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Understanding policy and technology responses in mitigating urban heat islands: A literature review and directions for future research

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Abstract: Policy and technology responses to increased temperatures in urban heat islands (UHIs) are discussed in a variety of research; however, their interaction is overlooked and understudied. This is an important oversight because policy and technology are often developed in isolation of each other and not in conjunction. Therefore, they have limited synergistic effects when aimed at solving global issues. To examine this aspect, we conducted a systematic literature review and synthesised 97 articles to create a conceptual structuring of the topic. We identified the following categories: (a) evidence base for policymaking including timescale analysis, effective policymaking instruments as well as decision support and scenario planning; (b) policy responses including landscape and urban form, green and blue area ratio, albedo enhancement policies, transport modal split as well as public health and participation; (c) passive technologies including green building envelopes and development of cool surfaces; and (d) active technologies including sustainable transport as well as energy consumption, heating, ventilation and air conditioning, and waste heat.

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Based on the findings, we present a framework to guide future research in analysing UHI policy and technology responses more effectively in conjunction with each other.

Keywords: Urban heat island; urban planning; sustainable development; urban policymaking; urban technology; climate change mitigation

1. Introduction

Amidst the climate crisis, cities worldwide are increasingly affected by the urban heat island (UHI) effect, which describes the phenomenon of higher temperatures in urban areas compared to their surrounding rural areas (Gunawardena et al., 2017; Levermore et al., 2018; D. Li et al., 2019; Sanchez-Guevara et al., 2019; Stone et al., 2012; Yu et al., 2020). With regard to UHI mitigation strategies, various measures were identified and conceptualised including urban design, cool building envelopes, high albedo materials, green roofs, green facades, shade trees, ground vegetation and waste heat (Akbari et al., 2012; Aleksandrowicz et al., 2017; Mirzaei & Haghighat, 2010; Ulpiani, 2021). Further, the political implementation of UHI mitigation outcomes is still under-researched due to a lack of understanding how research corresponds to the needs, priorities and limitations of the political domain (Aleksandrowicz et al., 2017). There are three stakeholder groups most relevant for mitigating UHI effects: (a) the government, including politicians acting at a local or national level; (b) the city administration, including city planners and public health officials; and (c) the inhabitants, as individuals or as societal groups living in the urban area (Hintz et al., 2018). The private sector is also important since most buildings are privately held, and many of the UHI mitigation solutions are produced by industry. Various methods are used to enhance UHI analytical techniques. These include using satellite images to analyse temperature patterns (Deilami et al., 2018), or to sense parameters that explain characteristics of UHI patterns related to the heat magnitude, the surface UHI magnitude and the land surface temperature (Ward et al., 2016). The UHI research has focused on different spatial scales, such as South Asia (Kotharkar et al., 2018), India (Veena et al., 2020), or Greater Kuala Lumpur (a.k.a. Klang Valley) (Ramakreshnan et al., 2018). Other studies focus on policy responses to UHI mitigation (Parsaee et al., 2019) as well as technological developments including active technologies, such as heating, ventilation and air conditioning (HVAC) systems related to building energy consumption (X. Li et al., 2019), and passive technologies, like thermal properties of asphalt concrete for cool pavements and roofs (Mohajerani et al., 2017; Santamouris, 2013, 2014), which can substantially contribute to reducing temperatures in urban environments.

We develop a novel framework drawing on existing literature reviews such as Santamouris (2014) and other academic works that discuss UHI policy and technology responses. Our framework explains how joint policy and technology interventions reduce anthropogenic heat and alleviate the incremental environmental burden. We include two different aspects to anthropogenic heat: (a) heat pollution from human activities, and (b) exacerbated heat “when vegetation and water bodies are replaced by materials such as concrete and asphalt, which have higher heat capacities and thermal conductivity” (Estrada et al., 2017, p. 403). Building on the proposed framework, we present 13 research questions to help guide future research on the synergistic effects of combined policy and technology interventions. This is much needed in UHI research because policy and technology are often developed in isolation of each other and not in conjunction; therefore, they have limited reaffirming effects when aimed at solving global issues. This is particularly true for UHIs, where both policy and technology responses are vital for mitigating their effect. To analyse this aspect, we conducted a systematic literature review with a focus on capturing the current understanding of policy and technology responses in mitigating the UHI effect. Previous literature reviews predominantly focus on policy and technology aspects separately, such as mitigation strategies for improved policymaking (Aleksandrowicz et al., 2017; Parsaee et al., 2019), or urban materials production and technical properties of cool surfaces (Qin, 2015; Santamouris, 2014). The current state of UHI research overwhelmingly looks at either policy or technology aspects, which we scrutinise in our literature review. We aim at combining both aspects for joint optimisation in a complex city context, where the isolation of policy and technology tends to increase deleterious effects on the city's performance (Patorniti et al., 2017).

This review conceptualises trends in policy and technology responses for UHI mitigation. It contributes to UHI research by combining both streams of mitigation strategies and proposing directions for future research to enable effective interactions between policy and technology. It affords the potential to reinforce the benefits of conjoining policy and technology responses and generate coordination effects (Arthur, 1988; Jänicke, 2015). To this end, policy refers to any course or principle of action to guide decisions to mitigate UHIs, while technology relates to any kind of object or system informed by scientific knowledge and crafted by human intervention. We include the policy arenas of urban planning, public health, as well as transport and land use policies. Our framework informs policymakers on the interaction of policy and technology, for which we propose action research as an adequate approach to develop policy processes to implement the different policies in city-level decision-making. We present study suggestions and key approaches at the end of our study.

The paper is structured as follows. After this introduction, we provide an overview of our approach to conducting the review, present the results of our literature search, and synthesise the literature by developing a concept matrix. Then, we discuss identified concepts including evidence base for policymaking identified in the literature review as well as policy and technology responses. Finally, we build on the insights from our literature review and present a conceptual framework of policy and technology responses in mitigating the UHI effect. Based on the proposed conceptual framework, we present directions for future research and close with conclusions.

2. Literature review

2.1. Methodology

We followed a four-stage guide (Okoli, 2015) for conducting a systematic literature review and begin with Stage 1, ‘planning’, where planning required the formulation of the purpose and the search strategy. In Stage 2, ‘selection’, we set up the selection criteria and justified the records for consideration and elimination. We compiled a database of records for consideration in the systematic review. In Stage 3, ‘extraction’, the review team labelled the records and extracted essential information for the systematic review. Finally, in Stage 4, ‘execution’, the systematic review was produced after processing the labelled records (see Fig. 1).

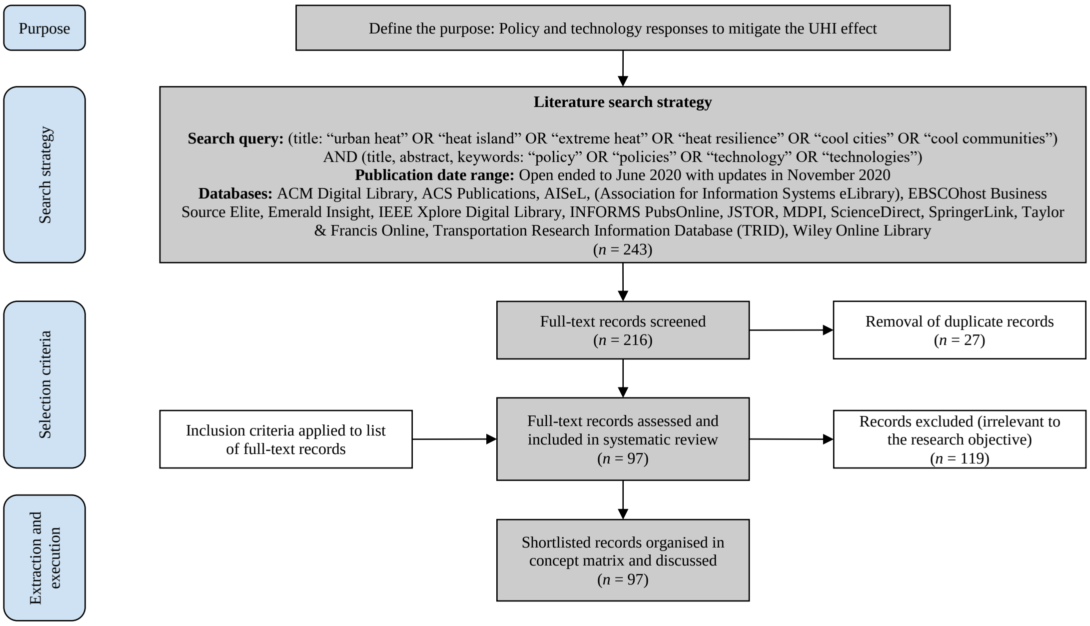

Fig. 1. The literature review search strategy.

In Stage 1, the purpose of the review was to identify the trends in policy and technology responses to mitigating the effects of UHIs. To ensure a clear scope within the boundaries of the chosen literature review methodology, we focused on academic literature. Nevertheless, we acknowledge existing practical literature produced for policymakers. For example, the *Cooling Singapore* project is developing solutions to address UHI challenges in Singapore and has identified 86 strategies to measure and mitigate the UHI effect, which are grouped into seven clusters in a published report: vegetation, urban geometry, water features and bodies, materials and surfaces, shading, transport and energy (Ruefenacht & Acero, 2017). Another report of the *Cool Neighborhoods NYC* project outlines efforts of the New York City (NYC) Government to tackle extreme heat, where mitigation, adaptation, and monitoring strategies are discussed, including tree planting, cool roof and pavement implementation, climate risk training for home health aides, and data collection and analysis strategies for health-focused climate policymaking (NYC Government, 2017). Since government reports are beyond the scope of our review of academic literature, we suggest future research to review and synthesise such reports and city policies, which we expect will provide practical recommendations for city policymakers to mitigate the UHI effect. As such, policy documents can list measures already taken, to be taken, or should be taken according to administrative bodies and policymakers.

In Stage 2, the literature search was conducted in June 2020 with updates in November 2020. The following search query string was used in database searches: (title: “urban heat” OR “heat island” OR “extreme heat” OR “heat resilience” OR “cool cities” OR “cool communities”) AND (title, abstract, keywords: “policy” OR “policies” OR “technology” OR “technologies”). The following databases were selected and searched: ACM Digital Library; ACS Publications, AISeL (Association for Information Systems eLibrary), EBSCOhost Business Source Elite, Emerald Insight, IEEE Xplore digital library, INFORMS PubsOnline, JSTOR, MDPI, ScienceDirect, SpringerLink, Taylor & Francis Online, Transportation Research Information Database (TRID), and Wiley Online Library. We excluded journals and conferences that were not indexed in these research databases to establish a valid search parameter. We acknowledge that as a result some outlets were not covered by our review such as the International Conference on Countermeasures to Urban Heat Islands (IC2UHI). However, including those would exceed the scope of our review; therefore, we decided it would be reasonable not to consider them. Our search returned 243 articles in total, and 27 duplicates were removed.

We defined selection criteria based on the review's stated purpose, and records (*n* = 119) were excluded based on the following reasons:

- The papers articulated the findings of the measurement, modelling, simulation and tracking of a UHI using a variety of research methods. We excluded this body of research since it has been discussed in detail in other systematic reviews (Huang & Lu 2018). These records also did not make distinctive policy or technology inferences to mitigation tactics and were excluded (*n* = 83).
- The papers discussed other issues related to UHIs that did not directly relate to policies or technologies deployed to mitigate the UHI effect (*n* = 36).

Records were captured in a database during Stage 3 and were processed and labelled. We followed guidelines by vom Brocke et al. (2015) to screen the literature for applicability based on the keywords that we used to search for literature as a coding scheme. We documented the screening process in Microsoft Excel and as we screened each article, we compiled a concept matrix identifying the following categories: (a) evidence base for policymaking including timescale analysis, effective policymaking instruments as well as decision support and scenario planning; (b) policy responses including landscape and urban form, green and blue area ratio, albedo enhancement policies, transport modal split as well as public health and participation; (c) passive technologies including green building envelopes and development of cool surfaces; and (d) active technologies including sustainable transport as well as energy consumption, HVAC and waste heat. We also included research aim, region and Köppen climate classification (where applicable). We utilised Microsoft Excel's Pivot Table functionality to view the different relationships among the records under review.

2.2. Results of the systematic literature search

Based on our systematic literature review, the shortlisted records (*n* = 97) were considered in this study. Most records were retrieved from the following sources: ScienceDirect (*n* = 38), SpringerLink (*n* = 35), and Taylor & Francis Online (*n* = 11) (see Fig. 2). Most of the shortlisted articles (*n* = 72, or 74%) were published from 2015 on and can, therefore, be considered very recent.

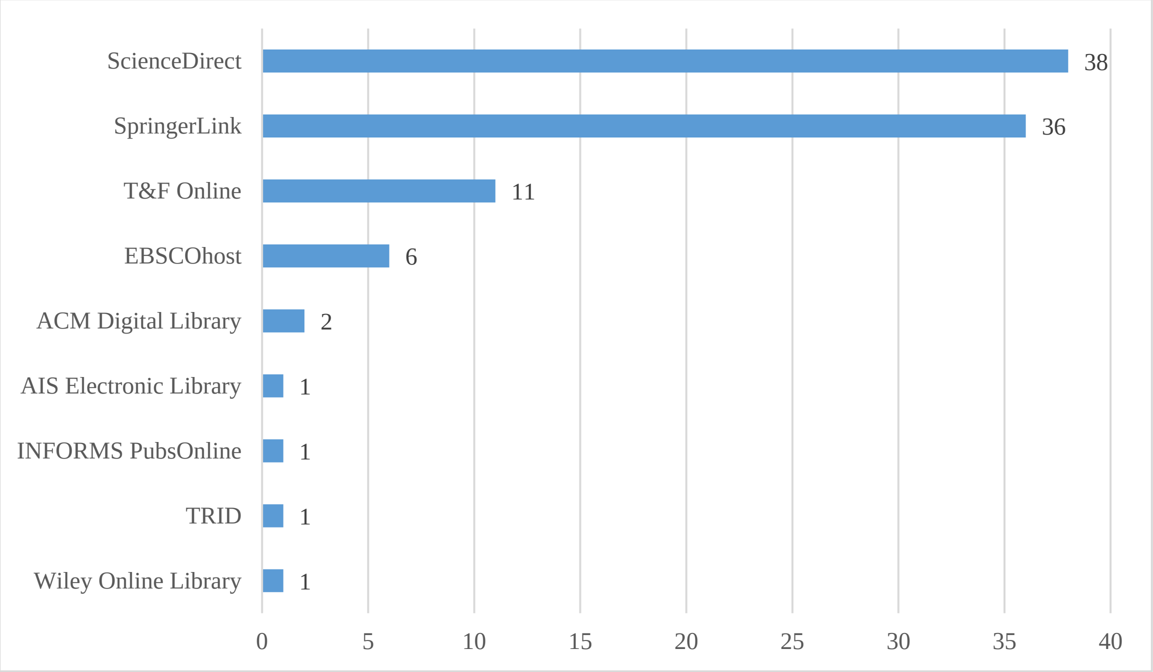

Fig. 2. Records retrieved from selected databases.

Most records (n = 63, or 65%) focused on a specific region and these were further classified under the Köppen climate classification. The studies were mostly conducted in Cfa/*Humid subtropical climate* (n = 22), Cfb/*Temperate oceanic climate* (n = 12), Csa/*Hot-summer Mediterranean climate* (n = 8), BWh/*Hot deserts climate* (n = 6) and Dfb/*Warm-summer humid continental climate* (n = 4) (see Fig. 3).

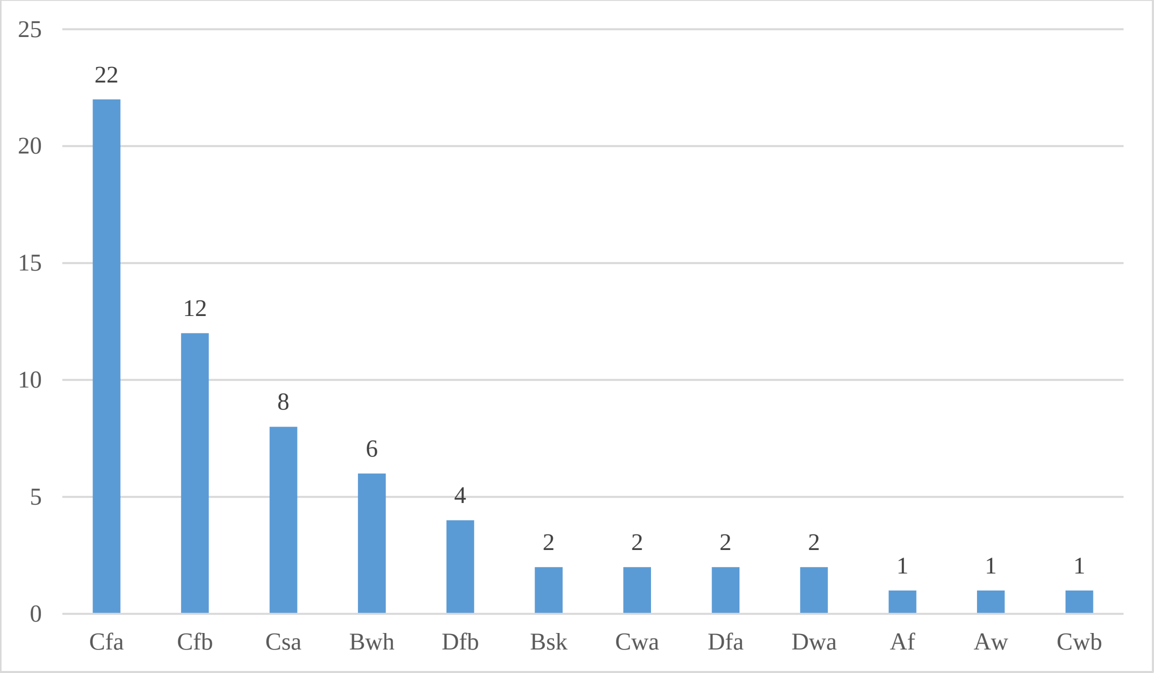

Fig. 3. Köppen climate classification of selected records.

We further classified the identified regions under the World Bank Country Income Classification. The studies were carried out in high-income (n = 54), upper-middle-income (n = 9), lower-middle-income (n = 2) and low-income (n = 1) countries. We further classified the geographic distribution of authors (see Fig. 4). Based on the 97 articles, we identified 362 authors from 30 countries of whom five had multiple affiliations.

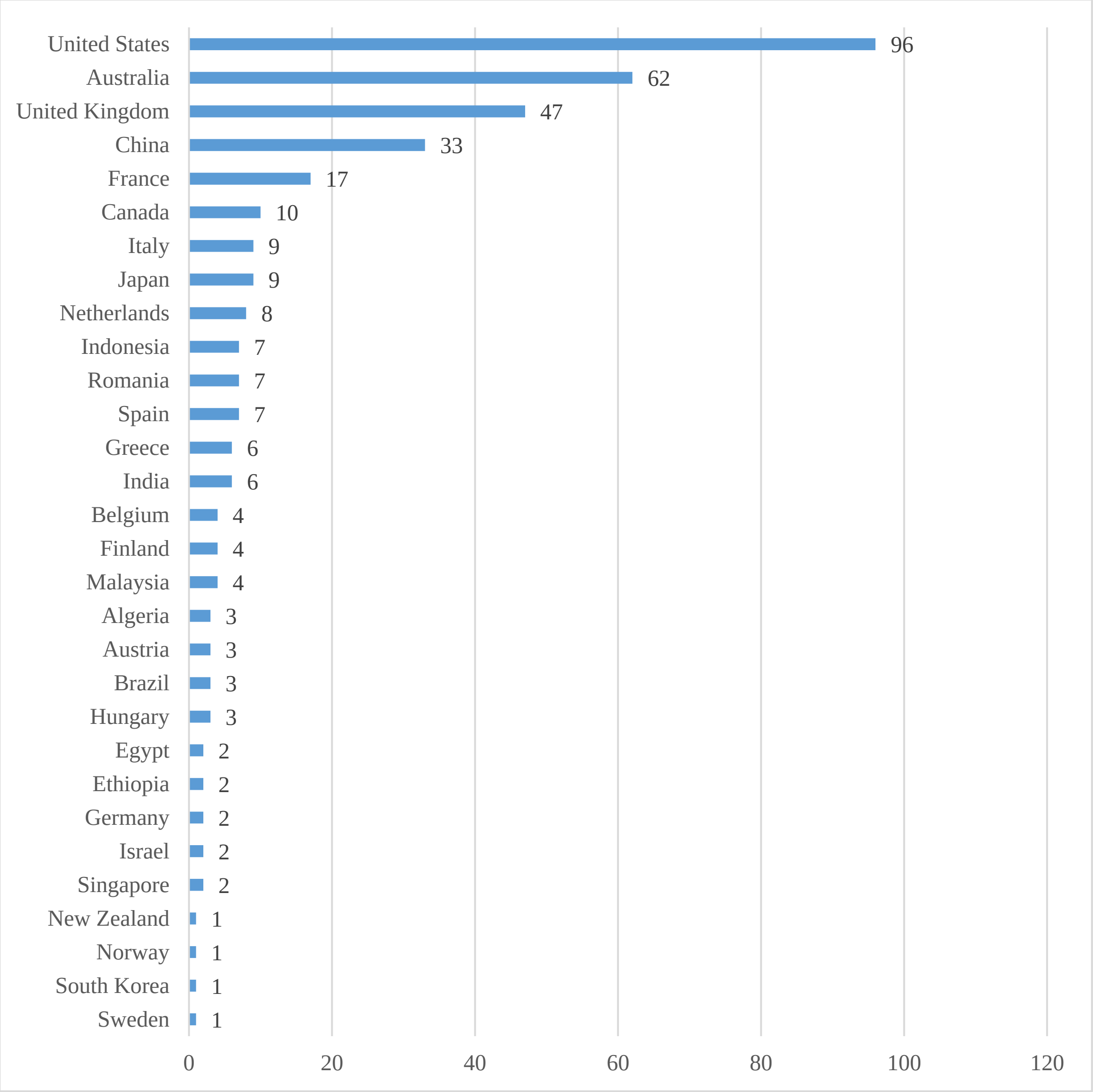

Fig. 4. Geographic distribution of authors.

In Stage 4, we synthesised the selected literature by discussing each identified concept, which allowed us to compile a concept matrix (Webster & Watson, 2002). We followed a logical approach to grouping the key concepts and uncovered further dimensions to detect units of analysis. We included concepts receiving major focus in five or more of the reviewed articles. Additionally, we included transportation because currently it plays an underrated role in the UHI context, which is anticipated to increase in the future (Louiza et al., 2015; Wagner & Viswanathan, 2016). The concept matrix in Appendix A provides an overview of the literature and the concepts.

2.3. Discussion of identified literature

2.3.1. Evidence base for policymaking

The majority of UHI research over the past three decades has been in the domain of modelling, simulating and tracking the UHI phenomenon (Deilami & Kamruzzaman, 2017; Huang & Lu, 2018). Due to our focus on policymaking, we excluded these technical aspects of UHI research and only focused on the technology aspects that are relevant for policymaking. In this regard, we have identified three areas of evidence base for policymaking: timescale analysis, effective policymaking instruments as well as decision support and scenario planning.

2.3.1.1. Timescale analysis

Policymakers have a range of methodologies to track the spatiotemporal changes in UHIs. It is essential to note the variety of timescale analyses deployed. Timescale analysis allows policymakers to understand spatiotemporal variable conditions of the UHI over the long term and track the UHI intensity and heat stress over shorter periods.

For example, a short-term numerical simulation in a Chinese city reveals a significant peak in heat stress during rush hour in the diurnal cycle of UHI intensity (Gao et al., 2017). Policymakers could use these data to improve early warning systems in such scenarios. Longitudinal studies are helpful to measure and track UHIs over space and time. In Delhi, researchers utilised the UrbClim (urban climate) model to project short-term climate change projections to forecast near-future (2026–2045) and far-future (2081–2100) changes with a focus on ten extreme heat indices (Sharma et al., 2019). These data were useful in the drafting of shorter-term climate resilience and adaptation strategies.

Timescale analysis also supports policymakers to identify the land uses that have the most influence on UHIs. For example, research showed that an industrial park was the most vulnerable urban precinct when changes in the UHI were measured over the period 1980–2011 by a spectral mixture analysis based on Landsat images (Henits et al., 2017). A study on the UHI of two American cities over the period 1984–2016 argued for closer attention to urban growth patterns, also called urban morphology (Mbuh et al., 2019). Policymakers are therefore required to understand the thermal qualities of different land uses and the variance that atmospheric humidity plays (Roy & Singh, 2015).

2.3.1.2. Effective policymaking instruments

Concerted efforts to combine climate resilience interventions with UHI mitigation strategies results in multi-sector and multi-dimensional policy interventions (Santamouris et al., 2019). In China, the so-called ‘sponge cities’ policy adopted in 2014 seeks to implement a range of surface water retention and related runoff management approaches. He et al. (2019) investigated the co-benefits of this policy as it pertains to UHI mitigation and discussed their findings in five dimensions: social, economic, political/institutional, climate-related and building. A framework based on the policy analysis informs stakeholders to address the urban flooding problem and manage increasing urban temperatures. Pathways to co-benefits from the implementation of sponge city and UHI mitigation strategies are proposed because policymakers should develop a synergistic technical system, define integrative plans and policies, communicate among different departments and various stakeholders, and implement pilot projects for quantifying and optimising a co-benefits approach. He et al. (2019)

conclude that the sponge city approach is an opportunity to technically mitigate UHI effects with higher compatibilities in cool pavement and green infrastructures.

Other studies focus on specific policies, such as an analysis of a tree protection policy in Woodlands Township in Texas, which consists of tree removal permits and minimum tree and shrub cover regulations (Sung, 2013). Here, the effect of the policy is analysed on UHI mitigation by comparing the mean land surface temperatures derived from thermal infrared bands of Landsat TM images between the Woodlands' neighbourhoods and nearby control neighbourhoods without a tree protection policy. Results show that the Woodlands' neighbourhoods were 1.5–3.9 ºC lower on average than those of the control neighbourhoods, providing evidence of the mitigative impact of such policies. The study concludes that a local tree protection policy is effective in UHI mitigation at the neighbourhood scale, and further suggests that the cooling effect of the Woodlands' tree protection policy was more prominent in summer when UHI mitigation was needed most. There are other projects assessing the role of trees in addressing air pollution and UHIs; for example, *The Nature Conservancy* published a report where tree planting policies are discussed as a cost-effective solution to improve health and tackle UHIs (McDonald et al., 2016).

These exemplary studies show that policy analysis has been conducted mostly on a regional scale. Thus, we propose that our framework of policy and technology responses will help policymakers to mitigate the UHI effect on a broader scale and guide researchers for future policy analysis.

2.3.1.3. Decision support and scenario planning

Policymakers require active community engagement, decision support and scenario planning systems premised on scientific data used in the simulation and assessment of UHIs. With such scientific data at hand, it is argued that a more dynamic relationship is required between urban climate knowledge and the formulation of urban development plans and actions (Parsaee et al., 2019). Community participation systems informing local mitigation strategies remain weak in Canadian cities (Parsaee et al., 2019). The portrayal of the UHI in popular media was studied in Australia and overall there was positive reportage on actions to mitigate the UHI effect (Iping et al., 2019). The tone and language of communicating scientific knowledge are marked by words such as ‘the apparent’ or ‘so-called’ UHI, which “highlights that climate change is still a politicised term within media at various scales” (Iping et al., 2019, p. 427). In New York, localising global climate change science requires co-production between stakeholders since interventions are not divorced from their social settings (Corburn, 2009). Including essential stakeholders such as utility companies in decision-making can account for shared benefits of UHI mitigation strategies, in this case, ‘cool city’ programs, and can be quantified in cost–benefit tests (Shickman & Rogers, 2019).

It is therefore essential that urban climate knowledge is incorporated within the planning and action strategies of local councils, which has an implication on budgeting and performance management. A response to this challenge shows that the design of an optimisation model for decision support can maximise revenue for selling or leasing land to developers while limiting the UHI intensity to find an optimal balance between buildings and vegetation in urban planning (Tuczek et al., 2019). It is argued that such a tool must “show city planners, based on quantitative values, that it is necessary to integrate appropriate countermeasures of the UHI effect, such as the integration of vegetation zones in the relevant districts” (Tuczek et al., 2019, p. 11). Social computing could support the response to the wicked problem of UHIs in terms of data sharing and interactive forums (Kuznetsov & Tomitsch, 2018).

A similar model was developed to assess the impact of different urbanisation patterns on Amsterdam’s UHI (Koomen & Diogo, 2017). Such decision support models are usually underpinned by defining the appropriate indicators ‘rolled up’ into a performance framework, which is utilised to compare results and create a community of practice to refine these management strategies (Echevarría Icaza et al., 2016). Decision-makers should also be aware that a mix of science and user-generated data might enhance the responsiveness of urban interventions. One such example is *Smart Community Centric Urban Thermal Sensing*, first tested in Georgia, United States, where crowdsensing data and a community engagement strategy were incorporated into the data mix for improved decision-making (Tonekaboni et al., 2018).

2.3.2. Policy responses

In this section of the literature review, we discuss the policies deployed in mitigating UHIs. The five overarching topics in this discussion are: (a) landscape and urban form, (b) green and blue area ratio, (c) albedo enhancement policies, (d) transport modal split, and (e) public health and participation.

2.3.2.1. Landscape and urban form

The natural landscape and form of cities have a causal relationship with land surface temperatures observed over space and time. Urban densities, the direction and strength of seasonal variations in wind, the sky-view factor (a measurement of urban microclimate at scales below 100m) and the proportion of open spaces among buildings have an influence on the intensity of the UHI (Chun & Guldmann, 2018; Wang & Akbari, 2016). Denser city centres tend to have higher levels of UHI intensity due to the compact nature of build-to-open-space ratio (Connors et al., 2013). Urban planners and policymakers utilise urban design, land-use controls and spatial planning strategies to ensure the balance between the built environment, street widths, open spaces, permeable surfaces and transportation options, resulting in a naturally ventilated and cool city centre (Koomen & Diogo, 2017). The architectural form in cities with an already existing UHI is also vital to ensure thermal comfort, as researchers found in their assessment of indoor climate variations in London (Oikonomou et al., 2012) and Paris (Dhalluin & Bozonnet, 2015).

Cities characterised by low-density residential sprawl might measure a lower UHI effect than more compact and dense city centres, explained by the higher proportion of open spaces and permeable surfaces, but this does not necessarily result in more sustainable cities and energy use (Kohler et al., 2017). In Brisbane, researchers tested the land-use scenarios of transit-oriented development—or, intensifying land use in compact development in close proximity to public transport interchanges—and found that infill development or brownfields regeneration were the most productive forms of land use to maximise compact development within the bounds of the UHI (Deilami & Kamruzzaman, 2017; Kamruzzaman et al., 2018). When policymakers consider UHI mitigation measures early in the design process, as observed in the case of the London Olympic Village, urban regeneration can contribute to the cooling of cities (Hamilton et al., 2014). Such positive outcomes benefit greatly from multi-disciplinary teams, including built environment professionals, economists and climate scientists, who improve the UHI policy response in terms of materials, technologies and practices (Golden, 2004). For example, from an economic point of view, considering the benefit–cost ratio for urban planning policies helps to calculate differences of net benefits and aggregated costs of implementing various policy options to assess economic impacts caused by UHIs (Estrada et al., 2017).

2.3.2.2. Green and blue area ratio

The so-called ‘cool islands’, including green and blue spaces but also urban design and other strategies, are responsible for offsetting UHIs. Consider the thermal qualities of Central Park in New York and the River Thames in London. With regard to green spaces, Gaffin et al. (2008) looked at the effect of Central Park and studied the UHI of New York during the 20th century (i.e., 1900–2000). They found that the average annual temperature in the vicinity of Central Park increased from 11.6°C in 1900 to 13.1°C in 2000. The historical data revealed that the UHI was responsible for 33% of the overall warming of the city. An essential contribution of this study was to contest the findings of Peterson (2003), who disputed the formation of UHIs in other American cities such as Boston, Dallas and Seattle. In those cities, the influence of other microclimate 'inhomogeneities' such as rural elevation was suggested would dispel the UHI effect.

Regardless of such variations in microclimatic factors, it has been proven that provisions for green (e.g., parks, forests, riverbanks, biodiverse regions) and blue (e.g., water bodies such as rivers, lakes, ponds, wetlands) infrastructure remains the most effective measures in cooling UHIs (Gunawardena et al., 2017; Teferi & Abraha, 2017). During periods of heatwaves and the intensification of UHIs through anthropogenic heat generation, healthy ecosystems provide essential services to moderate the microclimates found in cities (Jenerette et al., 2011; Marando et al., 2019). Not only do these existing natural environments contribute to UHI cooling, but large-scale landscaping projects act as natural heat sinks (C.-f. Li et al., 2014; Vasilakopoulou et al., 2014). Cities have recognised these benefits; for example, Paris has added nearly 70 hectares of green infrastructure and rooftop gardens to reduce the UHI effect (C40, 2015). However, the effect of parks and water on a UHI depends on the size of these spaces, where depth plays a major role (Targino et al., 2019; Xiao et al., 2018; Zhu & Jia, 2011).

In environments of constrained resources and the limits of ecological services, policymakers strive to achieve co-benefit agreements when considering the impact of urban development. In China, a focus on sponge city policies has been an effective integrated planning approach to achieve such co-benefits (He et al., 2019). In other cases, adopting policies aimed at water-sensitive urban design and urban-greening policies can result in innovative projects such as *Park Cool Islands* and the reforestation of cities, and these ‘green lungs’ effectively become networks of green spaces that are equally enjoyed by city dwellers as recreational areas (Hiemstra et al., 2017; Jamei & Tapper, 2019). Hence, policy instruments such as tree protection policies (Sung, 2013) and wetland protection policies (Cai et al., 2016) are essential in maintaining quality green and blue spaces. Policymakers should also consider the water use requirements of maintaining ecological services since scenarios of urban densification include evaporative cooling, shading and reflectance, which are all factors that influence the general albedo of cities (Gober et al., 2009; Lemonsu et al., 2015).

2.3.2.3. Albedo enhancement policies

Albedo refers to the energy balance of the earth’s surface, which is defined by the equation $(1 - \alpha_{abs})$, where α_{abs} is the absorptivity of the surface (Abd El-Hakim & El-Badawy, 2019). Therefore, albedo is measured on a scale between 0 and 1, where a surface with 0 albedo is perfectly absorptive and a surface with an albedo of 1 is perfectly reflective. The high proportion of dark paved surfaces (often asphalt), such as pavements and roads, which can account for up to 20–40% of a typical city’s area (Qin, 2015), results in heat storage and aggravates the UHI (Vasilakopoulou et al., 2014). Policymakers have a range of options to increase the albedo factor by using available and novel approaches. Urban greening policies have an albedo enhancing effect. In Montreal, researchers found that three main UHI mitigation measures of urban canopy, urban vegetation and light paved areas increased the city’s albedo factor when assessed against the sky-view factor control and wind speed (Wang & Akbari, 2016).

Microclimate simulations can help to generate a multi-criteria ‘cool city model’ when the variables of cool pavements, cool roofs and vegetation variables are considered (Wang et al., 2016). Such simulation models can support urban planners and policymakers to justify the investment in albedo enhancing projects.

2.3.2.4. Transport modal split

Cities prioritising investments in public transport aim to achieve a modal split where more commuters opt for public transport options. An overreliance on private car policies, which reinforce road construction projects and low residential density sprawling neighbourhood extensions, result in increased fuel consumption, greenhouse gas emissions, and pollution in cities (Kamruzzaman et al., 2015). It has been established that heat transfer and radiation of these emitting vehicles are negative side effects of congestion and intensify the UHI (Louiza et al., 2015). A simulation of transportation options in Beijing found that the greatest UHI intensity mitigation effect for transport was to replace conventional vehicles with energy-efficient public transport (Kolbe, 2019).

Transport policy also has an influence on land use planning. In Brisbane, Australia, five alternative neighbourhood planning scenarios aligned with smart growth policies were simulated against UHI mitigation: (a) business as usual, (b) transit-oriented development, (c) infill development, (d) motorway corridor-oriented development, and (e) sprawl development (Deilami & Kamruzzaman, 2017). Results from a geographically weighted regression analysis showed that the infill development scenario as a smart growth policy has a marginally better potential to mitigate the UHI effect in Brisbane in 2023 compared to the sprawl development scenario.

Transport policies such as transit-oriented development are generally preferred over low-density urban sprawl but do not necessarily reduce the UHI. A balancing act is therefore required between natural and built-up areas (Kamruzzaman et al., 2018). Numerical and multi-criteria models are also useful to test various scenarios informing policy choices related to power consumption, transportation options and their relationship with land use (Silva & Fillpot, 2018). However, the issue is much more complex due to the transportation system's high dependence on the city's layout, which in turn varies across the globe (Xu et al., 2020; Yang & Gakenheimer, 2007).

2.3.2.5. Public health and participation

During climatic periods where the UHI intensifies through heatwaves, vulnerable populations are at risk, and this poses a public health policy challenge. This is particularly relevant in pandemic outbreaks such as COVID-19, which require an urgent need for enhanced urban monitoring and coping strategies to improve urban resilience and environmental quality (Ulpiani, 2021). In this regard, extreme heat exposure has important implications for health costs and delivery quality, imposing a substantial economic burden on healthcare systems (Si et al., 2019; Wondmagegn et al., 2019). A review of the literature suggests that UHI mitigation strategies have a positive impact on public health (Heaviside et al., 2017). In Finland, a risk mapping was conducted, considering five different zoning options; 11 different weighting options were applied to assess vulnerability, for example, to elderly people prone to dehydration and heat stress, which leads to serious health implications (Räsänen et al., 2019). Such data support policymakers to target relief efforts. Vulnerability is also the focus of another study that finds tensions between addressing heat as an emergency and heat as a source of chronic stress, which affects people's health as well as physical and mental well-being (Bolitho & Miller, 2017). In Madrid, it was found that low-income households that cannot afford to regulate their indoor temperatures using, for example, air conditioning, face overheating problems in periods of UHI intensity, which has an adverse effect on public health (Sanchez-Guevara et al., 2019).

Heatwaves caused by anthropogenic emissions of greenhouse gases and the expansion of UHIs through rapid urbanisation (Sun et al., 2014) have a substantial effect on a variety of health outcomes from mortality to mental stress. For example, the 2011 heatwave in Houston, Texas, led to a 3.6% excess risk in emergency department visits and a 0.6% increase in mortality risk (Zhang et al., 2015). Elderly patients are particularly at risk of exposure to adverse health conditions during hot periods, such as dehydration, hyperthermia, malaise, hyponatremia, renal colic, and renal failure (Josseran et al., 2009). Heatwaves have also been shown to lead to mental health illness (Thompson et al., 2018), particularly during the COVID-19 pandemic, where heat stress affects cognitive and physical performance (Davey et al., 2020). An increase in research dealing with heatwave resilience and health implications can be expected due to the stimulus of current and anticipated pandemics.

2.3.3. Technology responses

In this section of the discussion, we consider technology responses to the UHI effect. We classify these technologies as passive and active and indicate the interrelationships between policy formation and technology development in attempts to mitigate UHI effects. In this regard, passive technology usually has a single function, such as pavements and roofs in the urban context, while active technology is multi-functional, such as HVAC systems, allowing users to interact with multifaceted functions. In our policy-focused review, we identified green building envelopes and cool surfaces as the main passive technologies discussed in the identified literature, and sustainable transport and HVAC systems as the main active technologies.

2.3.3.1. Passive technologies

2.3.3.1.1. Green building envelopes

The thermal comfort and qualities of buildings can either neutralise or aggravate the UHI since HVAC systems are energy-intensive and create anthropogenic heat (Oikonomou et al., 2012). In the United Kingdom, researchers tested passive design solutions for natural ventilation by using thermal modelling to measure the performance of non-domestic buildings (Short et al., 2004). In California, a review of ‘cool community’ interventions resulted in community co-benefits including reduced utility bills, improved air quality and enhanced urban liveability (Gilbert et al., 2016). Greening building envelopes are therefore not only important to increase urban sustainability and metabolic flows but innovations such as green roofs in combination with albedo modification (for example, lighter walls) deliver a cooling effect (Lehmann, 2014; Price et al., 2015). Four building materials (brick, aerated concrete, wood with glass-wool insulation, and glass fibre-reinforced concrete with glass-wool insulation) were tested to assess thermal qualities of buildings in existing UHIs in a tropical climate (Wonorahardjo et al., 2020).

2.3.3.1.2. Development of cool surfaces

The albedo of buildings can also be increased through reflective building materials, and the effectiveness of these materials coincide with other factors such as building characteristics, urban environment, meteorological and geographical conditions (Dizdaroglu et al., 2012; Yang et al., 2015). A low albedo and high ratio of impervious surfaces perpetuate the UHI, and technologies have been developed to cool down urban surfaces. To develop effective technology responses to heating surfaces, it is important to address the thermal properties of urban materials. Besides absorptivity and emissivity, which are independent of each other and describe the absorption of radiation energy from the sun and the ability to emit infrared energy, albedo plays an important role in the UHI context. It is important to take albedo into consideration in passive technology development because the albedo of pavement surfaces differs substantially given the materials used in construction. In Atlanta, future urban development could increase the proportion of dark-coloured pavements by 45% over 10 years, reaching two-thirds of impervious surfaces. To counteract this low albedo, researchers recommend that light surfaces be selected to increase albedo (Lee & French, 2009). Cool pavements with technologies such as sustainable urban drainage (consisting of bioswales, permeable paving, wet basins, and flower beds) are effective in mitigating the UHI effect (Dwivedi et al., 2019). Studies in Paris have demonstrated that regular pavement watering can also increase albedo and mitigate heat stress (Hendel et al., 2016).

Furthermore, anthropogenic heat generation can be mitigated by increasing the earth's albedo factor through renewable energy infrastructure such as solar panels (Rossi et al., 2013). Cool roofs are perhaps the most globally applicable cooling intervention to mitigate UHI and increase the reflection of incoming solar radiation in urban areas by increasing the albedo of roof surfaces (C.-f. Li et al., 2014). Technology development can look into the design and materials of cool roofs, which are single ply or liquid applied, including white paints, elastomeric, polyurethane or acrylic coatings (Santamouris, 2014). In Beijing, researchers tested a willingness-to-pay valuation approach for cool roofs with building tenants, and it was found that government credibility and education are important factors in promoting public participation (Zhang et al., 2019).

2.3.3.2. Active technologies

2.3.3.2.1. Sustainable transport

Since urban transport contributes to the formation of UHIs, making transportation more sustainable is a technological challenge to support UHI mitigation (Louiza et al., 2015). A comparison of different transport technologies including internal combustion engine vehicles, electric vehicles, hydrogen vehicles and public transportation shows the impact of different mobility concepts on UHI mitigation and carbon dioxide emissions (Kolbe, 2019). It is argued that the release of heat from combustion engines intensifies the UHI effect, and a scenario analysis in Kolbe's study finds that the largest UHI mitigation is in a scenario where conventional vehicles are replaced with energy-efficient metro travel; the saving potential for carbon dioxide emissions is highest for electric vehicles with renewable electricity generated from wind turbines, closely followed by hydrogen vehicles that are fuelled with hydrogen generated from the electrolysis of water using wind electricity (Kolbe, 2019). While Kolbe's study only looked at wind and hydro energy, we acknowledge that other renewable sources such as solar energy might lead to similar results. In our review, we found very little research on the impact of transportation on UHIs. Therefore, we suggest that future research delves deeper into the role of transport in mitigating the UHI effect because two areas that are considered to be the largest contributors to an increase in UHI effects are the built environment and transportation (Wagner & Viswanathan, 2016).

2.3.3.2.2. Energy consumption, HVAC and waste heat

HVAC systems play an important role in urban energy consumption because through the densification of cities, the overall energy consumption increases, and HVAC systems significantly contribute to the increase of energy consumption as their load increases with warming (Louiza et al., 2015). Hence, there is a requirement to advance the technological capabilities of HVAC standards to enhance energy efficiency. Based on a study in Mumbai, a combination of HVAC usage and structure cooling (which prevents heat from entering living spaces through a system of pipes that absorb heat from the building structure) can significantly reduce the load on HVAC systems, resulting in a substantial reduction of energy consumption (Dwivedi et al., 2019). Other studies look into how urban-sprawl countermeasures influence UHI intensities and energy demands for space heating buildings (Kohler et al., 2017), or how UHI impacts state residential energy costs and carbon dioxide emissions (Roxon et al., 2020).

From a technology development point of view, it is promising for UHI mitigation in hot regions to design HVAC systems that are more efficient under hot conditions to mitigate peak load during extreme heatwaves (Burillo et al., 2019). The current standards EER (energy efficiency ratio) and SEER (seasonal energy efficiency ratio) are primarily for air temperatures at or below 35°C. Another important aspect is waste heat from HVAC systems, which requires technological upgrades for the waste heat collection through improved insulation and tightness to limit heat loss (He, 2019). Waste heat intensifies the local air temperature contributing to UHI effects and increasing the probability of extreme heat (Olivo et al., 2017). Our review reveals that energy consumption, HVAC and waste heat appear to be marginal topics in the UHI literature. Due to the critical importance of these topics for UHI intensification, we suggest that future research should place greater emphasis on this area.

2.3.4. Literature including both aspects of policy and technology responses

Our literature review reveals that policy and technology responses are loosely interlinked in the current UHI literature. Out of the 97 identified studies, we found only five with a major focus on both policy and technology aspects. Four of these articles concentrate on landscape and urban form, green and blue area ratio, and albedo enhancement policies from a policy response perspective; and from a technology response view, the articles focus on green building envelope and development of cool surfaces. One article considers transport modal split as a policy response, and sustainable transport from a technology aspect. Below, we describe how policy and technology are integrated in these articles. A count of policy and technology aspects for all articles is included in the concept matrix in Appendix A.

- Dhalluin and Bozonnet (2015): Analysis of the awareness and consideration level of UHI constraints by organisations that influence the design of building hosting sensitive people to high temperature (nursery, retirement homes).
  Policy focus: Landscape & urban form. Regulatory issues of national and international policies are analysed. The focus is on different schemes and plans including SRCAE (Regional Climate, Air and Energy Scheme), PCET (Territorial Climate Energy Plan), SCOT (Territorial Coherence Scheme), and PLU (Local Urbanism Plan). The study is conducted for the French Ministry of Ecology, Sustainable Development and Energy (MEDDE) and recommendations are given to improve policymaking.
  Technology focus: Green building envelope, development of cool surfaces. Passive technologies in ten French cities are analysed including vegetation (green space, green screens and roofs) and specific coatings on facades and roofs (variation of radiative properties by using different colours and materials).

- Gober et al. (2009): Investigation of trade-offs between water use and nighttime cooling inherent in urban form and land use choices.
  Policy focus: Landscape & urban form, green & blue area ratio, albedo enhancement policies. The study builds on identified shortcomings of the downtown redevelopment policy of the city of Phoenix, AZ and provides implications for the City of Phoenix Water Services Department.
  Technology focus: Development of cool surfaces. Passive technologies are

investigated regarding attributes of the surface in Phoenix with a focus on planting more trees and other irrigated vegetation to prevent daytime heat storage and facilitate nighttime cooling, which requires water resources that are limited in a desert city like Phoenix.

- He et al. (2019): Examination of co-benefits for policymaking of UHI and urban flooding management.
  Policy focus: Landscape & urban form, green & blue area ratio. The study builds on the policy of the Ministry of Housing and Urban-Rural Development of China (MOHURD) “Construction guideline of sponge city in China–low impact development of the stormwater system (trail)”.
  Technology focus: Development of cool surfaces. Technical codes for roof engineering and technical specifications for asphalt and concrete pavements as well as green roofs are examined. To facilitate co-benefits, a synergistic technical system is suggested due to commonalities but also differences between the techniques and performances of UHI and sponge city management.

- Hendel et al. (2016): Conduct of an experiment in Paris, France on differences between watered and dry portions of a street to examine the effects of watering to reduce maximum daily heat stress.
  Policy focus: Landscape & urban form. The study is providing recommendations for improved policymaking for the Water and Sanitation Department of the City of Paris.
  Technology focus: Development of cool surfaces. Pavement-watering materials are analysed including road materials and impervious asphalt concrete.

- Kolbe (2019): Examination to what extent a range of different mobility concepts can lead to a reduction in UHI intensity and carbon dioxide emissions in the city of Beijing, China.
  Policy focus: Transport modal split. Recommendations for policymakers are given in three different scenarios to discuss the impact of a transition from conventional vehicles to electric vehicles.
  Technology focus: Sustainable transport. Technical characteristics between conventional vehicles and electric vehicles are compared including fuel efficiency and heat emission to assess a reduction of UHI intensity.

Further, in the identified literature the evidence base of timescale analysis, effective policymaking instruments as well as decision support and scenario planning is mainly used. Nevertheless, using this evidence base comes with limited possibilities to analyse policy and technology responses in conjunction. We propose that further research methods and approaches will be necessary to help establish intervention cycles to evaluate coordination effects of policymaking in conjunction with technology development in order to address responses to UHI mitigation more effectively. We explain our directions for future research along with our conceptual framework in the next section regarding the use of different types of research methods to analyse policy and technology responses, as well as regarding how to overcome the lack of interaction between policy and technology responses to UHI mitigation.

3. Conceptual framework and directions for future research

3.1. Framework and purpose of research questions

Based on the systematic literature review, we conceptualise the impacts of policy and technology interventions on anthropogenic heat and incremental environmental burden (Fig. 5).

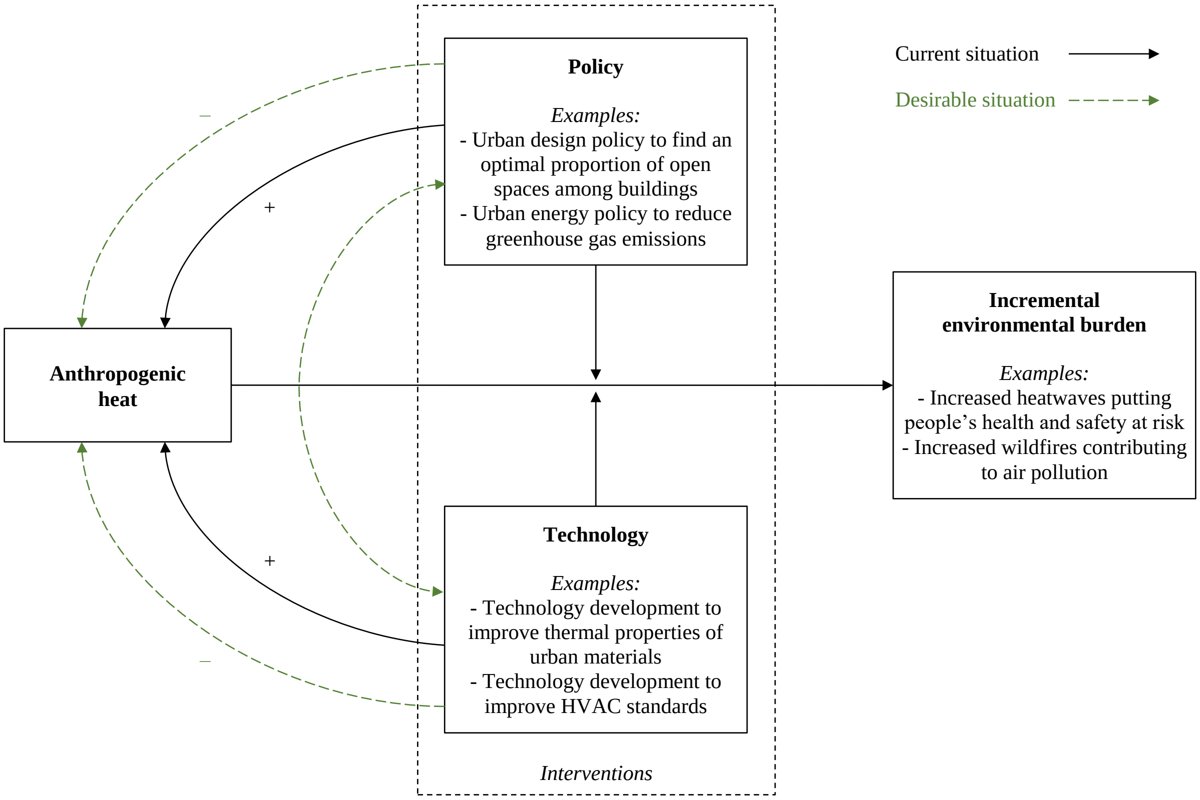

Fig. 5. Conceptual framework of the interplay between policy and technology interventions to reduce anthropogenic heat and alleviate incremental environmental burden.

We propose that a lack of interaction between policy and technology responses will lead to limited effects to mitigate heat and environmental burden, while effective interactions will reinforce the benefits of conjunction and generate coordination effects (Arthur, 1988; Jänicke, 2015). The framework informs future research on the direct effects of policy and technology on anthropogenic heat (Mortoja & Yigitcanlar, 2020), and the moderating effects on the relationship between anthropogenic heat and incremental environmental burden. Our main assertion is that policy and technology are often developed in isolation, which is evident in the current state of UHI research (see, e.g., Aleksandrowicz et al., 2017; Hintz et al., 2018; Parsaee et al., 2019).

Our proposed questions will inform future UHI research in four main areas: (a) coordination effects of policy and technology responses, (b) synergistic effects of combined policy and technology interventions, (c) aggravating effects of poor policy and technology responses, and (d) moderating effects of policy and technology responses on the relationship between anthropogenic heat and incremental environmental burden. Our study revealed that all of these four areas are currently under-researched and require focal attention due to two reasons. First, an extension of knowledge in these areas will help to tackle UHI-related issues because policy and technology synergies can increase the effectiveness of UHI mitigation strategies, aggravating effects of poor policy and technology responses are a real-world phenomenon that needs our attention, and our understanding of the incremental environmental burden due to UHI intensification is currently limited. Second, in UHI research, we have currently reached a certain level of saturation in other important areas including the conceptualisation of UHI mitigation strategies, the classification of UHI analytical techniques, and the analysis and comparison of global UHI characteristics. However, there is still a wide gap in our regional/local specific understanding of what mix of strategies should be implemented in the most effective and viable way. While we believe that these important areas need continuous attention, we suggest that our proposed areas can be combined because coordination, synergistic, aggravating, and moderating effects can be looked at from different angles, including conceptualising UHI mitigation strategies, classifying UHI analytical techniques, and analysing global UHI characteristics. For example, one combination opportunity is to conceptualise policy and technology synergies for UHI mitigation strategies; another opportunity involves investigating analytical techniques to counteract the aggravating effects of poor policy and technology responses. Regarding global UHI characteristics, we can expect that there will be regional differences regarding coordination, synergistic, aggravating, and moderating effects, which provide further opportunities for future UHI research.

3.2. Effects of policy and technology responses

The first question refers to the use of different types of research methods and approaches to analyse policy and technology responses to UHI mitigation. Our study revealed that current research methods in the UHI literature provide limited possibilities to analyse coordination effects of policy and technology responses. We suggest that further types of research methods are required, such as action research, which is considered to be "a research process that is relevant for both the practitioner who is struggling with a system of problems, as well as for the scholar whose purpose is to advance the current state of knowledge" (Baburoglu & Ravn, 1992, p. 19). We expect that such robust practice approaches can include the researcher as an active participant rather than a passive observer to meet the double hurdle of rigour and relevance (Eden & Ackermann, 2018; Järvinen, 2007). This is particularly important in our case of policy and technology responses to UHI mitigation because local actors constantly shape the research process and design by the values, knowledge and perspectives of regional differences in UHI dynamics (Douglas et al., 2018). The action research process requires the researcher to complete four stages, where (a) the practice-inspired and theory-ingrained problem is formulated, (b) the problem framing and theoretical premises are used to build and evaluate the interventions, (c) the intervention results are reflected to capture lessons learned, and (d) the lessons learned are formalised to generalise outcomes (Sein et al., 2011). With regard to the two types of interventions in our context of UHI mitigation (i.e., policy and technology), which is central in our conceptual framework, we expect that action research will help to establish intervention cycles through action-planning with a policy focus and action-taking with a technology focus (Lindgren et al., 2004). Other research approaches, such as the socio-technical systems approach (Leavitt, 1965), might also help to explain the interrelatedness of social and technical aspects of systems, which will clarify the structure and roles of policy formation, and the task and physical conditions of technology responses (Bostrom & Heinen, 1977). This will allow researchers to evaluate the coordination effects of policymaking in conjunction with technology development in order to address responses to UHI mitigation more effectively and provide contributions to knowledge and utility (Sein et al., 2011). There are examples where UHI interventions in the form of policy formation and technology development have been built and evaluated such as the *Cooling Singapore* project or the *Cool Neighborhoods NYC* project, where UHI mitigation strategies have been developed to address UHI challenges in Singapore and New York City (NYC Government, 2017; Ruefenacht & Acero, 2017).

The next five questions refer to the combined intervention of policy and technology responses, as depicted in the framework. Most studies address either policy or technology responses from a separate viewpoint; however, a combined approach has the potential to increase the effectiveness of the intervention through coordinated policy and technology responses (Arthur, 1988). Such coordination effects can contribute to a reinforced diffusion of both UHI-mitigating technology and the supporting policy. While the diffusion of technologies and supporting policies is typically interlinked (Jänicke, 2015), our knowledge on interactions between policy and technology is currently limited. Thus, we propose a set of research questions to help guide future research on synergistic effects of a combined approach of policy and technology interventions.

The next set of research questions relates to the direct impact of policy and technology responses on anthropogenic heat. We propose that policy and technology are both direct contributors to anthropogenic heat; for example, a lack of policy on HVAC efficiency will contribute to heat, whereas an effective HVAC efficiency standard will lower the effect of HVAC heat exchange. The absence of or poor policy directly contributes to heat generation. While the current state of UHI research has the main focus of UHI mitigation through policy responses or technology intervention, little is known about aggravating effects through a lack of or poor policy and technology response. A recent study suggests that UHI warming will be equivalent to about half the warming caused by climate change by the year 2050 (Harvey, 2019), which makes research on aggravating effects even more important. An example of research tackling aggravating effects is a group of scientists at the University of Georgia in the United States, who developed a network of sensors deployed on buses and citizens' bodies for measuring local temperatures (Lapidus, 2019). Such a network of local sensors provides an early warning system for city planners, for example, to decide where to plant trees. Communities can also use such systems, for instance, to ensure that people at risk are less exposed to UHI effects and have access to water and air-conditioned spaces. Besides increased environmental degradation, UHI effects can also worsen economic loss; this could amount to a loss of over 10% of gross domestic product in cities by 2100 (Estrada et al., 2017). For example, the economic loss reached 2.5 million EUR for each heatwave day in Cluj-Napoca city, Romania (Herbel et al., 2018). In particular, this shows the importance of transitioning from current situations where a lack of or poor policy and technology responses are aggravating anthropogenic heat to desirable situations where improved policies and technologies are needed to help mitigate the UHI effect. While we acknowledge that a continuation of research on mitigation effects is necessary, we propose that future research explores aggravating effects on heat as an additional stream of research to develop a better understanding of poor policy and technology responses and how governments can improve those.

Our final set of research questions pays attention to the widely neglected moderating effects of policy and technology responses on the relationship between anthropogenic heat and incremental environmental burden. While heat mitigation is mainly covered in the current state of UHI research, the anthropogenic heat–environmental burden relationship is under-researched, particularly regarding the moderating effects of UHI policy and technology. Thus, we call for research that goes beyond short-term outcomes regarding heat generation and explores longer-term outcomes related to environmental degradation leading to natural hazards, such as heatwaves, wildfires, storms, floods, and droughts. From a health perspective, elderly people are considered to be most vulnerable to heatwaves but are also most vulnerable to infectious diseases such as COVID-19 (Batcheller, 2020; Yigitcanlar et al., 2020). A recent study found that environmental hazards and the lack of access to green spaces affect low-income neighbourhoods of colour, leading them to be hotter than their wealthier, whiter counterparts (Karlson, 2020).

There are various reasons to analyse policy and technology interventions in different contexts including health outcomes, pandemic shocks, wealth distribution and racism, which can be a result of the incremental environmental burden caused by anthropogenic heat, and link government policies to unequal exposure to extreme heat. For example, the incremental environmental burden of increased heatwaves put people's health and safety at risk, even more so during the COVID-19 pandemic (Davey et al., 2020). We propose that research on the moderation of UHI policy and technology interventions will extend our knowledge on how anthropogenic heat leads to incremental environmental burden.

3.3. Future research and overview of research questions

We suggest research that informs on the "policy → technology" and "technology → policy" relationship nexus will require interdisciplinary teams. We understand that such a nexus implies complex interdependencies, which will be better addressed with expertise from diverse research disciplines, such as management to assist the decision-making process of policy formulation and implementation, or engineering in driving technology development. Other disciplines such as urban planning will help to form the nexus from a holistic approach. To support the information flow between policy and technology instantiations, the information systems discipline will enable an integrated network of people, processes and computer systems to be established to support organisational and societal goals of UHI mitigation. Table 1 summarises the 13 research questions that emerged from our literature review along with suggestions on how to study the questions and key approaches to consider, which we propose will help guide future research on UHI mitigation.

Table 1
Emergent research questions of policy and technology responses to UHI mitigation.

Research area	Research question	Study suggestion	Key approach
Coordination effects of policy and technology responses	RQ1: What are the appropriate research methods/approaches such as action research or the socio-technical systems approach to analyse the coordination effects of policy and technology responses to UHI mitigation?	Review of various research methods/approaches to identify the level of appropriateness for the analysis of coordination effects	Identify strengths and weaknesses of appropriate research methods/approaches
Synergistic effects of a combined approach of policy and technology interventions	RQ2: What are appropriate policy responses to enable effective UHI mitigation through technology development and diffusion?	Review of governmental policies with a focus on technology development for UHI mitigation	Identify best practices of policy responses to UHI mitigation
	RQ3: To what extent is a coordination between policies leading to a set of harmonised, reinforcing policies that will maximise the impact of UHI mitigation through technology development and diffusion?	Conduct a comparative analysis of governmental policies with a focus on technology development for UHI mitigation	Identify reinforcement effects between policy responses to UHI mitigation
	RQ4: How can governments effectively prioritise policy options to maximise the impact of UHI mitigation through technology development and diffusion?	Expert interviews and focus group analysis with governmental organisations on policy prioritisation	Create a list of priorities using a heat map analysis to determine the level of attention for UHI mitigation

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	RQ5: How can governments improve policy design and implementation to support the development and diffusion of technologies for UHI mitigation?	Conduct an action research study to evaluate policy and technology intervention cycles	Identify shortcomings in the design and implementation of governmental policies to elaborate improvements
	RQ6: Which mechanisms should deliberately be considered to learn from policy feedback on UHI mitigation to reinforce technology development and diffusion?	Conduct a case study on policy feedback mechanisms to explain why policies change over time	Identify factors that explain how existing policies affect the probability and design of future policies
Aggravating effects of poor policy and technology responses	RQ7: How does a lack of or poor policy and technology response contribute to an aggravation of anthropogenic heat?	Comparative study of differences in anthropogenic heat in various regions	Compare existing policies as the independent variable to determine the effect on anthropogenic heat as the dependent variable
	RQ8: How can governments effectively detect and counteract a lack of or poor policy and technology response to alleviate UHI aggravation?	Risk analysis to identify and assess factors that lead to UHI aggravation	Develop and implement early warning systems
	RQ9: Which decisions/processes lead to poor policy and technology responses that aggravate anthropogenic heat?	Analysis of decision-making to analyse aggravation effects of policymaking in conjunction with technology development	Develop and implement decision support systems
	RQ10: To what extent are multiple, conflicting policies hampering UHI mitigation through deficient technology development and diffusion?	Conduct a comparative analysis of governmental policies with a focus on technology development for UHI mitigation	Identify diminishing effects between policy responses to UHI mitigation
Moderating effects of policy and technology responses on the relationship between anthropogenic heat and incremental environmental burden	RQ11: What are the specific variations of the impact of anthropogenic heat on the incremental environmental burden in the presence and absence of UHI policy and technology interventions?	Experimental study to manipulate the presence and absence of UHI policy and technology interventions	Analyse different scenarios to extend the knowledge about the impact of anthropogenic heat on the incremental environmental burden
	RQ12: How can governments design and implement UHI policy and technology interventions that fundamentally address both anthropogenic heat and the incremental environmental burden?	Conduct an action research study to evaluate policy and technology intervention cycles	Advance knowledge on the design and implementation of governmental policies
	RQ13: What is an appropriate approach for governments to make decisions about whether the development of UHI policy and technology interventions will help alleviate the impact of anthropogenic heat on the incremental environmental burden?	Analysis of decision-making to determine the moderation effects of policymaking in conjunction with technology development	Develop and implement decision support systems

4. Conclusions

UHIs are a growing concern for policymakers and city planners due to natural degradation, health risks, and economic loss (Estrada et al., 2017). While UHI policy and technology responses are considered separately in current reviews, a synthesis of combined interventions is missing. We take an initial step towards a unified policy and technology approach and present a systematic literature review including 97 UHI research articles that we conceptualise in various dimensions. A closer look at the current state of UHI research reveals that the following four areas are underrepresented:

1. Coordination effects of policy and technology responses.
2. Synergistic effects of a combined approach of policy and technology interventions.
3. Aggravating effects of poor policy and technology responses.
4. Moderating effects of policy and technology responses on the relationship between anthropogenic heat and incremental environmental burden.

We derived 13 research questions to guide future research from the framework of UHI policy and technology responses. These questions will inform policymakers and city planners in their tasks to mitigate the UHI effect on a broader scale and guide scholarship to enable effective interactions between policy and technology responses.

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Appendix A. Concept matrix of the literature review

Article	Evidence base			Policy responses					Technology responses				Policy	Technology	Research aim	Region	Climate
									Passive		Active						
	Timescale analysis	Effective policymaking instruments	Decision support & scenario planning	Landscape & urban form	Green & blue area ratio	Albedo enhancement policies	Transport modal split	Public health & participation	Green building envelopes	Development of cool surfaces	Sustainable transport	Energy consumption, HVAC & waste heat					
Abd El-Hakim and El-Badawy (2019)		○							●	●	●	●		●	This strategic review of technologies utilised to mitigate the UHI is presented as a framework with recommendations.	N/A	N/A
Aflaki et al. (2017)		●		●	●	●							●		A review of the influence of urban vegetation on reducing UHI intensity; proposes practical guidelines for East Asian cities.	Kuala Lumpur, Malaysia	Af
Akbari and Kolokotsa (2016).				○					●	●			○	●	A review over the past three decades of the development and evaluation of mitigation measures, including cool roofs, cool pavements and urban vegetation.	N/A	N/A
Aleksandrowicz et al. (2017)		●		○	○	●			○	○			●	○	This systematic review of UHI mitigation strategies for the period 2009–2013 found that research inclines to urban cooling interventions and most studies are conducted in subtropical climates.	N/A	N/A

Bolitho and Miller (2017)			●						●							●		Reducing heat vulnerability involves many government departments and external relations. Improving these governance arrangements could help address extreme heat as a chronic stressor in the longer term rather than an emergency in the shorter term.	Melbourne, Australia	CfB
Burillo et al. (2019)					●									●			●	An estimation of vulnerabilities of neighbourhood-scale electricity infrastructure due to increasing air temperatures found that trade-offs are required to prevent substation overloading.	Los Angeles, USA	Csa
Cai et al. (2016)	●				●	●										●		Establishes a causal relationship between land surface temperature (LST) and land-use change caused by urbanisation and proposes the protection of wetlands.	Fuzhou City, China	Cfa
R. Chen and You (2019)					●	●	●				○	○				●	○	By utilising a combination of a computational fluid dynamics model with remote sensing, it was established that urban greening is the most natural and effective mitigation strategy.	Tianjin, China	Dfa
D. Chen et al. (2013)	●				●	○	○									●		Using a forecasting model, the LST was projected to 2050 and 2090 and the cooling benefit of urban greening was assessed for present-day and future climate.	Melbourne, Australia	Cfb
Chun and Guldmann (2018)	●				●	●										●		The impacts of urban greening are influenced by seasonal variations of the UHI.	Columbus, Ohio, USA	Cfa
Connors et al. (2013)		○	○		●	●										●		Land use policy and its subsequent implications for urban form and design have an influence on LST and UHIs.	Phoenix, Arizona, USA	BWh
Corburn (2009)		●	●		●		●				○	○				●	○	Localising global climate change science for effective policymaking is not divorced from its social setting and requires a multi-stakeholder co-production of solutions.	New York City, USA	Cfa
Deilami and Kamruzzaman (2017)		●	●		●	○		○			○	○	○			●	○	Addresses the question of whether smart growth policies reduce the UHI and proposes five growth scenarios. In this case, infill development could be marginally effective to control the UHI.	Brisbane, Australia	Cfa

Deilami et al. (2018)		●											A systematic review of the spatiotemporal factors contributing to the UHI; develops an understanding of causalities and improves urban policymaking.	N/A	N/A
Dhalluin and Bozonnet (2015)		●	○	●	○	○		●	●		●	●	Situational analysis of 10 French cities’ response to the UHI impact revealed that mitigation strategies are not yet mainstreamed in decision-making.	10 French cities	N/A
Dwivedi et al. (2019)		○						●	●	●		●	An investigation into passive architectural design to lessen the burden on HVAC systems.	Mumbai, India	Aw
Echevarría Icaza et al. (2016)		●				●					●		The development of indices of indicators to effectively measure and track the UHI in six Dutch cities.	6 Dutch cities	N/A
Fu and Weng (2018)		○	○	○			●				○	●	Alternative growth scenarios are required for Atlanta after the UHI simulation revealed that the status quo is harmful to public health.	Atlanta, Georgia, USA	Cfa
Gaffin et al. (2008)	●			○	○						○		A study of historical climate data revealed that the UHI effect is responsible for one-third of climate change observed in New York City over the past century.	New York City, USA	Cfa
Gao et al. (2017)	●			○	○						○		Researchers conducted numerical simulation, which revealed significant peak during rush hour in the diurnal cycle of UHI intensity.	Xi'an, China	BSk
Gilbert et al. (2016)			●										A review of recent ‘cool community’ interventions across California indicates that strong leadership, broad support and policy complementarity are critical success factors.	California, USA	Csa
Gober et al. (2009)				●	●	●		○	●		●	●	In this study, trade-offs between water use and night-time cooling were modelled by considering urban form and land-use choices, finding that water bodies contribute to UHI mitigation.	Phoenix, Arizona.	BWh
Golden (2004)			●	○	○	○					○		This contribution makes a link between built environment professions, urban economics and climate science to improve the UHI policy response in terms of materials, technologies and practices.	Phoenix, Arizona.	BWh

Guindon & Nirupama (2015)		●	○				○								○		Local land-use plans are essential to modify the urban form and reduce heat storage.	Montréal, Toronto, Canada	Dfb
Gunawardena et al. (2017)		●			○	○	●				○	○			●	○	Green and blue spaces mitigate UHI intensity effectively and have positive outcomes on the microclimates of urban centres.	N/A	N/A
Hamilton et al. (2014)		●			○	○	●				○	○			●	○	Substantial urban regeneration such as the London Olympic Village has the potential to modify urban microclimates when UHI mitigation is considered in the design process.	London	Cfb
He et al. (2019)		●			●	●					○	●			●	●	Co-benefits can be achieved when urban policy, in this case that of Sponge City, and UHI-mitigation strategies are jointly considered.	China (numerous)	N/A
Heaviside et al. (2017)		●			○	○	●	●	●		○	○		○	●	○	A review of the literature suggests that UHI mitigation strategies have a positive impact on public health.	N/A	N/A
Hendel et al. (2016)					●	○						●			●	●	Data collected from two cases of pavement watering in Paris as a means of increasing shortwave absorptivity indicates this technique to be effective in reducing heat stress.	Paris, France	Cfb
Henits et al. (2017)	●				●										●		Land-use changes increase the impervious surface ratio and result in UHI intensification.	Szeged, Hungary	Dfb
Herbel et al. (2018)	●				●				○						●	○	Land-use changes can intensify existing UHIs and impact local economies during periods of heatwaves.	Cluj-Napoca city, Romania	Dfb
Hiemstra et al. (2017)		●			○	●	●				○	○			●	○	Park Cool Islands and the reforestation of cities can be planned as a network of green spaces.	Europe (Numerous)	N/A
Huang and Lu (2018)	●																Based on a comprehensive literature survey, UHI determination (intensity, heat source, modelling and remote sensing) remains the dominant topic of UHI studies.	N/A	N/A
Iping et al. (2019)		●	●						●						●		Analysis of media reporting on the UHI effect found that, overall, there was positive reportage on actions to mitigate the UHI effect; however, climate denialism appears to still be socially construed.	Australian cities	N/A

Jamei and Tapper (2019)		●		○			●		○			●	○	The link between climate science and planning for green and blue space is essential in UHI mitigation strategies.	N/A	N/A
Jenerette et al. (2011)	●		○	○					○			○	○	A systems evaluation is required to measure the water loss requirements associated with land-surface cooling.	Phoenix, Arizona, USA	BWh
Jones (2018)		●					●					●		Early warning and detection systems alongside longer-term planning and preparedness can help reduce extreme heat risks.	N/A	N/A
Kamruzzaman et al. (2018)	●		○	○		●			○			●	○	Transit-oriented development strategies are preferred over low-density urban sprawl but do not necessarily reduce the UHI. A balancing act is therefore required between natural and built-up areas.	Brisbane	Cfa
Kohler et al. (2017)			○					●			●	○	●	An urban growth simulation was developed to ascertain floor-space heating energy demands, and it was found that a scenario of a compact city is similar to that of a sprawling city. Therefore, urban form does not influence the energy demands required to heat buildings.	Strasbourg–Kehl urban region (France–Germany)	Cfb
Kolbe (2019)						●				●		●	●	A simulation found that the greatest UHI intensity mitigation effect for transport was to replace conventional vehicles with energy-efficient public transport.	Beijing, China	Dwa
Koomen and Diogo (2017)			●			●						●		Land use controls and spatial planning instruments should contain urban growth as sprawling land use cover perpetuates UHI.	Amsterdam, Holland	Cfb
Kuznetsov and Tomitsch (2018)		●					●					●		The UHI effect presents as a wicked problem, and no single intervention can effectively mitigate this effect. It is proposed that social computing can assist through data sharing and interactive forums.	Sydney, Australia	Cfa
Lee and French (2009)		○			●				○			●	○	In Atlanta, it was estimated that two-thirds of the impervious surface would be dark-coloured pavement, an increase of 45% over 10 years. It is recommended that light surfaces be selected to increase albedo.	Atlanta, Georgia, USA	Cfa

Lehmann (2014)			○				●					○			●	○	In addition to green roofs, urban farming, roof-top gardening and green walls mitigate the UHI effect through the process of evapotranspiration.	Sydney, Australia	Cfa
Lemonsu et al. (2015)			○			●						○			●	○	Scenarios of urban densification require an engagement with the water requirements to maintain urban greenery in UHI mitigation.	Paris, France	Cfb
C.-f. Li et al. (2014)	●		○			●						○			●	○	Large-scale landscaping projects including green belts, forests and parklands have had a positive mitigating influence over the UHI of Shanghai.	Shanghai, China	Cfa
Louiza et al. (2015)								○	○				○		○	○	Heat transfer and radiation are negative side effects of congestion and intensify the UHI.	Paris, France	Cfb
Marando et al. (2019)			○		○	●						○			●	○	Green infrastructure is an effective ecosystem-based climate adaptation strategy.	Rome, Italy	Csa
Mavrogianni et al. (2011)			●		○	●			○						●	○	A decision support tool was developed to guide UHI mitigation measures since urban development processes are interlinked and complex.	London, UK	Cfb
Mbuh et al. (2019)			○		○												This simulation proves that the denser urban centre of Chicago has a higher UHI than St. Paul.	Chicago, USA	Dfa
Mees et al. (2015)		●															The ‘mainstreaming’ climate mitigation measures into existing policies, programs and projects could result in efficiency gains and increased collaboration in public and private interests in ‘cool’ governance.	Netherlands	CfB
Mirzaei (2015)			○														This literature review categorises and explains different types of models suitable for various objectives and scales of UHI studies.	N/A	N/A
Oikonomou et al. (2012)		●			●		○				○			○	●	○	Variation of higher indoor temperatures can be explained by architectural form and the existence of a UHI.	London, UK	Cfb
Parsaee et al. (2019)		●	●						●						●		Information management systems are required to improve decision-making processes considering urban action plans and spatial maps. Such collaborative platforms can increase participation.	N/A	N/A

Pomerantz (2018)					●					●		Increasing the albedo factor by 0.2 due to cool surfaces results in a reduction in electrical energy by < 1 kWh per modified m^2 per year. The size of the benefit is small and hence decision-makers need to select mitigation measures carefully.	California, USA	Csa
Price et al. (2015)							○	○			○	Vertical green walls complement green roofs in mitigating UHI in green building envelopes.	N/A	N/A
Qin (2015)					●			○		●	○	It has been established that cool pavements are an effective UHI-mitigation factor. Less is known of heat-harvesting pavements and should be reviewed against energy output and durability over time.	N/A	N/A
Räsänen et al. (2019)		●	○			●				●		In this risk mapping, 5 different zoning options and 11 different weighting options were applied to assess vulnerability.	Helsinki, Finland	Dfb
Richards and Edwards (2018)				●				○		●	○	Co-benefits can be achieved by using water infrastructure for flood management and mitigating the UHI.	N/A	N/A
Romero Rodríguez et al. (2020)		●	○			○				○	○	A generic methodology is proposed for the estimation of the UHI and allows improved mitigation strategies and economic investments into vulnerable areas.	Seville, Spain	Cfa
Rosenfeld et al. (1998)	●											Investments in ‘cool communities’ can result in $1.2b savings for the Los Angeles basin.	Los Angles, USA	Csa
Rossi et al. (2013)					●		○		○	●	○	Anthropogenic heat generation can be mitigated by increasing the earth’s albedo factor through renewable energy infrastructure.	N/A	N/A
Roxon et al. (2020)							●		●		●	UHI studies have tended to focus on peak summer temperatures, and this study suggests that UHI could save energy costs for regions in cold climates.	USA (Various)	N/A
Roy and Singh (2015)			○	●						●		Water bodies have an influence on the humidity levels observed within Delhi’s UHI.	Delhi, India	Cwa

Sánchez-Guevara Sánchez et al. (2017)	○	●			○	●	○	Low-income households can face overheating problems in periods of UHI intensity, which has an adverse effect on the public health of Madrid’s vulnerable populations.	Madrid, Spain	Csa
Santamouris (2013)				●			●	Reflective and permeable/water-retentive ‘cool pavements’ hold the greater promise for cool pavements to make a substantial contribution to UHI mitigation.	N/A	N/A
Santamouris et al. (2018)				●			●	Building cooling demand increases three times at the peak of UHI intensity in Sydney, which is up to a 6°C increase in local temperature. Cool pavements have reduced peak ambient temperature by 3°C and reduced building cooling demand by 20%.	Sydney, Australia	Cfa
Santamouris et al. (2019)	●					●		Three case studies from Australian cities indicate the positive synergies between investments in green infrastructure and reduction of the UHI effect.	Sydney, Australia	Cfa
Sharma et al. (2019)	○	●				●		This study reports on the UrbClim (urban climate) model used to forecast near-future (2026–2045) and far-future (2081–2100) changes, with a focus on ten extreme heat indices.	Delhi, India	Cwa
Shickman and Rogers (2019)	○	●	○	○	○	●	○	Utility providers can account for benefits of UHI mitigation/cool city programs provided in cost–benefit tests.	USA (Various)	N/A
Short et al. (2004)			○		○			Passive design for natural ventilation is explored by using thermal modelling to measure the performance of non-domestic buildings in the United Kingdom.	United Kingdom (Various)	N/A
Si et al. (2019)		●				●		Analysis of the quality of health care provided during heatwaves indicates that a higher quality of care is provided during extreme heat but can be explained by fewer patients.	Xi'an, China	BSk

Silva and Fillpot (2018)		●					○		○		○	A zero-dimensional energy balance model was utilised to measure energy cost savings by taking account of four modelled UHI-mitigation strategies; conductivity was found to be the most effective mitigation strategy.	Phoenix, Arizona, USA	BWh
Silva et al. (2010)		●			●		○	○	○	●	○	A zero-dimensional energy balance model was utilised to measure the impact of mitigation strategies, and it was found that 4 strategies would lead to a 48% reduction in heat-related emergency service calls, where increasing albedo is the most effective mitigation strategy.	Phoenix, Arizona	BWh
Stone et al. (2010)			●							●		A study of metropolitan areas in the USA over five decades revealed that sprawling suburbs are two times more susceptible to extreme heat events than compact city centres.	USA	N/A
Stone and Rodgers (2001)		●	○	○			○		○	○	○	Low-density residential developments contribute to radiant UHI formation, and compact medium-to-high density development and green area ratio are recommended.	Atlanta, Georgia, USA	Cfa
Su et al. (2020)						●				●		Occupational injuries and insurance payouts decreased by 13% and 24% respectively over a two-year period after the labour protection policy, Administrative Measures on Heatstroke Prevention (AMHP2012), was adopted by the Chinese Government in 2012.	China	N/A
Sung (2013)	●	●		○						○		By comparing the LST of neighbourhoods, it was found that the cooling effect in Woodland can be attributed to its tree protection policy.	Woodland, Texas, USA	Cfa
Susca and Pomponi (2020)		●										Life cycle assessments are expanded by coupling the land use and local climate as a means of measuring the UHI.	N/A	N/A
Takebayashi and Moriyama (2012)							●				●	A study of the heat transfers in an urban street canopy revealed that mitigation measures are most effective when prioritised for large roofs, followed by smaller roofs and then wall surfaces.	Japan	Cfa

Takebayashi et al. (2014)					●				●		Tree canopies, green walls and reflective pavements should consider the orientation of streets and solar penetration at the urban block scale.	Japan	Cfa
Targino et al. (2019)		●		○			○		○	○	A simulation study found that a park would be sevenfold cheaper than building a city pond and is more effective in mitigating the UHI.	Londrina, Brazil	Cfa
Teferi and Abraha (2017)		●		○			○		○	○	This longitudinal study confirms that green spaces are one of the most promising local climate change adaptation strategies.	Addis Ababa, Ethiopia	Cwb
Tonekaboni et al. (2018)		●		○		○	○		○	○	A propositional framework combines a variety of human, vehicle, and drone-borne sensors which is joined with data from satellite and weather stations in a decision-making support system.	N/A	N/A
Tuczek et al. (2019)		●		○		○	○	○		○	A propositional framework for decision support that maximises revenue while maintaining an optimal building/vegetation balance within the UHI limits.	N/A	N/A
Vargo et al. (2016)		●		○		○	○	○		○	Comparison of heat-related avoided mortality rate between albedo, green and combined scenarios	N/A	N/A
Vasilakopoulou et al. (2014)		●		○	○		○	○		○	This systematic review of albedo enhancements concludes that such interventions successfully mitigate the UHI.	N/A	N/A
Wang and Akbari (2016)			○	○	○			○			The three main UHI interventions used in Montréal (urban canopy, urban vegetation, and albedo of paved-over areas) is reviewed against the sky-view factor control and wind speed.	Montréal, Canada	Cfb
Weber et al. (2015)	●	●									This case study provides insights into policy formation based on vulnerability indices informed by the modelling of the UHI.	Philadelphia	Cfa
Wilhelmi and Hayden (2016)						●			●		The System for Integrated Modelling of Metropolitan Extreme Heat Risk project funded by NASA is a good example of an iterative, evidence-based and responsive stakeholder engagement platform at the science-policy interface of heat-health research.	Houston, Texas, USA	Cfa

Wondmagegn et al. (2019)								●							●		Extreme heat events place a demand on the healthcare system when reviewed against indicators such as ER visits, hospitalisation and ambulance call-outs.	N/A	N/A
Wonorahardjo et al. (2020)										●						●	Four building materials (brick, aerated concrete, wood with glass-wool insulation, and glass fibre-reinforced concrete with glass-wool insulation) were reviewed to assess thermal qualities in an observed UHI.	N/A (Tropical Area)	N/A
Xiang et al. (2016)								●							●		Survey results indicate that workplace heat exposure during extreme heat events requires risk management and prevention strategies.	Adelaide, Australia	Csa
Yamaguchi and Ihara (2020)																	Energy efficiency strategies have proven useful to combat UHI intensity in Japan, when considered alongside other countermeasures, such as greening.	Tokyo, Japan	Cfa
Yang et al. (2015)				○		○				○					○	○	The potential of increasing albedo by means of reflective materials and mitigating the UHI effect depends on a set of factors, including building characteristics, urban environment, meteorological and geographical conditions.	N/A	N/A
Zhang et al. (2019)			●			○				○	○				○	○	A willingness-to-pay valuation approach was tested for cool roofs, and it was found that government credibility and education are important factors in promoting public participation.	Beijing, China	Dwa
Zinzi et al. (2014)			●			○				○	○				○	○	The study presents an energy-rating scheme for cool roofs and, based on simulations, the performance of the cool roof's radiative properties was assessed.	Italy	Csa
Total ●	12	19	27	18	14	18	4	17	8	9	2	5	54	16					
Total ○	0	4	11	26	23	10	2	7	21	29	2	9	18	39					

Notes: ● major focus, ○ minor focus; Af = Tropical rainforest climate; Aw = Tropical savannah, wet; BSk = Cold semi-arid (steppe) climate; BWh = Hot deserts climate; Cfa = Humid subtropical climate; Cfb = Temperate oceanic climate; Csa = Hot-summer Mediterranean climate; Cwa = Monsoon-influenced humid subtropical climate; Cwb = Subtropical highland climate or temperate oceanic climate with dry winters; Dfa = Hot-summer humid continental climate; Dfb = Warm-summer humid continental climate; Dwa = Monsoon-influenced hot-summer humid continental climate

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