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Understanding systemic cooling poverty

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Temperature records are being broken across the world, leading to incalculable suffering. The poorest and most disadvantaged people, who contributed the least to global warming, are the ones bearing the most severe consequences of extreme heat because of their limited adaptive capacity. Understanding the needs of the most disadvantaged is imperative to develop fair and adequate strategies to adapt to extreme heat and keep cool. This Perspective discusses how to understand systemic cooling poverty with the aim of informing policy and practice to support vulnerable people.

Anthropogenic activities have driven global warming of 1.1 °C since the nineteenth century[1], with 2014–2020 registering as the hottest period in 140 years (ref. 2) and a high likelihood of reaching 1.5 °C warming in the next 10–30 years (ref. 1). Heatwaves are increasing in frequency, duration and intensity around the world[3] with consequent rises in heat-related mortality[4]. In 2022, it is estimated that 15,000 people died because of heat-related complications[5]. A recent systematic review[6] shows that across climatic heterogeneities, a 1 °C increase is enough to spike cardiovascular-related mortality and morbidity around the world, especially among the older population (over 65 years). The magnitude of the already observed heat-related deaths and morbidity shows how unprepared society is in adapting to a warming world. As temperatures in the urban built-environment increase due to overheating[7], current indoor and outdoor heat prevention strategies are considered inadequate[8]. The existing geometry of the urban environment traps heat and prevents natural ventilation[9], while street surfaces and the construction materials of buildings tend to absorb heat in excess[10]. Rapid and uncontrolled urbanization exacerbates the thermal well-being of urban areas as green and blue surfaces are often lost to make space for new constructions. The heat stress an individual ultimately perceives is the result of a heat cascade[11] and the heat accumulated from the environment, which is transferred to buildings and individuals.

The most immediate and widespread adaptive solution to higher temperatures has been a 100-year-old technology (air-conditioning (AC)), which is projected to dominate and heavily affect energy demand in emerging economies[12]. While the benefits of AC are difficult to substitute in places such as hospital wards, health facilities and certain severe working environments, its use also brings detrimental effects for the environment and society, particularly through the use of fluorinated refrigerant gases and fossil-fuel sourced energy[13], exacerbating peak electricity load and urban heat islands.

Without sustainable and affordable adaptive cooling solutions, humanity could face an increase of new types of thermal inequalities. People living in low-income neighbourhoods are more exposed to the urban heat-island (UHI) effect and have less access to cooling resources, such as green and blue surfaces and cooling centres[14]. In countries reporting high inequalities in the distribution of income and fundamental services such as safe housing, sanitation, education, health and energy access[15], important questions about who is going to benefit the most and who will be left behind in the quest for safe thermal conditions in hot and humid weather arise.

Until recently, most available research focused on increasing surface air temperatures without considering the levels of humidity[16]. Recent studies indicate that rising temperatures will be accompanied by growing levels of humidity, a combination that can intensify the occurrences of heat stress and mortality[16] and make public interventions less effective[17]. To measure the combined heat and humidity temperatures, scientists often use wet bulb temperature (WBT), the index of thermal discomfort, measuring the minimum temperature to which air can be cooled by evaporative cooling. High WBTs are expected to change the biophysical, natural and urban landscape in ways that have not been sufficiently understood and can make some cities unliveable[18].

This Perspective puts forward the concept of systemic cooling poverty (SCP), which incorporates the multiple dimensions of vulnerabilities that stem from spatial, infrastructural and material deficiencies in accessing cooling. SCP is different from current definitions

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of energy and fuel poverty. We discuss this conceptualization and examine each dimension that constitutes SCP, laying the groundwork for the development of an SCP multidimensional index. This index will aid policy-makers in identifying vulnerable regions, communities and individuals and, importantly, facilitate the implementation of context-specific mitigation measures to enable thermal justice.

Conceptualizing SCP

The history of energy and fuel poverty is replete with hundreds of definitions and attempts to measure it. Bradshaw and Hutton[19] first defined 'fuel poverty' in terms of thermal comfort in 1983 as "the inability to afford adequate warmth at home" (p. 249). Boardman proposed that if households spend more than 10% of their total income on energy services, they can be considered fuel poor[20] highlighting the importance of building size and energy efficiency. Subsequent indicators for fuel poverty in the UK have focused on affordable warmth[21], which includes the 'green home grant voucher scheme' to improve the energy efficiency of buildings.

Another study[22] expanded the definition of energy poverty for the developing world as "the absence of sufficient choice in accessing adequate, affordable, reliable, high-quality, safe and environmentally benign energy services to support economic and human development". In particular, it refers to the lack of energy access[23] and energy infrastructures in relation to economic and social development[24]. Until recently, the issue of energy poverty in the developing world tended to overlook thermal comfort. Addressing this gap, Robles-Bonilla and Cedano[25] developed a multidimensional energy deprivation index (MEDI), which accounts for thermal comfort in terms of AC/heating ownership. While useful, this index does not consider actual appliance use postpurchase. Moreover, it does not account for the materials, orientation and energy efficiency of the building stock, how this could influence the use of AC and how the availability of other cooling technologies, such as fans, can reduce the use of AC[26].

So far, existing definitions of energy and fuel poverty do not fully consider the importance of cooling as a growing problem[27]. Recently, research attempting to address the increasing demand for cooling (for example, refs. 28,8,29) has provided an extension of the existing concept of fuel and energy poverty. One author[29] defined cooling poverty as "the difficulty one has buying and installing air conditioners for the summer heat". Other research[30] has investigated the issue of indoors overheating during summertime and fuel poverty but has not provided a definition for cooling-related energy poverty. More recently, different terms have been used to highlight how a considerable portion of the global population will be left behind in the adaptation efforts to increasing hot weather events, such as, the 'cooling deficit'[12] or 'cooling gap'[31]. The cooling gap is defined as the "difference between the population affected by heat stress and the population with the socio-economic ability to own AC" (p. 4)[31] while a cooling deficit is "characterized by millions of less well-off electrified households that need but cannot obtain air conditioners" (p. 2)[12].

These approaches, while different in their nomenclature, try to define the lack of cooling with a focus on the socio-economic opportunities of households to purchase and use an AC. In doing so, they preclude that cooling can be achieved through numerous other ways, which include passive and behavioural-based approaches, such as water use, natural ventilation, green roofs, natural shading, evaporative cooling and place-based knowledge[32]. Further, another crucial omission in thermal comfort and energy poverty studies is the role of vegetation and blue surfaces, which are linked to a reduction of air temperature of 1–2 °C in urban areas[33] as well as to how the geometry of the built-environment can provide shading. The characteristics and interactions of the built and natural environment for bioclimatic analysis are therefore fundamental to understanding thermal comfort and energy poverty. Finally, existing energy poverty metrics lack an intersectional understanding of the intrahousehold dynamics about who benefits and who is still left behind in the opportunities created by energy services[34]. Previous attempts to capture intrahousehold gender inequality in energy poverty do so only at the case-study level and with qualitative methods (see ref. 34).

Learning from the existing work on energy poverty and thermal comfort, we propose a definition of SCP that seeks to complement existing cooling poverty definitions by looking at infrastructural, thermal interactions and justice deficiencies in the quest to achieve sustainable cooling. This paper defines SCP as: the condition in which organizations, households and individuals are exposed to the detrimental effects of increasing humid heat stress as a result of inadequate infrastructures. Such infrastructures can be: physical, such as passive retrofit solutions, cold chains or personal technological cooling devices; social, such as networks of support and social infrastructures; or intangible, such as knowledge to intuitively adapt to the combined effects of heat and humidity.

This definition departs from existing concepts of energy and fuel poverty in several ways. It highlights the role of passive cooling infrastructures (water and green and white surfaces), building materials for adequate outdoor and indoor heat protection and social infrastructures. SCP goes beyond the financial constraints of households to pay for energy services and looks at the state of basic infrastructures (sanitation and clean water provision). Its systemic scope also considers the state of cooling provision for outdoor working, education, health and refrigeration purposes. In this sense, space and place play a key role in this conceptualization of cooling poverty. Finally, SCP looks beyond energy and embraces a more multidimensional and multileveled analysis of infrastructures, spaces and bodies.

The dimensions of SCP

To best capture the multidimensional nature of SCP while maintaining humans at the centre, we build on the multidimensional poverty index (MPI) developed by Oxford Poverty and Human Development Initiative[35]. As in the MPI, we retain the health and education dimensions of human well-being, whereas living standards are extended to other dimensions related to sustainable passive and affordable cooling, including infrastructures, working standards, justice and climate. Below we discuss each dimension of the SCP index.

In this paper, we will not measure the levels of insufficiency or deprivation of cooling infrastructures; however, a brief definition of deprivation on a conceptual level is needed to identify people's exposures to excessive heat in relation to the dimensions identified. The Merriam-Webster dictionary defines deprivation as "the state of being kept from possessing, enjoying or using something: the state of being deprived". Deprivation can be absolute or relative. Sen[36] defines absolute deprivation as the fundamental absence of basic needs such as food, clothing, shelter, clean water and sanitation facilities. Unlike relative deprivation based on subjective perceptions of being deprived of something in relation to the social group in which the individual is situated, absolute deprivation represents a more objective absence of basic necessities. The two concepts are not mutually exclusive but rather complement each other according to Sen[36] and help characterize different nuances and degrees of poverty on the basis of local realities and social standards. On this occasion, we will focus on a more objective absence of determined infrastructures, socio-economic assets and intangible factors, which can help in cooling spaces and human bodies outdoors and indoors.

Figure 1 summarizes the five core dimensions defining the SCP and illustrates their 15 subdimensions or variables. Table 1 provides a first selection of variables that could be used to operationalize the five dimensions of the SCP. Box 1 then develops a potential workflow of the empirical implementation and exploitation of the SCP.

Climate

Humidity is fundamental to human physiological functions; however, excess humidity can have several negative direct and indirect impacts on human health. The combination of increasing temperatures and

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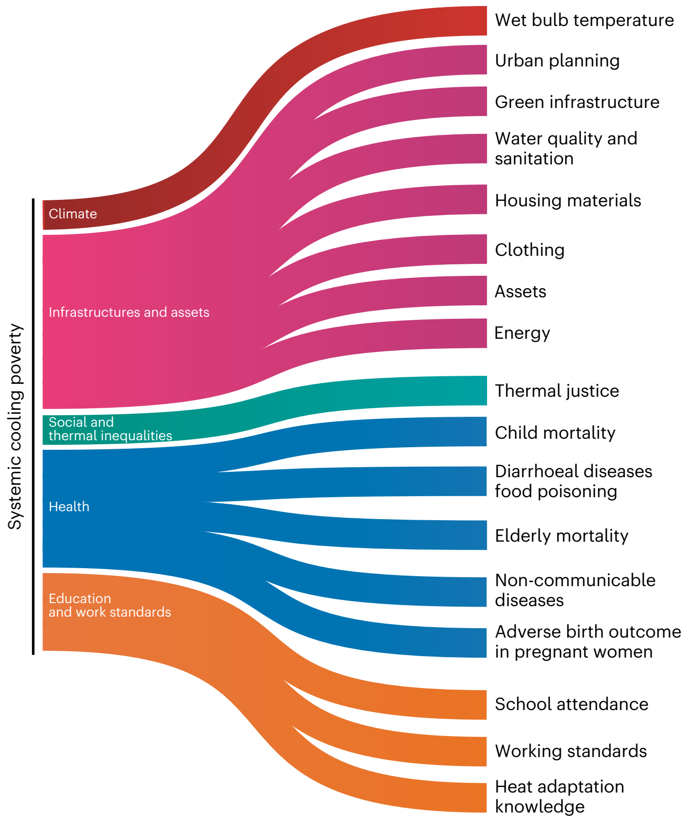

Fig. 1 | Defining dimensions of SCP. The five core dimensions defining the SCP and their 15 subdimensions or variables.

humidity increases the deadly effects of heat stress, posing a serious threat to human survival because high humidity reduces the body's ability to sweat and therefore to cool via evaporative cooling. Yet, most existing research relies on dry ambient air temperature that has been found to be an insufficient metric to measure heat stress[16]. In fact, in hot and drier climatic conditions, humans have adapted to survive in temperatures as high as 38 °C, while combined hot–humid temperatures measured in WBT can be deadly when as low as 32 °C, especially among outdoor workers and the elderly[16]. As noted by Coffel et al.[37], some regions are more at risk of extreme WBTs unsafe for humans, such as northeast India, east China, West Africa and the southeast USA[37]. WBT is the minimum temperature to which air can be cooled by evaporative cooling. Commonly referred to as a measure of 'mugginess'[38], it is a combined measure of ambient air temperature (T) and relative humidity (RH), thus representing both heat and moisture content of the immediate surroundings. Although other measures of humid heat stress such as the wet bulb globe temperature (WBGT) and apparent temperature (AT) exist in the climate and health literature, our choice of WBT as a thermal discomfort index (TDI) is motivated by the following: (1) WBT is directly measurable and routinely recorded at meteorological stations; (2) compared to other TDIs, WBT puts a higher weighting on RH; and (3) unlike other TDIs, WBT is used in both climate–health[39] and climate–energy impact assessments[12].

People find themselves in cooling deprivation in relation to combined high heat–humidity levels, above which passive cooling solutions alone are incapable of maintaining safe thermal comfort levels. Physiological studies using experimental laboratory conditions have demonstrated a specific range of indoor heat–humidity levels that are deemed unsafe for an average human body. The SCP index can be constructed using a corresponding WBT level computed at high granularity (specific locations or grid cells), wherein active and sustainable cooling would be required to maintain safe thermal conditions.

Infrastructures and assets

Deficiencies in physical infrastructure are a direct cause of SCP. Extreme heat exposure is magnified in urban areas because of the UHI effect[40], the process according to which heat is 'trapped' by the building stock, pavements and reduced land surface. Appropriate urban planning development should allow the circulation of natural ventilation, shading and the reflection of heat in the atmosphere[9].

Nature-based solutions or green infrastructure are effective in the reduction of urban anthropogenic heat through shading and evapotranspiration, important in the mitigation of UHI effects[41]. Across geographies, researchers have proven the effectiveness of nature-based solutions, such as green roofs, which, compared to bare roofs, lowered surface temperatures by 1–2 °C in densely populated urban areas such as New York City[42], Rio de Janeiro[43] and Putrajaya in Malaysia[44]. Similarly, urban greenery can also reduce the UHI effect. Others[33] found that even a relatively small green area in Melbourne (Australia) can cool the surrounding built-up area with a mean maximum cooling reaching 1.0 °C during peak daytime heating. One study[45] argues that water-sensitive urban design helps improve outdoor human thermal comfort in urban areas in Australia. Public spaces surrounding green and water bodies can be also be understood as social infrastructures, which are spaces where people gather to socialize while coping with extreme heat[46].

Thermal comfort also depends on the ability to cool the body with water, diet and beverage intake. The level of hydration and water used to cool the skin are two of the most efficient[47] and intuitive remedies to prevent heat-stroke and heat stress. However, in countries with poor sanitation and water security, this intuitive and life-saving solution is not an option. According to the World Health Organization (WHO), there are over two billion people in the world lacking access to safe drinking water and sanitation and three billion people lack access to handwashing facilities[48].

Improving indoor thermal comfort remains a key challenge. Most dwellings are not equipped with resilient housing materials[49] that could reduce energy consumption in both hot and cold weather. Recent research shows how the built stock in the UK (including commercial, hospitals and residences) is inadequate to resist increasing temperatures[50]. Moreover, rapid urbanization is favouring the proliferation of informal settlements and slums[51] with evident infrastructural deficiencies[52] and detrimental effects on its resident's health during heatwaves. Understanding the thermal efficiency of the building stock and the countries' adoption of green building codes can help identify regions vulnerable to cooling poverty.

Wearing adequate protective clothing is an established adaptive strategy that facilitates evaporative cooling and air movement; however, it can be challenged by social norms and cultures. Studies conducted in Brazil[53], Singapore[54], Japan[55] and China[56] show how office fashion modulates AC uses in the summer. Uniforms used in schools have also been linked to increased thermal discomfort in Nepal[57]. Preferences for synthetic, often low-cost fast-fashion fibres were linked to thermal discomfort[58] because of reduced air permeability, moisture management and thermal conductivity. Understanding the diffusion and use of inadequate clothing for thermal comfort is key to reduce cooling maladaptation.

In cases where passive cooling is insufficient to ensure health and well-being, access to active and sustainable cooling is fundamental. The absence of adequate energy infrastructure can jeopardize the functioning of cold chains that are essential for food safety, vaccines and human fertility[28]. A Harvard-led study showed how the electricity grid in India and Indonesia is not sufficient to support the increasing demand for cooling by 2050[59]. Unplanned power outages could damage people with comorbidities and non-communicable diseases (NCDs) who need specific and continuous health services[60]. On the residential side, affordability of purchasing and use of AC and cooling technologies such as refrigerators/freezers is a problem for low-income households

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Table 1 | Key dimensions and considerations of SCP

Dimensions	Variables	Deprivations in relation to systemic cooling	Refs.
Climate	WBT	Deprived if combined temperature/humidity reaches unliveable levels	93
Thermal comfort infrastructures and assets	Urban planning	Deprived if passive and natural cooling is not available (natural ventilation, shading, public squares, cool pavements and cool roads)	41
	Green infrastructure	Deprived if green roofs, blue/green areas, soil moisture, rain gardens, green belts, wetlands (among others) are not (or insufficiently) available	41
	Water quality and sanitation	Deprived if water is not available or safe for human consumption or hygienic practices Adequate sanitation avoids cross-contamination of waste and treated water	94
	Housing materials	Deprived if inadequate housing conditions hinder or block the passive cooling potential of a building	55
	Clothing	Deprived if appropriate clothing for heat protection is not available (for example, synthetic clothing traps heat)	32
	Assets	Deprived if appropriate refrigeration and space cooling devices are not affordable Deprived if obsolete highly inefficient cooling technologies are used, as they pose a burden to energy infrastructure and climate	28
	Energy	Deprived if inadequate and expensive energy services impede space cooling (evaporative cooling and fans) and food refrigeration	59
Social and thermal inequality	Thermal justice	Deprived vulnerable populations (by gender, age, ethnicity, race, migration status, disabilities, sexuality and class) are exposed to heat shocks and UHI effects	14
Health	Child mortality; diarrhoeal diseases; food poisoning; elderly mortality and morbidity	Deprived if space cooling (active and/or passive) is not available to keep children safe from heat-related illnesses Deprived if refrigerators to preserve food are not available and extreme heat increases enteric pathogens and disrupts intestinal microbiota balance	70
	NCDs	Deprived if space cooling (active and/or passive) is not available to relieve people affected with NCDs (cardiovascular diseases, chronic respiratory diseases, diabetes, cancers and mental health conditions)	75
	Adverse birth outcome in pregnant women	Deprived if space cooling (active and/or passive) is not available to pregnant women who will risk preterm birth, low birth weight and stillbirths	78,79
Education and work standards	School attendance	Deprived if the lack of appropriate space cooling (active and/or passive) hinders the attendance of educational courses	83
	Working standards	Deprived if appropriate active and/or passive space and personal cooling are not provided for worker's health and well-being	88
	Heat adaptation knowledge	Deprived if people do not have cultural capital to mitigate the effects of extreme heat	89

in developed[29] and developing geographies[12]. The adoption of cooling appliances that are obsolete and inefficient can burden households' expenditures with energy services. Understanding the regulation, diffusion and adoption of cooling appliances with minimum energy performance standards is key to identifying countries and regions within them, which can be vulnerable to SCP.

We posit that people are deprived of physical cooling infrastructures: if they lack available and accessible green/blue areas; if rural and urban areas are not planned in ways that increase shading and ventilation; if nature-based solutions are not in use; if safe water and sanitation are not available; if building materials and building codes are worsening indoors thermal comfort; if cooling textiles and clothing are unaffordable and not available; and if there is a condition of energy infrastructure insecurity and lack of access to affordable and efficient mechanical cooling. At macrolevel analysis, remote-sensing based data and indicators, such as the normalized difference vegetation index, could support the characterization of the spatial distribution of green areas, also in relation to the prevalent characteristics of the population in different areas of a city. At the microscale (city-level or neighbourhood-level), surveys could characterize the fraction of population living within a given distance range from green spaces[61].

Thermal inequality and social isolation

We have identified inequality as another major indirect cause of SCP. Social inequality, rooted in individual characteristics (gender, ethnicity, race and sexuality), economic conditions and cultural preferences (traditions, beliefs and religions), is entwined with spatial residential segregation patterns. Vulnerable people not only are economically and socially segregated but they are more at risk of environmental and health hazards. For example, ref. 62 found that in 25 cities around the world there is a strong spatial relationship between low-income neighbourhoods and the severity of UHIs. Two studies[63,46] highlighted how social isolation, resulting from discrimination, neglect and segregation, is responsible for higher exposure to the detrimental effects of heatwaves among most vulnerable people. The use of AC in urban areas can further exacerbate thermal injustices. For example, the heat dumped from high-income dwellings can worsen outdoor thermal conditions. A heat dump occurs when the heat expelled by AC raises external temperatures. In China, Wen and Lian[64] found that in the city of Wuhan heat waste of ACs was responsible for a rise in atmospheric temperature of 2.56 °C under inversion conditions and 0.2 °C under normal conditions. Others[65] evaluated the impacts of heat exhaust on pedestrian's thermal comfort and found that the heat waste from ACs reduces people's thermal comfort in El Hussein Square in Egypt.

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BOX 1

Initial considerations for operationalization of the SCP framework

The proposed SCP framework needs a consideration of: (1) the level of the implementation, which can range from the local scale (for example, a city), to country level, up to a globally relevant assessment; and (2) the granularity of the implementation, which can span from the individual or household level up to macroscale, population-wide analysis. On the basis of these dimensions, different potential data sources, variables and measurement and processing techniques can be used to operationalize the SCP framework.

First, ad hoc collected household survey data are suitable for capturing dimensions of: (1) micro-infrastructure; and (2) expenditure capacity in relation to the cost of services. Second, subnational or national statistics have the potential to inform about: (1) access to services (electricity and water); (2) costs and prices of, for example, utility bills, appliances and products; as well as (3) prevalence of health-related issues such as NCDs among different strata of a population. Third, geospatial data and related geographic information system (GIS) processing techniques have large potential to contribute to measuring urban infrastructure and its availability, accessibility and distribution of inequity and inequality in relation to different population groups. Relatedly, climate re-analysis and Earth observation data products are important in operationalizing the SCP framework. They allow measurement of the values and distribution of different climate-related metrics, such as WBT, in terms of both cumulative (long-run average values) and acute values (for example, peaks). High-resolution, downscaled products (or/and local weather station networks) can allow differentiating between exposure levels within a city and in relation to different characteristics of the population. Fourth, policy analysis and qualitative methods allow assessment of dimensions such as heat adaptation knowledge and adaptation behaviour drivers and responses, as well as broader regulatory contexts.

The scale and granularity of the SCP will determine the level of aggregation of each dimension, spanning from high-quality data and ad hoc collected information at the level of individual household and cities to country and population-wide implementations that increasingly rely on existing nationally representative survey data and big data, such as GIS infrastructure archives and Earth observation data. A mixed-methods approach is necessary to incorporate the different dimensions of the SCP illustrated in Table 1.

Finally, it is crucial to identify approaches integrating a systemic index. This requires careful steps of standardization, weighting and aggregation. Important references include the MEDI[25] and the MPI mentioned in the main text, the heat vulnerability index[95] with its applications to temperate[96], as well as tropical[97], regions.

As such, people living in vulnerable housing conditions, outdoor workers and dispossessed people can disproportionately suffer the negative externalities of AC use. Such uneven distribution of opportunities and externalities of thermal cooling technologies recalls issues explored in climate and environmental justice[66]. We use the term 'thermal justice', a concept that remains yet to be fully defined, as a subdimension of climate justice to characterize specific exclusionary patterns concerning thermal comfort within the SCP framework.

We posit that people are deprived of social infrastructures if the intersection between gender, age, ethnicity, race, migration status, disabilities, sexualities and class exacerbate social isolation and inequalities in relation to exposure to combined heat and humidity. A humidity-adjusted heat vulnerability index intersected with social vulnerability characteristics (low-income people and the older population among others) could be used to identify the neighbourhoods more exposed to heat shocks[67]. The index could also benefit from qualitative data gathering to enrich the level of details of perceived cooling poverty lived experiences and to include the ones who are usually invisible in surveys because of lack of intersectional characterization (for example, people in a situation of homelessness).

Health and cooling for nutrition and medical purposes

Cooling is fundamental for health and well-being in at least three important ways. Vaccines, organs for transplant and fertility treatments need appropriate cold chains[68] and cryopreservation technologies[69]. According to the WHO, cold-chain supported vaccinations and prenatal care are key to preventing deadly infections in children, such as diarrhoea, measles, pneumonia, polio and whooping cough[70]. Cooling is also responsible for ensuring proper nutrition. Cold chains and adequate commercial and residential refrigeration can save children and vulnerable people from diseases and mortality linked to improper and/or insufficient food conservation, which leads to food spoiling, intoxication by harmful bacteria, diarrhoeal diseases and malnutrition[71]. This may happen because of faulty appliances or lack of appropriate food cooling techniques, which increase food waste[71].

Humans react differently to increasing temperatures owing to personal attributes such as metabolism, age, sex, ethnicity, body mass and other physiological, biological and corporeal differences[72]. Body fat and skin thickness, for example, are responsible for the different reactions of the body to external temperatures, humidity and air velocity[73]. People affected by NCDs such as obesity, are more vulnerable to heat stress because adipose tissue impedes adequate heat loss[74]. People with diabetes and hypertension, are also more exposed to heat-related risks and conditions worsen in older population affected by chronic illnesses[75]. NCDs also include mental health illnesses, which have been proven to deteriorate during hot and humid periods, with an increase of suicidal rates[76].

Adequate temperatures throughout the gestational period are essential for pregnant women and unborn babies. Research[77] in Sub-Saharan Africa, shows important changes in fetal heart rates among pregnant working mothers. Stillbirths and preterm births were linked with higher temperatures during summers in Quebec[78], Australia[79] and the USA[80], while fetal growth and birth size were found to be irregular among pregnant women in Bangladesh[81].

People are deprived of cooling for medical purposes and nutrition if space cooling (active and/or passive) is not available. Children, people affected with NCDs, pregnant women and unborn babies are not safe from heat-related illnesses, if food preservation cannot be guaranteed. In the quantification of SCP, this dimension can be framed as a 'consequence' of cooling deprivation in the health and refrigeration sector. Understanding the epidemiology of heat-related health mortality and morbidity can help to identify the severity of cooling deprivation in a particular geography.

Education and working standards

Heat can also affect student performance and cognitive abilities. A study[82] conducted in the USA shows how heat probably alters human physiology and cognition affecting learning abilities and professional outcomes. Similar findings have been gathered by others[83] who found that students in non-AC buildings had reduced cognitive functions during the heatwave of 2016. In the summer of 2022, teachers in the UK reported lower concentration in students and many had to purchase portable AC[50]. Beyond the use of AC for cooling, water access is also fundamental for better education. A WHO study found that 35% of schools across Brazil do not have handwashing facilities[84]. In China, access to drinking water in schools had an impact on educational performance and school attendance among young rural students[85].

The lack of appropriate cooling infrastructure and working standards deeply affects outdoor workers and this is likely to be exacerbated by climate change[86]. Outdoor workers are more exposed to climate extremes, higher ultraviolet radiation, noise and air pollution[87]. A study conducted in Iran showed that 75% of the outdoor workers considered were exposed to heat stress in the hottest hours of the day (12:00–15:00)[88]. In such conditions, workers should be given appropriate hydration and clothing; they should take frequent breaks and be encouraged to suspend their activities to avoid heat stress.

The role of knowledge in intuitively adapting to excessive heat is crucial. This knowledge can be seen as an intangible infrastructure that guides people in effectively protecting themselves during heatwaves. Institutional knowledge plays an important role when health advisories are promptly and adequately disseminated to all segments of the population. Additionally, vernacular knowledge[89], including ethnic, local-based, intergenerational and Indigenous knowledge, is essential in providing effective behavioural measures to cool both the body and living spaces. Losing this intangible capital can result in inability to combat excessive heat.

We theorize that cooling deprivation in educational and work environments requires adequate active, passive and personal cooling provisions. Additionally, people's cultural capital influences their ability to intuitively cope with extreme heat. Assessing cooling infrastructures in education and workplaces can aid in identifying the severity of cooling deprivation in specific regions. Qualitative data can be valuable in assessing deprivations related to knowledge informing adequate cooling adaptation strategies.

We recognize some limitations of this paper. First, we did not include intrahousehold inequalities, which are also crucial and widely explored in the literature on gender and energy poverty (for example, see refs. 90,91). Second, we did not focus on the state of transportation infrastructures in urban and rural areas and their linkages with SCP, yet we do understand their importance, especially when people need to use affordable and available transport to reach the nearest cooling centres and hospitals. As the concept of cooling poverty develops and gains insights from empirical research, such limitations may be resolved.

Policy and practice implications

The multidimensionality of cooling poverty has important implications for both practice and policy. Given the heterogeneity in cooling needs for different vulnerable individuals and populations as well as the systemic nature of cooling poverty, it is essential that solutions are codesigned and implemented with multistakeholder input. The SCP index can help raise awareness to the understudied phenomena of heat vulnerability and thermal safety in diverse vulnerable populations. Ultimately, the SCP index should incorporate insights from a variety of professionals and practitioners (for example, community-based groups, architects, geographers, urban planners, health practitioners, engineers, sociologists, historians and intercultural experts) to inform the codesign of effective solutions. These codesigned solutions will need to take account of different scales, including individual, building and landscape-urban levels, which are incorporated in the SCP index.

For instance, as the rise in WBTs is increasingly affecting subtropical and temperate climates and record-breaking temperatures grip cities across multiple continents in the Northern Hemisphere, major cities of the developed and developing world are coming to terms with the serious threats posed by humid heat[92]. Chronic SCP is predominantly prevalent in tropical regions, where a combination of institutional, environmental and climatic factors, such as year-round persistent heat, render the population highly vulnerable to climatic events. This hampers their capacity to adapt to extreme heat and humidity, with some regions already facing insurmountable adaptation challenges. The combination of climate change, inadequate building infrastructure for hot weather and current geopolitical and economic shocks, can challenge temperate regions as well, which are already experiencing more frequent and long heatwaves and ecosystem tropicalization.

In policy-making, different considerations apply at the regional and country levels. Given the multidimensional and systemic nature of cooling poverty, effective coordination is needed between different sectors (for example, housing, healthcare, food and agriculture and transport). The SCP index can reveal promising areas for intervention, informing reasonable and ethical approaches for prioritizing the needs of different vulnerable groups and/or regions in the context of limited resources. For example, through quantification of chosen variables, the SCP index, could reveal that in tropical and subtropical regions, sanitation and accessible potable water should be prioritized over re-organizing urban infrastructure. The SCP index can help governments to make cooling interventions in a timely and ethical manner while accounting for trade-offs.

A key challenge to the operationalization of the SCP framework proposed here lies in its empirical calculation (Box 1), which we aim to demonstrate in future work.

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Author contributions
A.M. conceived the paper and wrote the manuscript. E.D.C. contributed to the conceptualization of the framework and writing. G.F. wrote Box 1 and edited the manuscript. A.J. contributed to the framework and prepared the health and policy sections. M.M. contributed to the climate section. R.K. contributed to the conceptualization of the framework and revision of the manuscript.

Competing interests
The authors declare no competing interests.

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