

Abbreviations

ITE	Investment–Time for implementation–Effectiveness of mitigation measures
AHP	analytic hierarchy process
LCZ	local climate zone
GW	green walls
GR	green roofs
RR	reflective roofs
EB	(thermally) efficient buildings
IC	indoor cooling
EP	evaporative pavement
CS	constructed shade
UF	urban forestry
AC	air conditioning
TiO_2	Titanium dioxide
SiO_2	Silicon dioxide
ZnO	Zinc oxide
CR	Consistency Ratio
MCDM	Multi-Criteria Decision-Making
TOPSIS	the Technique for Order of Preference by Similarity to Ideal Solution

only engineering and climatic aspects but also social and economic dimensions can be deeply integrated, understood, and quantified.Fig. 1.

Excess urban heat is bringing extensive societal challenges, including the heat-related burdens [10–12], the surge in energy demand for cooling [13–15] and resultant failures of electrical grids, worsening air quality due to a higher consumption of fossil fuels for space cooling [16, 17], disproportionate exposure to heat and resulting inequity issues [18], and economic losses due to heat-induced labor losses [19]. A recent study by Vicedo-Cabrera et al. (2021), based on empirical data from 43 countries correlated 37% of warm-season heat-related deaths to anthropogenic climate change [20]. In extreme weather conditions, for example, in the event of heat waves, Stone et al. (2021) reported a 60% increase in the occurrence of electrical 'blackout' events in the U.S. in the most recent 5 years due to the surge in energy demand for space cooling [21]. He et al. (2022) [19] concluded that an increase in disproportionate labor losses may cause a loss of 0.2% in the total account gross domestic product (GDP) of China by the 2050s, particularly in low-paid sectors. These negative impacts are not always uniformly distributed across the city, intercity, and intercountry scales [18].

Therefore, mitigating excess urban heat has never been a mere engineering problem. Rather, it is a complex, practical societal challenge that requires multidisciplinary knowledge and efforts. A recent comment by Keith et al. (2022) calls for an articulation of interconnections based on financial, economic, health and environmental aspects to galvanize attention to decision-making for the sustainable development of cities [22]. Rising et al. (2022) also advocate for efforts across the natural and social science communities to address research gaps [23]. However, existing and limited decision-making frameworks for heat mitigation largely rely on predefined technological evaluations involving the use of different single mitigation measures [24], with social and economic considerations being largely missing.

It has been widely accepted that one size does not fit all – a single urban heat mitigation measure is very unlikely to be able to address the challenge because the urban heat budget is governed by a series of physical processes at multiple scales, ranging from large-scale urban winds to the material-scale absorption of solar radiation [25–28]. *A whole-system approach that is advocated in the UNEP handbook* [9]*, where multiple mitigation measures are adopted as a solution set, is now believed to be the key to urban cooling.* As discussed in the handbook and in a comment made by Ürge-Vorsatz et al. [25], this whole-system approach calls for carefully selected solution sets to reduce heat at the urban scale, to reduce cooling needs in buildings, and to efficiently serve cooling needs in buildings under the principle of creating synergies while avoiding trade-offs [29]. Regarding the social and economic dimensions of heat mitigation solutions, there is little practice and knowledge with regard to how to build such dimensions into decision-making frameworks in which their impacts can be quantified along with technological evaluations.

From this perspective, we propose such a decision-making framework with a focus on the delivery of novel capabilities for integrating and quantifying the technological advantages and social and economic concerns of heat mitigation solution sets. As a repository of empirical experience with engineering practices and costs, we first cover the state of the art, technical and economic challenges of eight urban heat mitigation measures, including green walls, green roofs, reflective roofs, thermal insulation of building envelopes, energy-efficient techniques for indoor cooling, urban forestry and trees, evaporative pavement, and constructed shade. We then present a decision-making framework based on the **i**nvestment, **t**ime needed for implementation, and **e**ffectiveness (ITE index) of solution sets, designed to select the best among the eight individual mitigation measures and 247 possible solution sets composed of various combinations of the individual measures. The framework alongside an analytic hierarchy process (AHP) analysis provides unprecedented, multidimensional, and quantifiable decision-making capabilities for policy-makers.

2. UHI mitigation candidate measures at the building and neighborhood scales

As stated in the handbook, a whole-system based approach is needed to address three connected issues: reducing heat at the urban scale, reducing cooling needs in buildings, and serving cooling needs in buildings efficiently. Among the many candidate urban heat mitigation measures that have been studied in the research community [9], several have been found to be promising solutions. These include green walls (GW), green roofs (GR), reflective roofs (RR), thermally efficient buildings (EB), high-efficiency indoor cooling (IC), evaporative pavement (EP), constructed shade (CS), and urban forestry (UF), as illustrated in Fig. 1. Consequently, these measures were investigated further in this paper.

From an implementation perspective, these measures can be applied at either the building level or the neighborhood scale. Our discussion begins with key physics associated with the heat mitigation measures, followed by their primary benefits and the scale where they are most effective, as summarized in Table 1. These measures rely on seven major physical processes to combat urban heat, which include plant shade, transpirative cooling, reflection of solar radiation, resistance to outdoor heat, reduced heat emission from AC systems, evaporative cooling, and constructed shade. All these physical processes essentially mitigate urban heat in four ways: by reducing indoor cooling demand, reducing heat waste, reducing the temperature of the outdoor air, and reducing the temperature of the surface of the ground. Different measures act through a combination of different mechanisms and deliver benefits at different scales. No single measure can deliver all benefits at all scales, and this underlines the need to consider a whole-system approach through a combination of measures to mitigate heat.

3. Engineering practices and challenges

When it comes to implementing these mitigation measures, some experience and empirical understanding of the engineering and cost aspects have been acquired in the past, and they are worth reporting here as references for householders, urban planners, and policymakers. Key engineering considerations and indicative cost estimation from practice and the literature are summarized in Table 2. These cost estimates are based on our communications with UK-based suppliers and a

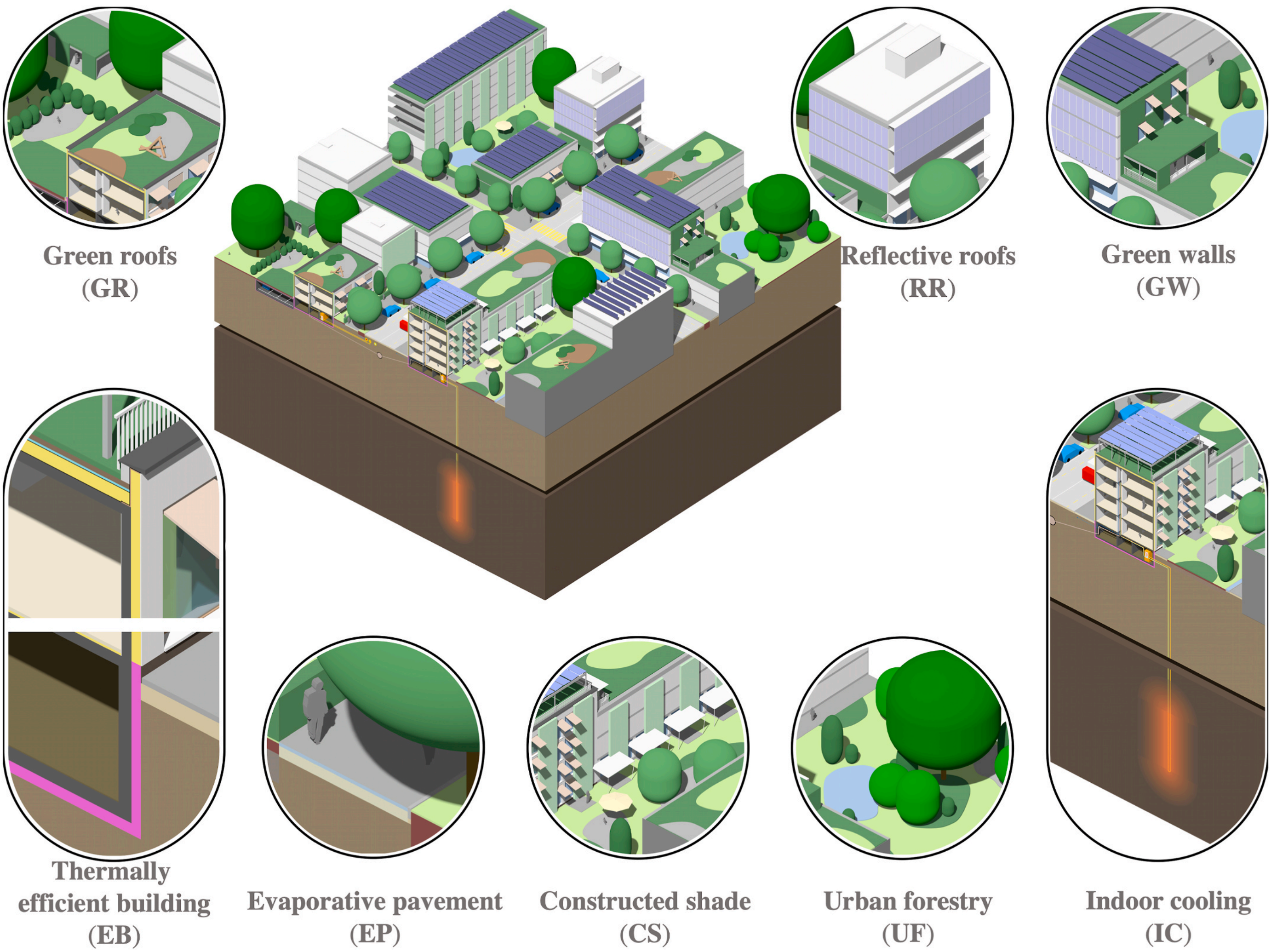


Fig. 1. A set of urban heat mitigation measures for buildings and neighborhood, including green roof (GR), reflective roof (RR), green wall (GW), thermally efficient buildings (EB), evaporative pavement (EP), constructed shade (CS), urban forestry and trees (UF), and high efficiency indoor cooling (IC). Credit for illustration: Andreas Rubin (andreas rubin architektur).

Table 1
Key mechanism of the individual mitigation measures.

Mitigation measures	Key mechanisms		
	Key physics	Key benefits	Primary Scales
GW	P1, P2	B1, B2, B3	Building, Neighborhood
GR	P1, P2	B1, B2, B3	Building, Neighborhood
RR	P3	B1, B2, B3	Building, Neighborhood
EB	P4	B1, B2	Building, Neighborhood
IC	P5	B2	Building, Neighborhood
UF	P1, P2	B3, B4	Neighborhood
EP	P6	B3, B4	Neighborhood
CS	P7	B3, B4	Neighborhood
Key physics	Plant shade (P1), Transpirative cooling (P2), Reflection of solar radiation (P3), Resistance to outdoor heat (P4), Reduced heat emission from AC systems (P5), Evaporative cooling (P6), Constructed shade (P7)		
Key benefits	Reduce indoor cooling demand (B1), Reduce waste heat (B2), Reduce outdoor air temperature (B3), Reduce ground surface, mean radiant, and pedestrian-level air temperatures (B4)		

survey of solutions that are commercially available in North America and Europe as well as data published in the literature. Considerable geographic variations may be expected among the individual cities.

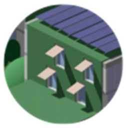
In terms of engineering considerations, measures involving vegetation often require careful planning, selection, and long-term maintenance. The effective application of reflective roofs, evaporative pavements, and thermal insulation for envelopes depends on the selection of the materials and attention to durability. For constructed shade, its application has to be linked to specific building geometry, orientation and local solar radiation conditions. As to reducing the emission of anthropogenic heat from AC systems, local climate, possibility of free cooling, and availability of geothermal or energy-efficient cooling systems must be assessed.

A preliminary assessment of costs suggests that the employment of reflective roofs is the most affordable mitigation measure. Vegetation-based measures entail not only upfront costs but also considerable routine maintenance costs. The cost for improving thermal insulation in building envelopes could vary significantly, depending on the construction plans. As for upgrading cooling systems, the cost assessment is complex as it largely depends on the type of new system to be employed.

3.1. Engineering practices of building-scale and neighborhood-scale mitigation measures

At the building scale, green walls, green roofs, and reflective roofs emerge as three options capable of reducing both the cooling demand for a building and the temperature of the local air. By designing buildings to be highly efficient thermally and tailoring designs for local climates, we

Table 2
Technical and cost considerations.

Mitigation measures		Engineering and cost consideration		
	GW	• Selection of plants	• Integrated construction	• Maintenance
		• Direct system 35–45 €/m^2 [30]	• Indirect system 0.5K–1K €/m^2 [30]	• Maintenance 4–30 €/m^2/year [30]
	GR	• Substrate thickness	• Thermal insulation	• Plant selection
		• Installation 100 €/m^2 [31]	• Maintenance 5 €/m^2/year [31]	• Disposal 12 €/m^2 [31]
	RR	• Material life cycle emissions	• Retrofitting solution	• Durability
		• Reflective coatings 2–4 €/m^2	• Maintenance 1.1 0.5 €/m^2/year	
	EB	• Thermal transmittance	• Thermal mass of exterior render	• Durability
		• Material cost 20–600 €/m^2 [32]		
	IC	• Local climate conditions	• Selection of heat source	• Cold storage systems
		• Cold storage systems 6.5–40 €/kWh [33]	• Free cooling by salt hydrate 1–40 €/kWh [33]	
	UF	• Selection of trees (canopy morphology)	• Integrated construction	• Growth management
		• Install urban trees 450–2000 €/tree	• Maintenance 40–175 €/tree/year	
	EP	• Choice of materials	• Layer thickness	• Porous structure
		• Porous asphalt costs 10–15% more [34]	• Porous concrete costs 25% more [34]	
	CS	• Building geometries and spacing	• Shade location	• Local climate
		• No cost for shade by buildings	• Cantilever umbrella (5 m width) 1600 €/pcs [35]	

can maximize indoor thermal comfort and minimize cooling needs. Subsequently, employing high-efficiency indoor cooling systems for the remaining cooling demand can significantly reduce the generation of anthropogenic heat due to indoor cooling. In this section, we first provide insight into the current engineering practices for each individual mitigation measure, and then proceed to summarize the challenges in the subsequent section.

Green walls (GW), referring to green facades and living walls, are effective to reduce the temperatures of the walls of buildings as well as the temperatures of the adjacent air [36–38], and this in turn could lead to considerable reduction in the cooling demand for the building and, hence, less generation of heat waste from conventional air conditioners. Currently, vertical green systems are being incorporated in buildings, for example, One Central Park - a mixed-use high-rise building in Sydney; the Rubens at the Palace – a hotel in London; and the Sihlcity Shopping Centre in Zurich. A surface temperature reduction up to 11.6 °C in a mid-day was observed in Singapore [39], and reductions in the range of 2–7.5 °C have been recorded outdoors at Berkshire (UK) and Berlin (Germany) [39,40]. The contribution of green walls to the reduction in building cooling demand varies from 5% to 65% [41], depending on the thickness of the concrete, the envelope materials, the condition of the existing insulation layer, etc.

Green roofs (GR) are featured with a waterproof barrier, an optional insulation layer, a root barrier, a drainage layer, substrate, and vegetation [42,43]. During the summer, 60% of the incoming solar radiation is absorbed by the leaves of plants for photosynthesis, and about 20–30% is reflected [44]. Only 10–20% of the solar radiation reaches the air layers underneath the foliage where heat is transmitted to the substrate [45] reducing building cooling energy [46] up to 10–75% and 13% when extensive green roofs are applied on non-insulated and on insulated rooftops, respectively [47] (direct effect). In turn, the reduction in the demand for cooling energy in buildings decreases anthropogenic heat releases from cooling systems limiting UHI [48,49] (indirect UHI mitigation). In 2009, the Toronto City Council adopted a green roofs by-law to promote the installation of green roofs installation [50]. In New York City, Chapter 15 of the construction code requires the installation of green roofs for new buildings or for buildings that are undergoing renovations of their rooftops [51].

Reflective roofs (RR) can be achieved using either of two approaches, i.e., reflective construction materials or reflective coatings [52]. Generally, reflective construction materials include white cement concrete and lighter-colored shingles that can be used for the construction of roofs [53]. However, reflective coatings typically are made of water-based polymers with an additional pigment (such as TiO_2, SiO_2, or ZnO) that is responsible for providing the high albedo [54]. In the U.S., New York City already has a program dedicated to applying coatings over roofs in existing buildings to mitigate heat [55], and this is backed by legislation requiring their gradual adoption. As a result, New York can expect a reduction in peak ambient air temperature of 0.4–0.8 °C [56]. Another study focused on the use of reflective roofs in Athens, Greece, and it indicated a potential reduction of 0.5–2.2 °C in the peak temperature of the ambient air during the summer [57].

Thermally highly efficient buildings (EB) reduce cooling energy consumption in buildings by reducing unwanted heat gain and loss, as well as often keeping buildings cooler than ambient temperatures through thermal mass or other passive solar methods. Urge-Vorsatz et al. [58] showed that high-efficiency buildings, often applying elements of climate-appropriate vernacular designs and typically involving high levels of thermal insulation [59], eliminated thermal bridges [60], and often a heat recovery ventilation system [61] can keep indoor thermal comfort at a much higher ambient temperature and reduce cooling energy demand significantly. Vandentorren et al. recommended improving insulation in existing buildings to provide protection from future heat waves [62]. Porritt et al. demonstrated that wall and loft thermal insulation based on UK Building Regulations can result in a 50% reduction in degree-hours over 28.0 °C for a south-facing bedroom in London [63]. An insulation initiative in Birdsville, Australia showed that the entire town's cooling energy bill in summer was reduced by 20% with building insulation, and indoor thermal comfort was ensured [64].

High efficiency indoor cooling (IC) is vital to urban heat mitigation due to the positive feedback relationship between the use of air-conditioning systems and urban warming [65,66]. Especially when we use air source heat pumps or cooling tower involved AC systems for space cooling, the cooling capacity supplied to the user and the consumed electricity are both converted into heat, and then this heat is discharged to the outdoors as anthropogenic heat, which contributes to higher temperatures and additional heat stress [67–69]. These effects are enhanced further by greenhouse gas-induced global warming, so these result in a positive climate feedback loop of warming. Possible solutions to the problem include the use of very high efficiency cooling systems such as evaporative cooling, geothermal cooling systems, and free cooling systems along with cold thermal energy storage. The refrigeration cycle is considered the most heat-exhausting process for space cooling. For moderate cooling loads, such as in the Spring and Autumn, free cooling may be applicable that does not require a refrigeration process with condensing heat to be released outdoors.

At the neighborhood scale, enhancing tree cover is one of the most promising means to mitigate urban heat, due to the well-established shade and evapotranspirational cooling contributions. Evaporative pavements have also demonstrated significant potential to reduce street surface temperatures, particularly when implemented alongside planned wetting. Constructed shade, as an underexplored solution, is truly a blessing in disguise because it is free and reduces pedestrians' exposure to direct sunlight. Therefore, the discussion in this section focuses on these three measures.

Urban forestry (UF) can modify the city-scale climate [70]. A notable recent study that considered three UK-based urban forests highlighted their evapotranspirational cooling potential to present a 1.28–13.4% reduction in modeled proximate air-conditioning energy consumption [71]. The significance of peripheral urban tree cover is evident, with greenbelts and peri-urban forests recognized for their beneficial cooling influence, driven by the formation of mesoscale phenomena like 'city-country breezes' or 'heat island flow' [72]. Meta-analyses of monitoring and simulation studies underscore that the significance of various features in enhancing urban thermal climate resilience primarily depends on the scale of those features [73–75]. Existing climatological evidence emphasizes the need for extensive coverage areas for city-scale climate modifications [73]. Meanwhile, significant localized shading and evapotranspirational cooling contribution can be achieved with relatively modest increases in street tree cover [73].

Evaporative pavements (EP) can be classified as water-permeable pavements, where water rapidly infiltrates the surface and reaches sublayers, and water-retentive pavements which can hold a relatively larger amount of water closer to the surface, e.g., by the addition of water-holding filler materials [76–78]. The duration of cooling depends highly on the composition of the pavement. In certain cases, reduction in the surface temperature is still observed on the following day after wetting [77–79]. For an effective application of evaporative cooling on pavements, water must be present close to the surface [77,80], which depends highly on the pavement material(s), e.g., the pore size distribution and the connectivity of the pores. An effective pavement design, enhancing capillary effect, helps replenish the water near the surface by upwards transport and prolongs evaporative cooling [77,78,81], and this can lead to a reduction in surface temperature of up to 20 °C [79]. Evaporative pavements also can be used in combination with high-albedo surfaces, which lower the maximum surface temperature in dry conditions and prolong the impact of evaporative cooling after wetting [82].

Constructed shade (CS) generated as a result of elevated built-up and natural features in cities is a much-underestimated urban heat mitigation measure. Constructed shade allows all living organisms to stay out of direct sunlight, reducing the risk of heat-induced exposure and illness. Shade also helps prevent urban surfaces from heating up, moderating urban ambient and indoor temperatures. Reductions in the surface temperatures in the range of 21.2 °C–23.5 °C at mid-day were observed in Phoenix (United States) and Guangzhou (China) [83], respectively, and reductions in the surface and air temperatures up to 19 °C and 7 °C, respectively, were recorded in Manchester (UK) [84]. Historic cities that have desert climates (e.g., Iran, Dubai, and UAE) embody this wisdom with arched passageways and cantilevered upper floors that cast shadows on streets and alleys [85,86]. Civano, a new urbanized town in Arizona in the southwestern United States, is a modern example where buildings are arranged to maximize the shade they provide over streets [87].

3.2. Challenges

While these individual building-scale and neighborhood-scale heat mitigation measures are viable for developed cities, they also have certain key technical challenges that need to be kept in mind. These are discussed briefly below.

Plant selection is one of the key technical considerations for the implementation of green walls and green roofs. For those greening systems without in-situ irrigation or in dry climates, plant survival is an issue. Therefore, drought-tolerant plants could be an option. Even though irrigation is key for plant transpiration [88], previous research has shown that a dry substrate can also decrease heat transfer within buildings [89,90], decreasing the use of air-cooling systems and, consequently, reducing heat waste release. In a humid subtropical climate, some native plants with a high health rating, for example *Brunneria Gracilis, Achillea millefolium*, and *Dicoria argentea* [91], are suitable candidates. For a tropical climate, those plants with rapid growth and high percentages of coverage, such as *Asystasia Gangetica* and *Melampodium Divaricatum*, could produce larger amounts of shade [92]. To have better biodiversity, vegetation of multiple species can be used in green systems. However, maintenance could be more demanding in this case because the survivabilities of different species of vegetation vary considerably [91].

Durability is a common concern with the coating and thermal insulation materials for reflective roofs and thermal insulation of building envelopes. For reflective roofs, observations have shown that the high initial albedo degrades over time and can eventually decrease to the same level as conventional materials, eliminating their benefit in the long run [93,94]. *Deterioration* is another issue with protective render and thermal insulation layers. Weathering forces, such as rain, sun, heat, cold, and anthropic factors, can lead to deterioration and thus a reduction in the durability of building materials. For example, thermal insulation systems have been found to be vulnerable to high loads of

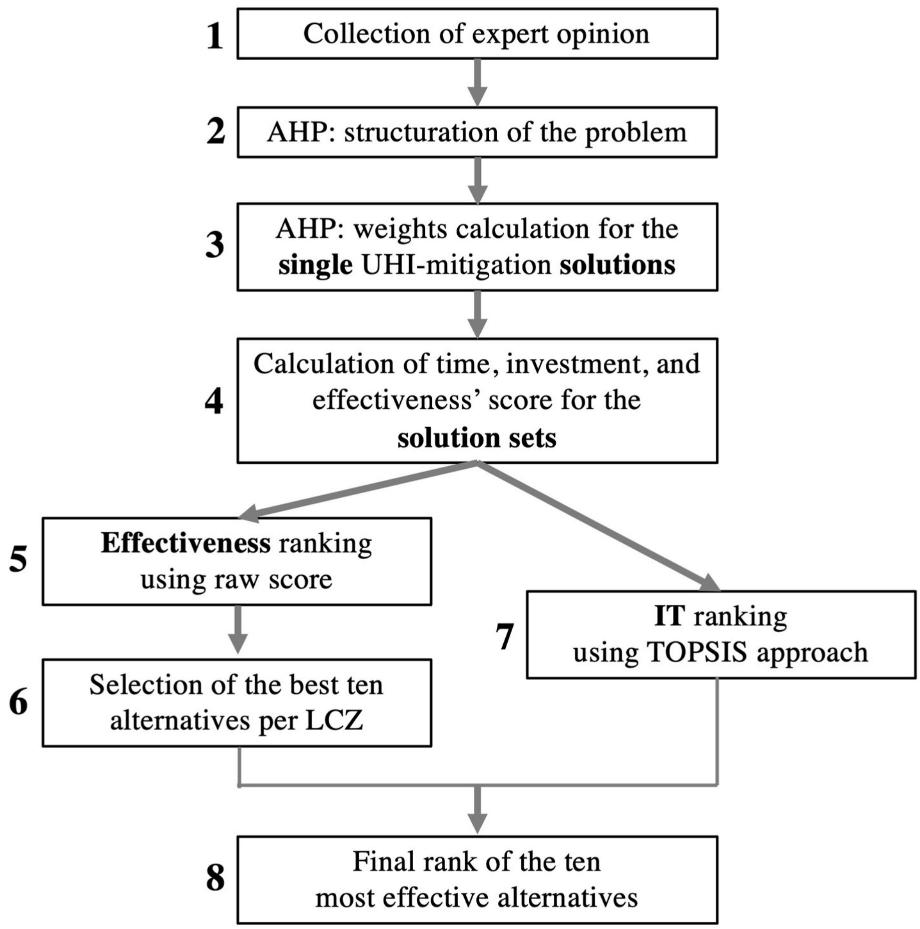


Fig. 2. Decision-making process adopted for the whole-system approach.

wind-driven rain [95]. The use of water-repellent finishing renderings is essential to protect thermal insulation systems from moisture problems. Regular replacement or reapplication of these reflective materials may be necessary as well as the proper protection for thermal insulation systems, which should be integrated into regulations for maintaining their optimal effectiveness in practice.

Upgrading indoor cooling systems often involves a lot of technical considerations in the compatibility of the new systems to the retrofitted buildings, to the existing air-conditioning infrastructure, and to the environmental impacts, and thus solutions often vary from building to building [96]. Specifically, technical assessment has to be done according to local climate conditions, the availability of heat sources around the target buildings, and the possibility of incorporating cold storage systems into existing systems. In fact, the condition of the local climate determines what the optimal upgrading options are [97]. Opportunities for upgrading indoor cooling systems are also discussed by The International Energy Agency in a report entitled 'The Future of Cooling – Opportunities for Energy-Efficient Air Conditioning.' [98].

Increasing urban forestry cover is challenging due to land supply and development pressures. Also, the types of trees to be utilized require consideration of their transpiration potential throughout their lifespans, as well as the surface roughness they present in their varied and changing canopy arrangements. Foliage density and planting patterns have been related directly to cooling efficiency in various cities and climates, presenting canopy morphology dynamics as a key urban greening design consideration [73,99–101].

Evaporative pavements face clogging, freeze-thaw damage, and reduction in strength. While clogging can be an issue by reducing hydraulic conductivity, particularly in cases where rapid infiltration is desired, it also can promote capillarity as a positive impact on evaporation [102]. Another issue with porous pavements is that they tend to have higher daytime maximum temperature in dry conditions compared to their dense counterparts. This is due to the combination of reduced thermal diffusivity [77,78,82,103] and lower reflectivity [104,105] of porous pavements which increase the maximum surface temperature by 3–8 °C.

Constructed shades, in the diurnal cycle, originate from buildings and almost disappear at solar noon on hot summer days. It might be hard to rely on building shade for cooling when extreme temperatures occur, and sun-exposed buildings around noon add to the increase in the temperature of the surrounding air. Engineered shade devices, such as shade sails and umbrellas, can supplement the lack of shade [106], alongside a careful selection of deployment locations under budget constraints.

4. The whole-system approach

To achieve effective and sustainable urban cooling, cities must have a combination of mitigation measures, so a multimeasure-centric whole-system approach is needed. However, when multiple measures are considered in combination with each other, decision makers must take several considerations into account. In this section, we propose a decision-making framework called an 'ITE-index' to enable decision makers to develop solution sets that work best for their cities (Fig. 4a). This framework considers the compatibility, effectiveness, and economic cost of solution sets consisting of one or more of the mitigation measures. Broadly, these considerations reflect the climatic, engineering, social, and economic considerations that should be taken into

Table 3
Statistical summary of compatibility scores assigned by the panel of experts.

Measure	Mean score	Standard deviation	Mean score (normalized)
GW	0.38	0.30	0.56
GR	0.40	0.30	0.58
RR	0.44	0.31	0.64
EB	0.54	0.31	0.79
IC	0.61	0.34	0.89
UF	0.68	0.36	1
EP	0.44	0.31	0.65
CS	0.50	0.34	0.74

account in the effort to identify the optimal solution for a city. Every city belongs to a Local Climate Zone (LCZ), which defines the climatic considerations. Within each LCZ, the effectiveness of individual mitigation measures and their compatibility with each other defines the engineering considerations, while the time to see benefits and economic cost represent the social and economic dimensions, respectively. The overall process for this decision-making framework is shown in Fig. 2 and is described systematically in the following sections.

4.1. Compatibility of measures

When considering a solution set that consists of two or more measures, the first consideration is whether the measures are compatible with each other and do not *decrease* each other's effectiveness, which is an engineering consideration. To assess this, we used the Analytical Hierarchy Process (AHP) decision-making framework [107] to poll 31 experts on the pairwise compatibility between each of the 8 measures (Fig. 4b). The participating experts are acknowledged in Supplementary Information 1 Table S11. Each expert ranked pairs of measures on Saaty's 1–9 scale, where a higher number indicated a measure that was more compatible with others, and the AHP was used to rank them on a compatibility score. Care was taken to ensure that the ranks assigned by each expert was internally consistent by requiring the Consistency Ratio (CR) to be less than 0.10. A statistical summary of the compatibility scores is provided in Table 3. A normalized score, with the highest mean score set to 1.0, is also shown for ease of comparison. Details of the methodology can be found in Supplementary Information 2. We used this expert opinion as a proxy for engineering analysis and simulations, but individual decision-makers may use those options instead of expert opinions. It may be noted that more sophisticated decision-making frameworks, such as Multi-Criteria Decision-Making (MCDM) or Fuzzy AHP, also are possible, but we chose AHP as a simple, illustrative approach.

The average response of the experts is shown in Fig. 3 in the form of the numbers next to the lines indicating pairs of mitigation measures. The compatibility score of each measure is shown in the solid circles in Fig. 3, and their rankings are shown at the bottom. UF has the best compatibility with other solutions, with a normalized average score of 1.0. IC is second at 0.89, and EB is third at 0.79. GR is the least compatible measure.

4.2. Economic cost of measures

After checking for the compatibility of different measures with each other, the next decisions that must be made are the economic and social costs. For this, we quantified the relative investment (I) and time (T) to see benefits of each measure as a way to capture economic and social costs, respectively. Investment is a relative indicator of the economic cost required to implement a measure. Due to the vast variation in material and labor costs in different countries, the assessment of investment here is qualitative in nature, and particular caution should be excercised if one wants to compare different solution sets that are not implemented in the same geographic area. Time is the other economic criterion that refers to the waiting period that is needed for implementing a mitigation measure from the start to the point when the benefit of the measure could be delivered. The tolerance for a longer time to see benefits depends on the prevailing social conditions in the city.

Like compatibility, expert opinions and AHP were used to assign a score and rank the mitigation measures on the I and T criteria. Table 4 shows the statistics of the scores for the I and T criteria based on these

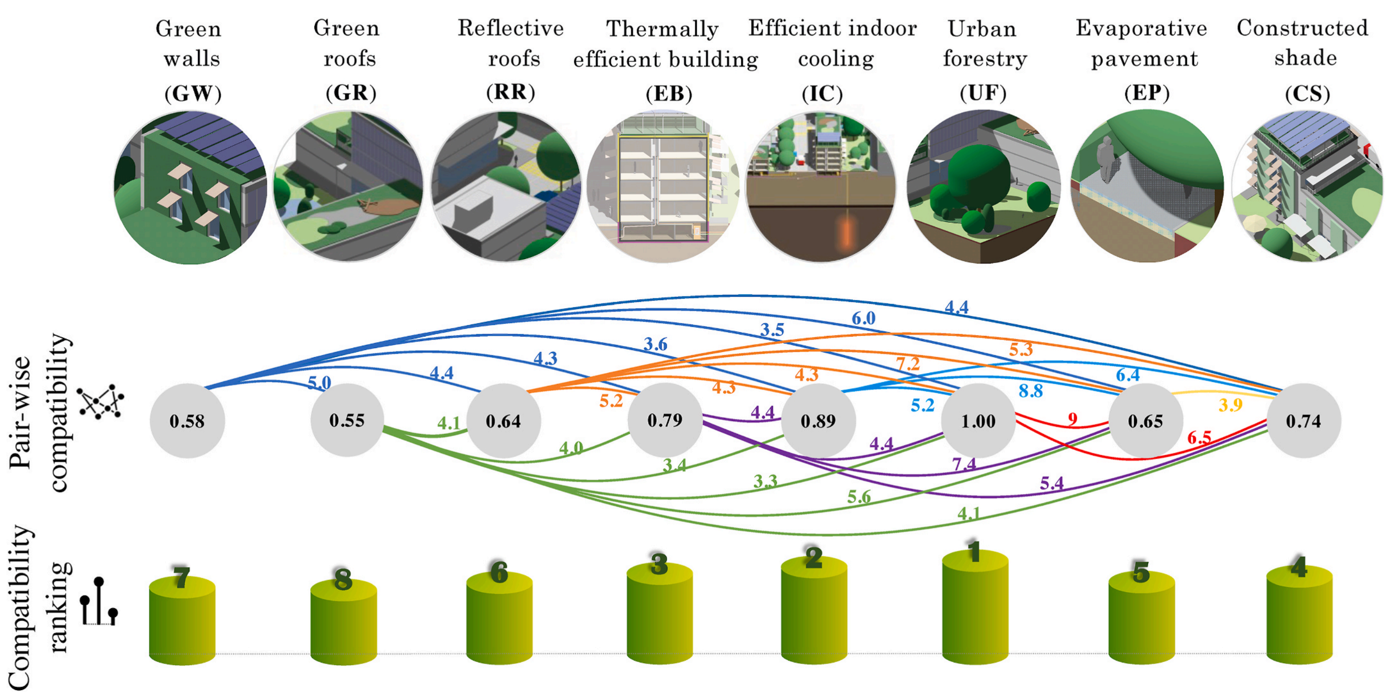


Fig. 3. Potential pairwise compatibility of the building-scale and neighborhood-scale mitigation measures. The values shown at the bottom indicate the average pairwise compatibility on Saaty's 1–9 scale, with a higher value indicating higher compatibility. The values in circles indicate the overall compatibility of a measure with others, with a higher value indicating a higher compatibility. The overall rank of each measure is shown at the bottom.

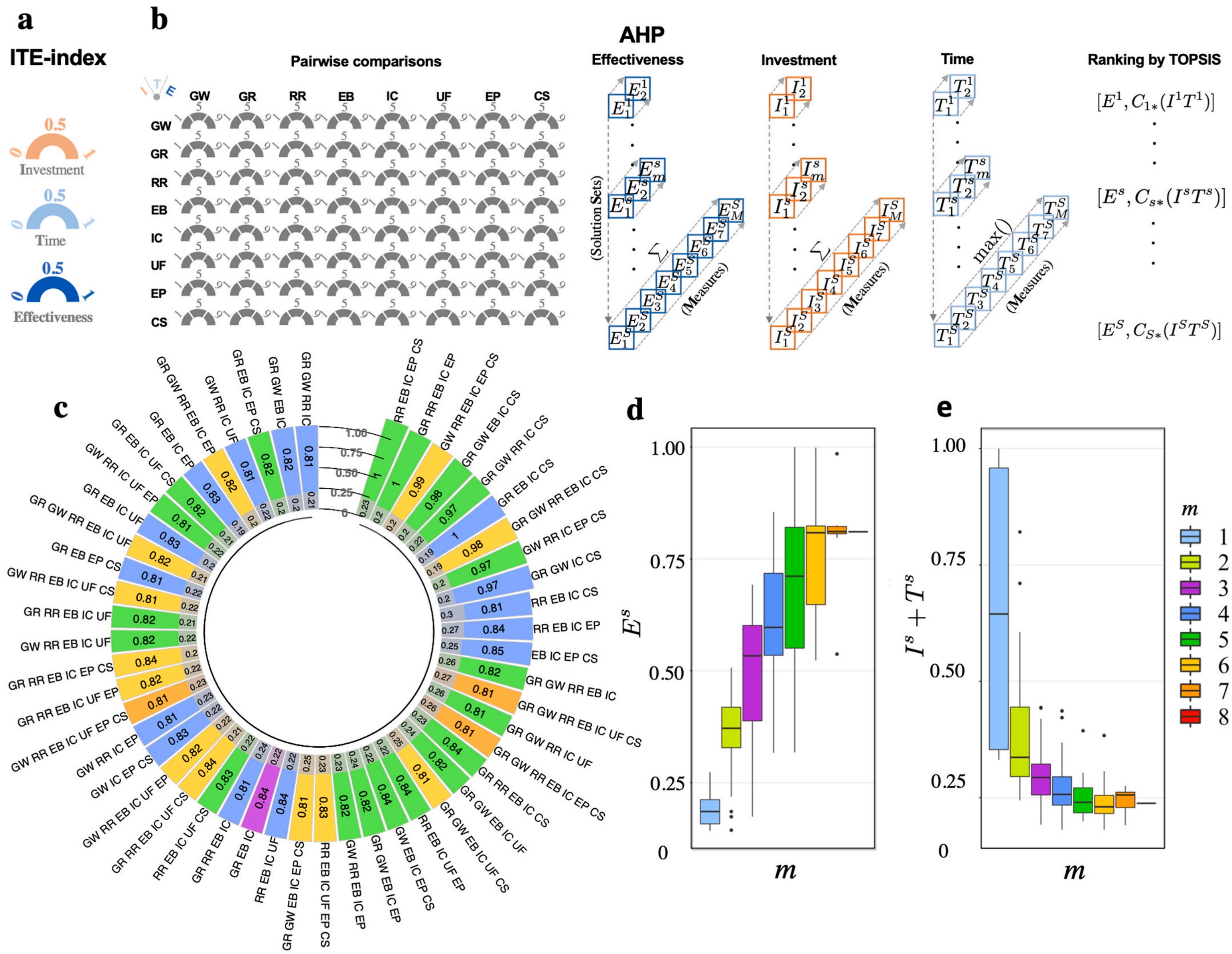


Fig. 4. AHP-TOPSIS framework for ranking solution sets based on the ITE index. (a) ITE index to evaluate investment, time, and effectiveness of solution sets; (b) AHP-TOPSIS starts with pairwise comparison of 8 measures according to the ITE index and ranks solution sets by the effectiveness indicator (*E*) and the economic indicator (*I* + *T*); (c) ITE index of top 50 solution sets for LCZ 1 (colors indicate *m* as presented in (d, e), the bars in grey denote I + T score); (d) and (e) the profile of the effectiveness score *E* and economic score (*I* + *T*) for solution sets consisting of different number *m* of individual mitigation measures for the top 50 solution sets across all LCZs.

Table 4
Mean and standard deviation of economic (I + T) scores.

Measure	Investment Score		Time Score	
	Mean	Std dev	Mean	Std dev
GW	0.64	0.28	0.22	0.20
GR	0. 63	0.22	0.31	0.21
RR	0.23	0.33	0.76	0.29
EB	0.63	0.28	0.52	0.34
IC	0.72	0.19	0.64	0.33
UF	0.72	0.27	0.19	0.25
EP	0.54	0.28	0.44	0.28
CS	0.46	0.31	0.58	0.37

opinions. The details of the calculation are provided in Supplementary Information 2. Individual decision-makers should conduct more rigorous economic analyses and assess their city's specific social needs when making decisions for their city.

Additionally, experts were also asked to compare the relative importance of the I and T criteria, and relative weights were assigned to them. The mean relative weight was 0.81 and 0.60, respectively, while the standard deviation of the weights was 0.33 and 0.37, respectively. The use of these weights will be discussed shortly.

4.3. Effectiveness

The crucial consideration that decision makers have to make is whether a measure is effective for their local conditions, which is an engineering and climatic consideration. Not all measures provide both the same effectiveness in mitigating urban heat and can also be practically applied to the urban contexts. Stewart and Oke [108] developed a climate-based classification system for urban areas based on the differentiation of surface structure and cover called Local Climate Zones (LCZs). LCZs are defined as "climate zones as regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometers in horizontal scale. Each LCZ has a characteristic screen-height temperature regime that is most apparent over dry surfaces, on calm, clear nights, and in areas of simple relief". Among the 17 LCZs identified by Stewart and Oke, the first nine are non-industrial ones and typical of the urban environment and were considered by us to quantify effectiveness. These nine LCZs are: compact high-rise (LCZ 1), compact midrise (LCZ 2), compact low-rise (LCZ 3),

Table 5
Summary of effectiveness scores of the individual mitigation measures in each LCZ (SD refers to standard deviation).

LCZ	GW		GR		RR		EB		IC		UF		EP		CS	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	0.70	0.30	0.49	0.29	0.49	0.29	0.79	0.20	0.93	0.18	0.63	0.31	0.63	0.28	0.55	0.34
2	0.77	0.20	0.68	0.23	0.67	0.24	0.81	0.20	0.88	0.19	0.69	0.25	0.69	0.24	0.63	0.28
3	0.68	0.20	0.82	0.17	0.77	0.20	0.79	0.20	0.85	0.19	0.69	0.24	0.70	0.23	0.65	0.24
4	0.68	0.23	0.42	0.24	0.47	0.27	0.81	0.20	0.84	0.20	0.70	0.23	0.63	0.23	0.62	0.25
5	0.70	0.21	0.63	0.23	0.62	0.22	0.82	0.19	0.79	0.21	0.76	0.24	0.66	0.22	0.68	0.21
6	0.57	0.24	0.75	0.22	0.68	0.20	0.75	0.20	0.76	0.21	0.72	0.26	0.66	0.23	0.68	0.20
7	0.55	0.29	0.75	0.24	0.76	0.22	0.73	0.22	0.75	0.24	0.69	0.23	0.64	0.21	0.66	0.26
8	0.48	0.27	0.77	0.25	0.76	0.26	0.67	0.20	0.74	0.24	0.70	0.25	0.65	0.24	0.65	0.25
9	0.50	0.28	0.54	0.29	0.55	0.29	0.66	0.26	0.66	0.28	0.64	0.27	0.56	0.26	0.70	0.25

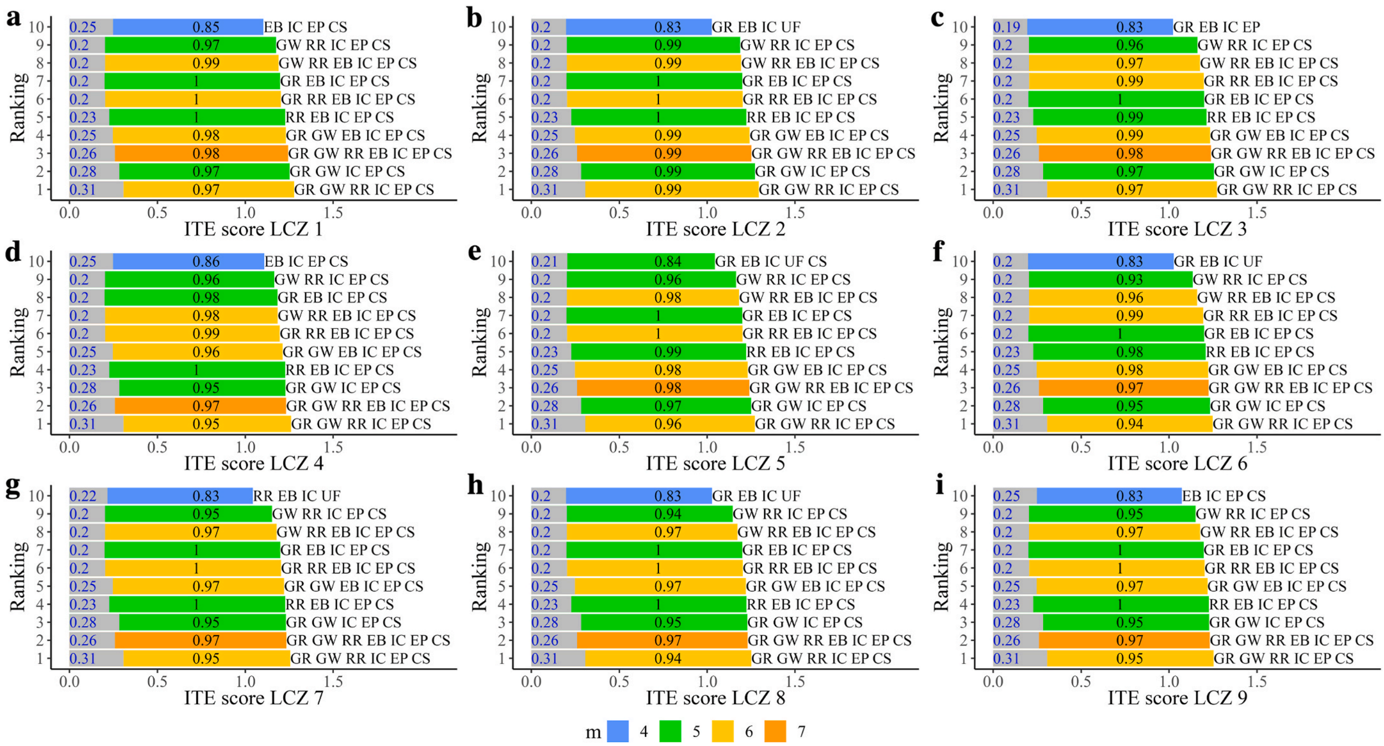


Fig. 5. Ranking of the top 10 solution sets for LCZs 1–9, (a)–(i), respectively. The number of measures within each set *m* is coded in different colors, and the economic and effectiveness scores for each also are shown in the grey and colored bars. The total of these scores is the ITE index.

open high-rise (LCZ 4), open midrise (LCZ 5), open low-rise (LCZ 6), lightweight low-rise (LCZ 7), large low-rise (LCZ 8), and sparsely built (LCZ 9). These are explained in more detail in Supplementary Information 3 Figure S31.

Not all the mitigation measures can effectively be applied to a specific LCZ or can efficiently mitigate UHI. For instance, the application of green roofs at LCZ1 (i.e., compact high-rise), featured with multi-story buildings, has no effect or a negligible effect on UHI mitigation at the pedestrian level [47]. To the contrary, the application of green walls on high-rise buildings (i.e., LCZ1 and LCZ4) can be very beneficial in decreasing urban heat [109]. Similarly, the use of reflective surfaces in LCZ1 may have only a very localized effect due to reduced ventilation [27]. Besides, LCZ4 (i.e., open high-rise) does not allow the installation of further evaporative pavements as most of the urban surfaces are already pervious. Therefore, the effectiveness of each mitigation measure within each LCZ must be quantified.

To do this, we again used expert opinions and AHP to develop the Effectiveness scores for each measure in the context of each LCZ, with the compatibility scores being incorporated into it. A statistical summary of the results of the polls is provided in Table 5. In practice, these expert opinions may be replaced with rigorous engineering analysis and simulations.

4.4. Ranking of solution sets

At this stage, we obtained relative scores indicating how good each of the 8 measures was in terms of its social and economic cost (time and investment, respectively) as well as its effectiveness in each of the nine LCZs (engineering and climatic considerations). The 8 measures could be combined into 255 possible solution sets consisting of one or more individual measures. To assess these 255 possible solution sets, a whole-system approach is needed, in which a composite score is developed and compared.

The final step was thus to rank the solution sets to develop a list of the 10 best ones that could be applied for each LCZ. For this, we used the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [110] to generate a composite Economic score considering the I and T criteria, the details for which are provided in Supplementary Information 4. For each LCZ, the 10 most effective solutions (based on the Effectiveness score) were then selected and their Effectiveness scores were then added to their corresponding Economic scores. The resultant score thus obtained for each solution set is what we call the 'ITE index',

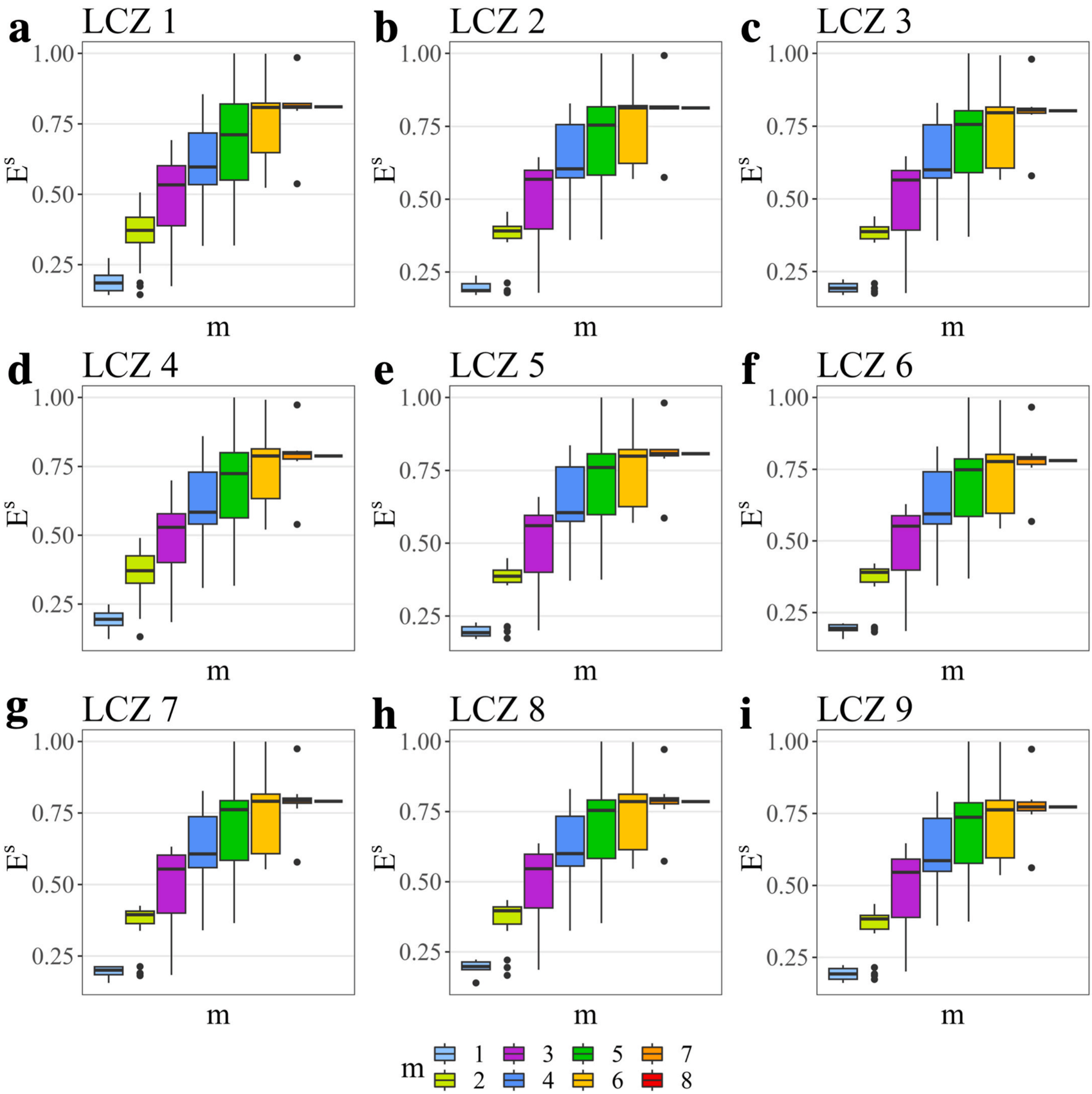


Fig. 6. Distribution of effectiveness scores with LCZ (a–i) and different number m of individual mitigation measures.

and it provides a balance between the effectiveness and compatibility of the measures in a solution set with their economic cost.

Based on the experts that we surveyed, Fig. 5 shows the top 10 solutions sets for each LCZ based on the ITE index. It can be seen that solution sets that combine more solutions are generally more favorable across all of the LCZs. Only a handful of solutions consisting of 4 measures made it to the top 10, and none with fewer. Solutions with 6–7 measures made up the majority. Interestingly, for all of the LCZs, the solution set implementing GR, GW, RR, IC, EP, and CS measures always was found to be the best, while there was significant variation among the remaining solution sets.

For LCZ 1, we combined all of the solutions and ranked the top 50 unique ones, as shown in Fig. 4c. It can be confirmed that even among the unique sets, those that combine more solutions generally are more favorable. The majority of our top 50 unique solution sets had 5 - 7 measures, with 15 having 4 measures, just 1 having 3, and none less than that. For these top 50 sets, effectiveness and economic scores of measures as a function of the number of mitigation measures *m* are shown in Fig. 4d and e, respectively. Sets that combined a greater number of measures had a higher effectiveness score but a lower economic score. For example, solution sets with just one mitigation measure had an average effectiveness score of just 0.2, but they had an economic score of about 0.7. In contrast, a solution set that had all 8 mitigation measures had a high average effectiveness score of 0.8 but a low economic score of about 0.25. The top 50 solution sets presented in Fig. 4c had the best trade-off between these two scores across all LCZs. Within each LCZ as well, the same observation was valid, as shown for the distribution of composite Economic scores in Fig. 6.

It is important to stress that these solution sets were ranked based on the scores provided by the 31 experts we consulted. The economic and social considerations, along with the specific engineering and climatic conditions, may vary for individual cities and decision-makers, which would naturally influence the corresponding scores and top solution sets. While our top solution sets may not apply universally, we believe the AHP-TOPSIS framework that we have developed can be utilized universally, enabling decision-makers to determine the solution sets most suitable for their specific cities and neighbourhoods.

5. Concluding remarks

The grand challenge of addressing urban excess heat lies in the fact that various physical processes contribute to and govern the urban heat budget at multiple scales, for instance, solar absorption by low-albedo built material and anthropogenic waste heat from cooling plants. Additionally, the significant inhomogeneity of urban forms present in cities complicates this issue. For these reasons, a single heat mitigation measure may not be effective.

From this perspective, we have summarized the state-of-the-art knowledge and challenges of 8 individual mitigation measures for implementation at both building and neighborhood scales. However, given the complexity of urban heat, a multimeasure-centric whole-system approach is required, where decision-makers weigh both the economic cost and the effectiveness of solution sets comprising one or more mitigation measures. To facilitate this, we have developed a complementary framework for decision-making, employing expert polling, to create the ITE index. This index is designed to select the optimal solution set for a given city. Balancing the effectiveness and compatibility of a solution set with its economic cost, the ITE index enables decision-makers to rank solution sets in accordance with their suitability for local conditions.

Utilizing this framework, we discovered that solution sets comprising several mitigation measures were generally more effective in mitigating heat than individual measures alone. This held true across all examined LCZs. When viewed in aggregate across all LCZs, the majority of the top 50 unique solution sets were composed of 4–7 out of the 8 measures considered. This implies that, according to our expert polling and the ITE index, solution sets with fewer measures may have lower economic costs, but their reduced overall effectiveness may not justify these costs. By taking a multimeasure-centric whole-system approach, costs and effectiveness can be balanced. For all LCZs, thermally-efficient buildings and high-efficiency indoor cooling emerged as two consistently recurrent measures contributing to the optimal solution set. Our findings, while based on expert opinions from a variety of geographies, may have limitations. Nonetheless, the same framework can be universally applied by decision-makers and experts in their specific contexts to address urban heat. Future work may involve exploring the policy readiness of the suggested measures.

Author contributions

Y.L. conceived and developed the work. Y.L. and S.S. led the writing of the article, and all authors contributed to writing. A.R. created the illustration and inserts for Fig. 1, Fig. 3, and Table 2; for re-using illustration materials, please contact A.R.. Y.L., T.S., J.I. and S.S. led the ITE index analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank the experts for providing their detailed evaluation of urban heat mitigation measures in the polls.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113668.

References

[1] Grimm NB, et al. Global change and the ecology of cities. Science 2008;319:756–60.
[2] Manoli G, et al. Magnitude of urban heat islands largely explained by climate and population. Nature 2019;573:55–60.
[3] Zhao L, Lee X, Smith RB, Oleson K. Strong contributions of local background climate to urban heat islands. Nature 2014;511:216–9.
[4] Liu Z, et al. Surface warming in global cities is substantially more rapid than in rural background areas. Communications Earth & Environment 2022;3:219.
[5] Chapman S, Thatcher M, Salazar A, Watson JEM, McAlpine CA. The effect of urban density and vegetation cover on the heat island of a subtropical city. J Appl Meteorol Climatol 2018;57:2531–50.
[6] Li Y, Schubert S, Kropp JP, Rybski D. On the influence of density and morphology on the Urban Heat Island intensity. Nat Commun 2020;11:2647.
[7] Fitria R, Kim D, Baik J, Choi M. Impact of biophysical mechanisms on urban heat island associated with climate variation and urban morphology. Sci Rep 2019;9:19503.
[8] Li D, et al. Urban heat island: aerodynamics or imperviousness? Sci Adv 2019;5:eaau4299.
[9] Campbell I, Sachar S, Meisel J, Nanavatty R. Beating the heat: a sustainable cooling handbook for cities. UN environment programme; 2021.
[10] Wang Y, et al. Tens of thousands additional deaths annually in cities of China between 1.5 °C and 2.0 °C warming. Nat Commun 2019;10:3376.
[11] Mitchell D. Climate attribution of heat mortality. Nat Clim Change 2021;11:467–8.
[12] Tong S, Prior J, McGregor G, Shi X, Kinney P. Urban heat: an increasing threat to global health. BMJ 2021;375:n2467.
[13] van Ruijven BJ, De Cian E, Sue Wing I. Amplification of future energy demand growth due to climate change. Nat Commun 2019;10:2762.
[14] Romitti Y, Sue Wing I. Heterogeneous climate change impacts on electricity demand in world cities circa mid-century. Sci Rep 2022;12:4280.
[15] Wang Z, Hong T, Li H. Informing the planning of rotating power outages in heat waves through data analytics of connected smart thermostats for residential buildings. Environ Res Lett 2021;16:074003.
[16] Liang L, Gong P. Urban and air pollution: a multi-city study of long-term effects of urban landscape patterns on air quality trends. Sci Rep 2020;10:18618.
[17] Welsby D, Price J, Pye S, Ekins P. Unextractable fossil fuels in a 1.5 °C world. Nature 2021;597:230–4.
[18] Hsu A, Sheriff G, Chakraborty T, Manya D. Disproportionate exposure to urban heat island intensity across major US cities. Nat Commun 2021;12:2721.
[19] He C, et al. The inequality labor loss risk from future urban warming and adaptation strategies. Nat Commun 2022;13:3847.
[20] Vicedo-Cabrera AM, et al. The burden of heat-related mortality attributable to recent human-induced climate change. Nat Clim Change 2021;11:492–500.
[21] Stone B, et al. Compound climate and infrastructure events: how electrical grid failure alters heat wave risk. Environ Sci Technol 2021;55:6957–64.
[22] Keith M, et al. A new urban narrative for sustainable development. Nat Sustain 2023; 6: 115-117..
[23] Rising J, Tedesco M, Piontek F, Stainforth DA. The missing risks of climate change. Nature 2022;610:643–51.
[24] Santamouris M, et al. On the energy impact of urban heat island in Sydney: climate and energy potential of mitigation technologies. Energy Build 2018;166:154–64.
[25] Ürge-Vorsatz D, et al. Locking in positive climate responses in cities. Nat Clim Change 2018;8:174–7.
[26] Fan Y, et al. Natural convection over vertical and horizontal heated flat surfaces: a review of recent progress focusing on underpinnings and implications for heat transfer and environmental applications. Phys Fluids 2021;33:101301.
[27] Sen S, Khazanovich L. Limited application of reflective surfaces can mitigate urban heat pollution. Nat Commun 2021;12:3491.
[28] Zhao Y, Li H, Kubilay A, Carmeliet J. Buoyancy effects on the flows around flat and steep street canyons in simplified urban settings subject to a neutral approaching boundary layer: wind tunnel PIV measurements. Sci Total Environ 2021;797:149067.

[29] Wang Z-H. Compound environmental impact of urban mitigation strategies: Co-benefits, trade-offs, and unintended consequence. Sustain Cities Soc 2021;75:103284.
[30] Rosasco P. Chapter 4.4 - economic benefits and costs of vertical greening systems. In: Pérez G, Perini K, editors. Nature based Strategies for urban and building Sustainability. Butterworth-Heinemann; 2018.
[31] Manso M, Teotónio I, Silva CM, Cruz CO. Green roof and green wall benefits and costs: a review of the quantitative evidence. Renew Sustain Energy Rev 2021;135:110111.
[32] Orsini F, Marrone P, Asdrubali F, Roncone M, Grazieschi G. Aerogel insulation in building energy retrofit. Performance testing and cost analysis on a case study in Rome. Energy Rep 2020;6:56–61.
[33] Hirschey Jason, Kumar N, Turnaoglu T, Gluesenkamp KR, Graham S. Review of low-cost organic and inorganic phase change materials with phase change temperature between 0°C and 65°C. In: 6th International high Performance buildings Conference at Purdue; 2021.
[34] Shoemaker L, Lahlou M, Doll A, Cazenas P. Stormwater best management practices in an ultra-urban setting : selection and monitoring. 2000.
[35] GSA advantage. 2023. www.gsaadvantage.gov.
[36] Cameron RWF, Taylor JE, Emmett MR. What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls. Build Environ 2014;73:198–207.
[37] Ebrahimnejad R, Noori O, Deihimfard R. Mitigation potential of green structures on local urban microclimate using ENVI-met model. Int J Urban Sustain Dev 2017;9:274–85.
[38] Anderson V, Gough WA. Nature-based cooling potential: a multi-type green infrastructure evaluation in Toronto, Ontario, Canada. Int J Biometeorol 2022;66:397–410.
[39] Wong NH, et al. Thermal evaluation of vertical greenery systems for building walls. Build Environ 2010;45:663–72.
[40] Perini K, Ottelé M, Fraaij ALA, Haas EM, Raiteri R. Vertical greening systems and the effect on air flow and temperature on the building envelope. Build Environ 2011;46:2287–94.
[41] Perini K, Rosasco P. Cost–benefit analysis for green façades and living wall systems. Build Environ 2013;70:110–21.
[42] U.S. Environmental Protection Agency. Reducing urban heat islands: Compendium of Strategies. GreenRoofs; 2008. 2008.
[43] Shafique M, Kim R, Rafiq M. Green roof benefits, opportunities and challenges – a review. Renew Sustain Energy Rev 2018;90:757–73.
[44] Cascone S, Coma J, Gagliano A, Pérez G. The evapotranspiration process in green roofs: a review. Build Environ 2019;147:337–55.
[45] La Roche P, Berardi U. Comfort and energy savings with active green roofs. Energy Build 2014;82:492–504.
[46] Sun T, Bou-Zeid E, Wang Z-H, Zerba E, Ni G-H. Hydrometeorological determinants of green roof performance via a vertically-resolved model for heat and water transport. Build Environ 2013;60:211–24.
[47] Susca T. Green roofs to reduce building energy use? A review on key structural factors of green roofs and their effects on urban climate. Build Environ 2019;162:106273.
[48] Santamouris M. Cooling the cities – a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol Energy 2014;103:682–703.
[49] Wong NH, Tan CL, Kolokotsa DD, Takebayashi H. Greenery as a mitigation and adaptation strategy to urban heat. Nat Rev Earth Environ 2021;2:166–81.
[50] City of Toronto green roof Bylaw. 2017. https://www.toronto.ca/city-government/planning-development/official-plan-guidelines/green-roofs/green-roof-bylaw/.
[51] New York City Council. Local law. 2019. https://www1.nyc.gov/site/buildings/codes/local-laws.page.
[52] Urban B, Roth K. Guidelines for selecting cool roofs. US Department of Energy Building Technologies Program and Oak Ridge National Laboratory; 2010.
[53] Levinson R, et al. Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials. Sol Energy Mater Sol Cell 2007;91:304–14.
[54] Li H, Saboori A, Cao X. Information synthesis and preliminary case study for life cycle assessment of reflective coatings for cool pavements. International Journal of Transportation Science and Technology 2016;5:38–46.
[55] City of New York. NYC CoolRoofs. 2022. https://www1.nyc.gov/nycbusiness/article/nyc-coolroofs.
[56] Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces. 2006. https://www.giss.nasa.gov/research/news/20060130/103341.pdf.
[57] Synnefa A, Dandou A, Santamouris M, Tombrou M, Soulakellis N. On the use of cool materials as a heat island mitigation strategy. J Appl Meteorol Climatol 2008;47:2846–56.
[58] Ürge-Vorsatz D, et al. Advances toward a net-zero global building sector. Annu Rev Environ Resour 2020;45:227–69.
[59] Yarbrough DW. Thermal insulation for energy conservation. In: Chen W-Y, Seiner J, Suzuki T, Lackner M, editors. Handbook of climate change mitigation. Springer US; 2012.
[60] Lu J, Xue Y, Wang Z, Fan Y. Optimized mitigation of heat loss by avoiding wall-to-floor thermal bridges in reinforced concrete buildings. J Build Eng 2020;30:101214.
[61] Picallo-Perez A, Sala-Lizarraga JM, Odriozola-Maritorena M, Hidalgo-Betanzos JM, Gomez-Arriaran I. Ventilation of buildings with heat recovery systems: thorough energy and exergy analysis for indoor thermal wellness. J Build Eng 2021;39:102255.
[62] Vandentorren S, et al. August 2003 heat wave in France: risk factors for death of elderly people living at home. Eur J Publ Health 2006;16:583–91.
[63] Porritt SM, Cropper PC, Shao L, Goodier CI. Ranking of interventions to reduce dwelling overheating during heat waves. Energy Build 2012;55:16–27.
[64] Architecture Design, Knauf's Earthwool insulation initiative in Birdsville helps residents save over 20% on home energy bills. 2015. https://www.architectureanddesign.com.au/suppliers/knauf-insulation/knauf-s-earthwool-insulation-initiative-in-birdsvi.
[65] Salamanca F, Georgescu M, Mahalov A, Moustaoui M, Wang M. Anthropogenic heating of the urban environment due to air conditioning. J Geophys Res Atmos 2014;119:5949–65.
[66] Wang Y, Li Y, Sabatino SD, Martilli A, Chan PW. Effects of anthropogenic heat due to air-conditioning systems on an extreme high temperature event in Hong Kong. Environ Res Lett 2018;13:034015.
[67] de Munck C, et al. How much can air conditioning increase air temperatures for a city like Paris, France? Int J Climatol 2013;33:210–27.
[68] Takane Y, Kikegawa Y, Hara M, Grimmond CSB. Urban warming and future air-conditioning use in an Asian megacity: importance of positive feedback. npj Climate and Atmospheric Science 2019;2:39.
[69] Takane Y, Ohashi Y, Grimmond CSB, Hara M, Kikegawa Y. Asian megacity heat stress under future climate scenarios: impact of air-conditioning feedback. Environmental Research Communications 2020;2:015004.
[70] Schwaab J, Meier R, Mussetti G, Seneviratne S, Bürgi C, Davin EL. The role of urban trees in reducing land surface temperatures in European cities. Nat Commun 2021;12:6763.
[71] Moss JL, Doick KJ, Smith S, Shahrestani M. Influence of evaporative cooling by urban forests on cooling demand in cities. Urban For Urban Green 2019;37:65–73.
[72] Bernatzky A. The contribution of tress and green spaces to a town climate. Energy Build 1982;5:1–10.
[73] Gunawardena KR, Wells MJ, Kershaw T. Utilising green and bluespace to mitigate urban heat island intensity. Sci Total Environ 2017;584–585:1040–55.
[74] Zhou W, Shen X, Cao F, Sun Y. Effects of area and shape of greenspace on urban cooling in nanjing, China. J Urban Plann Dev 2019;145:04019016.
[75] Gao Z, Zaitchik BF, Hou Y, Chen W. Toward park design optimization to mitigate the urban heat Island: assessment of the cooling effect in five U.S. cities. Sustain Cities Soc 2022;81:103870.
[76] Nakayama T, Fujita T. Cooling effect of water-holding pavements made of new materials on water and heat budgets in urban areas. Landsc Urban Plann 2010;96:57–67.
[77] Li H, Harvey JT, Holland TJ, Kayhanian M. The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management. Environ Res Lett 2013;8:015023.
[78] Wang J, Meng Q, Tan K, Zhang L, Zhang Y. Experimental investigation on the influence of evaporative cooling of permeable pavements on outdoor thermal environment. Build Environ 2018;140:184–93.
[79] Kubilay A, Derome D, Carmeliet J. Impact of evaporative cooling due to wetting of urban materials on local thermal comfort in a street canyon. Sustain Cities Soc 2019;49:101574.
[80] Qin Y, Hiller JE. Water availability near the surface dominates the evaporation of pervious concrete. Construct Build Mater 2016;111:77–84.
[81] Starke P, Göbel P, Coldewey WG. Urban evaporation rates for water-permeable pavements. Water Sci Technol 2010;62:1161–9.
[82] Ferrari A, Kubilay A, Derome D, Carmeliet J. The use of permeable and reflective pavements as a potential strategy for urban heat island mitigation. Urban Clim 2020;31:100534.
[83] Zheng S, Guldmann J-M, Liu Z, Zhao L. Influence of trees on the outdoor thermal environment in subtropical areas: an experimental study in Guangzhou, China. Sustain Cities Soc 2018;42:482–97.
[84] Armson D, Stringer P, Ennos AR. The effect of tree shade and grass on surface and globe temperatures in an urban area. Urban For Urban Green 2012;11:245–55.
[85] Emmanuel R, Rosenlund H, Johansson E. Urban shading—a design option for the tropics? A study in Colombo, Sri Lanka. Int J Climatol 2007;27:1995–2004.
[86] Adlington Kate. Arid cities must rethink planning and design to remain viable, Arup Report. 2018. https://www.arup.com/news-and-events/arid-cities-must-rethink-planning-and-design-to-remain-viable-says-new-arup-report.
[87] Kelly Turner V, et al. More than surface temperature: mitigating thermal exposure in hyper-local land system. J Land Use Sci 2022;17:79–99.
[88] Hoelscher M-T, Nehls T, Jänicke B, Wessolek G. Quantifying cooling effects of facade greening: shading, transpiration and insulation. Energy Build 2016;114:283–90.
[89] Jamei E, Chau HW, Seyedmahmoudian M, Mekhilef S, Hafez FS. Green roof and energy – role of climate and design elements in hot and temperate climates. Heliyon 2023;9:e15917.
[90] Zheng X, Yang Z, Yang J, Tang M, Feng C. An experimental study on the thermal and energy performance of self-sustaining green roofs under severe drought conditions in summer. Energy Build 2022;261:111953.
[91] Dvorak B, Yang S, Menotti T, Pace Z, Mehta S, Ali AK. Native plant establishment on a custom modular living wall system in a humid subtropical climate. Urban For Urban Green 2021;63:127234.
[92] Sasima C. The performance of outdoor plants in living walls under hot and humid conditions. Landsc Ecol Eng 2021;17:55–73. 2021 v.2017 no.2022.
[93] Bretz SE, Akbari H. Long-term performance of high-albedo roof coatings. Energy Build 1997;25:159–67.

[94] Miller WA, Desjarlais AO, Roodvoets DL. Long term reflective performance of roof membranes. In: Proceedings of the 2004 roof consultants institue convection; 2004.
[95] Kvande T, Bakken N, Bergheim E, Thue JV. Durability of ETICS with rendering in Norway—experimental and field investigations. Buildings 2018;8:93.
[96] Zhou X, Yan D, Feng X, Deng G, Jian Y, Jiang Y. Influence of household air-conditioning use modes on the energy performance of residential district cooling systems. Build Simulat 2016;9:429–41.
[97] Lundgren-Kownacki K, Hornyanszky ED, Chu TA, Olsson JA, Becker P. Challenges of using air conditioning in an increasingly hot climate. Int J Biometeorol 2018;62:401–12.
[98] International Energy Agency. The Future of Cooling - Opportunities for energy-efficient air conditioning. 2018. https://iea.blob.core.windows.net/assets/0bb45525-277f-4c9c-8d0c-9c0cb5e7d525/The_Future_of_Cooling.pdf.
[99] Chinchilla J, Carbonnel A, Galleguillos M. Effect of urban tree diversity and condition on surface temperature at the city block scale. Urban For Urban Green 2021;60:127069.
[100] Tsoka S, Leduc T, Rodler A. Assessing the effects of urban street trees on building cooling energy needs: the role of foliage density and planting pattern. Sustain Cities Soc 2021;65:102633.
[101] Wei J, Li H, Wang Y, Xu X. The cooling and humidifying effects and the thresholds of plant community structure parameters in urban aggregated green infrastructure. Forests 2021;12:111.
[102] Hendel M. 6 - cool pavements. In: Pacheco-Torgal F, Amirkhanian S, Wang H, Schlangen E, editors. Eco-efficient pavement construction materials. Woodhead Publishing; 2020.
[103] Stempihar JJ, Pourshams-Manzouri T, Kaloush KE, Rodezno MC. Porous asphalt pavement temperature effects for urban heat island analysis. Transport Res Rec 2012;2293:123–30.
[104] Xie N, Akin M, Shi X. Permeable concrete pavements: a review of environmental benefits and durability. J Clean Prod 2019;210:1605–21.
[105] Tziampou N, Coupe SJ, Sañudo-Fontaneda LA, Newman AP, Castro-Fresno D. Fluid transport within permeable pavement systems: a review of evaporation processes, moisture loss measurement and the current state of knowledge. Construct Build Mater 2020;243:118179.
[106] Parisi AV, Turnbull DJ. Shade provision for UV minimization: a review. Photochem Photobiol 2014;90:479–90.
[107] Saaty TL. Decision making — the analytic hierarchy and network processes (AHP/ANP). J Syst Sci Syst Eng 2004;13:1–35.
[108] Stewart ID, Oke TR. Local climate zones for urban temperature studies. Bull Am Meteorol Soc 2012;93:1879–900.
[109] Susca T, Zanghirella F, Colasuonno L, Del Fatto V. Effect of green wall installation on urban heat island and building energy use: a climate-informed systematic literature review. Renew Sustain Energy Rev 2022;159:112100.
[110] Yoon K, Hwang C-L. Multiple attribute decision making: an introduction. 1995.