Understanding systemic cooling poverty

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Preface

Heat records are being broken across the world, leading to incalculable suffering; and the poorest and most disadvantaged people are the ones who will bear the most severe consequences of extreme heat. To combat this injustice, it is imperative that we gain a better understanding of the needs of those people when it comes to adapting to extreme heat and keeping cool. In this manuscript, we highlight a novel approach to understand 'Systemic Cooling Poverty' with the aim of informing policy and practice to support vulnerable populace.

Abstract

Current definitions of energy and fuel poverty do not consider the challenges posed by global warming, for instance, the combined effects of humidity and heat on health. We analyse how systemic infrastructural deficiencies can impact people's thermal comfort and wellbeing. We define 'Systemic Cooling Poverty' to characterise multidimensional and multiscale infrastructural deficiencies and inform potential solutions related to heat stress. We propose the creation of a Systemic Cooling Poverty multidimensional index that can inform global and regional-specific policies to ensure thermal comfort for all.

Main

Anthropogenic activities have driven global warming of 1.1°C since the 19th century[1], with 2014-2020 registering as the hottest in 140 years[2] and a high likelihood of reaching 1.5°C in the next ten to thirty years[1]. Heatwaves are increasing in frequencies, 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 systemic review by Liu et al[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). The magnitude of the already observed heat-related deaths and morbidity shows how unprepared society is in facing 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 buildings' construction materials tend to absorb heat in excess[10]. Rapid and uncontrolled urbanisation exacerbates the thermal wellbeing of urban areas as green and blue surfaces are often sacrificed 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 or AC), which is projected to dominate and heavily affect energy demand in emerging economies[12], which already face high incidence of heat. While air-conditioning's benefits 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 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 point that rising temperatures will be accompanied by growing levels of humidity, a combination which 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, the index of thermal discomfort, measuring the minimum temperature to which air can be cooled by evaporative cooling. High Wet Bulb Temperatures (WBT) are expected to change the biophysical, natural and urban landscape in ways which have not been sufficiently understood and can make some cities unliveable[18]. It is not in the scope of this paper to define or measure the insufficiency or deprivation levels of current passive cooling infrastructures. Instead, in this Perspective, we discuss how systemic cooling poverty is different from current definitions of energy and fuel poverty. We then thoroughly examine each dimension of cooling poverty, laying the groundwork for the development of a systemic cooling poverty multidimensional index. This index will aid policymakers in identifying vulnerable regions, communities, and individuals and, more importantly, facilitate the implementation of context-specific mitigation measures to ensure thermal justice.

Conceptualising Systemic Cooling Poverty

The history of energy and fuel poverty is replenished with hundreds of definitions and attempts to measure it. Bradshaw and Hutton's[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 initiative 'green home grant voucher scheme' to improve buildings' energy efficiency.

Reddy[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'. Particularly, 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, 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, post-purchase. Moreover, it does not account for the building stock's materials, orientation and energy efficiency, 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, researchers attempting to address the increasing demand for cooling, such as Bhatia and Angelou[28], Sanchez-Guevara[8] and Fabbri[29] have provided an extension of the existing concept of fuel and energy poverty. Fabbri[29] defined *cooling poverty* as 'the difficulty one has buying and installing air conditioners for the summer heat'. Other researchers such as Bienvenido-Huertas et al.,[30] have investigated the issue of indoors overheating during summertime and fuel poverty, but have 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 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 intuitive 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 to 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 understand 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 intra-household gender inequality in energy poverty, but only at the case-study level and with qualitative methods (see[34]).

Learning from the existing work on energy poverty and thermal comfort, we propose a definition of Systemic Cooling Poverty (SCP from now on) which 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 Systemic Cooling Poverty as "**the condition in which organisations, households and individuals are exposed to the detrimental effects of increasing humid heat stress as 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 immaterial, 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, green and white surfaces), building materials for adequate outdoor and indoor heat protection, and social infrastructures. SCP goes beyond households' financial constraints to pay for energy services, but instead 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 therefore play a key role in this conceptualisation of cooling poverty. Finally, SCP looks beyond energy and embraces a more multidimensional and multileveled analysis of infrastructures, spaces, and bodies.

The dimensions of Systemic Cooling Poverty

To best capture the multidimensional nature of SCP while maintaining humans at the centre, we build on the Multidimensional Poverty Index developed by Oxford Poverty and Human Development Initiative (OPHI)[35]. As in the OPHI, we retain the health and education dimensions of human wellbeing, 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 Systemic Cooling Poverty 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. Amartya 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 that is 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 characterise different nuances and degrees of poverty based on local realities and social standards. On this occasion, we will focus on a more objective absence of determined infrastructures, which can help cooling spaces and bodies outdoors and indoors.

Figure 1 summarises the five core dimensions defining the SCP and illustrates their 15 sub-dimensions or variables. Table 1 provides a first selection of variables that could be used to operationalise the five dimensions of the SCP. Box 1 develops a possible workflow of the empirical exploitation of the SCP.

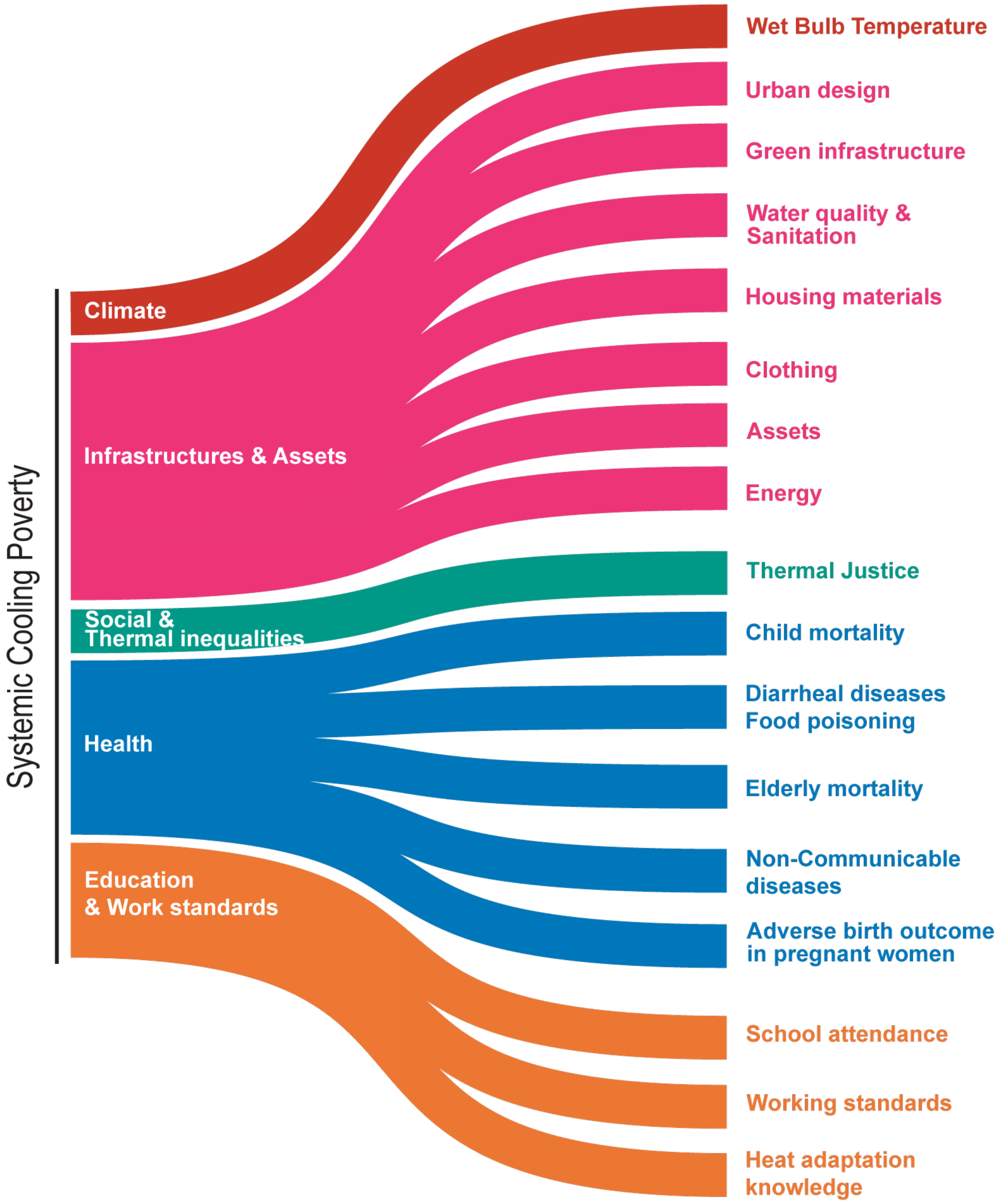

Figure 1 Defining dimensions of Systemic Cooling Poverty (SCP)

Climate

Humidity is fundamental to human physiological functions; however, excess humidity is related to several negative direct and indirect impacts for human health. The combination of increasing temperatures and 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 of existing research, relies on dry ambient air temperature which has been found 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 at temperatures as low as 32°C, especially among outdoor workers and elderly population[16]. As pointed by Coffel et al[37], some regions are more at risk of extreme WBT unsafe for humans, such as Northeast India, East China, West Africa and Southeast US[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 (Mistry 2020). Though 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 reasons: (i) WBT is directly measurable and routinely recorded at meteorological stations; (ii) Compared to other TDIs, WBT puts a higher weighting on RH ; (iii) Unlike other TDIs, WBT is used in both climate-health[39] and climate-energy impacts assessments[12].

We understand people find themselves in the condition of cooling deprivation in relation to combined high heat-humidity levels, above which passive cooling solutions on their own are incapable to maintain safe thermal comfort levels. Physiological studies using experimental laboratory conditions have demonstrated a specific range of indoor heat-humidity levels that are deemed uncomfortable 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 thermal comfort levels.

Infrastructures and Assets

Deficiencies in physical infrastructure is a direct cause of systemic cooling poverty. Extreme heat exposure is magnified in **urban areas** because of the 'urban heat-island' (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[9] and the reflection of heat in the atmosphere.

Nature-based solutions (NbS) or Green Infrastructure (GI) are effective in the reduction of urban anthropogenic heat through shading and evapotranspiration, particularly important in the mitigation of heat-island effects[41]. Across geographies, researchers have proven the effectiveness of NbS such as green roofs, which, compared to bare roofs, lowered surface temperatures 1-2 ºC in densely populated urban areas such as New York City[42], Rio de Janeiro [43] and Putrajaya in Malaysia[44]. **Similarly, urban green areas** and **urban parks** can also reduce urban heat-island effect. Motazedian et al[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. Coutts et al[45] argue that Water Sensitive Urban

Design (WSUD) 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 socialise 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 Organisation (WHO), there are over 2 billion people in the world lacking access to safe drinking water and sanitation and 3 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] which 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 urbanisation 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 vulnerable regions to cooling poverty.

Wearing adequate protective clothing is an established adaptive strategy which 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 culture 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 wellbeing, access to active and sustainable cooling is fundamental. The absence of adequate **energy infrastructure** can jeopardise the correct functioning of cold chains which 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, which is expected to increase by 75% by 2050[59]. Unplanned power outages could ultimately damage people with comorbidities and NCDs that 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 in developed[29] and developing geographies[12]. The adoption of cooling appliances which 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 (MEPS) is key to identifying countries, and regions within them, which can be vulnerable to systemic cooling poverty.

We understand 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 a way that increase shading and ventilation; if nature-based solutions are not in use; if safe water and sanitation is not available; if building materials and building codes are worsening indoors thermal comfort; if cooling textiles and clothing are unaffordable and not available; if there is a condition of energy infrastructure insecurity and lack of access to affordable and efficient mechanical cooling. At macro-level analysis, remote-sensing based data and indicators, such as the Normalized Difference Vegetation Index, could

support the characterisation 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 micro scale (city-level or neighbourhood-level), surveys could characterise 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. The inequality of cooling poverty is manifested in socio-spatial vulnerabilities which afflicts the most marginalised groups. **Social inequality** rooted in individual characteristics and preferences (gender, ethnicity, race, sexuality), economic conditions (income disparities, low-income), and dwelling conditions (generally low-quality materials with high-energy requirements) are entwined with **spatial residential segregation patterns** (building cluttering, extreme land use, scarce green areas/waterbodies) in which low-income dwellers tend to be located. **Vulnerable urban dwellers** not only are economically and socially segregated, but they are more at risk of environmental and health hazards. For example, Chakraborty et al[62] found that in 25 cities around the world there is a strong spatial relationship between low income neighbourhoods and the severity of Urban Heat Island (UHI). Keller[63] and Klinenberg[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. Vulnerable people are also affected by an **unequal use of AC** in urban areas. For example, the heat dumped from high-income dwellings can exacerbate 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. Girgis[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 of El Hussein Square in Egypt. 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 characterise specific exclusionary patterns concerning thermal comfort within the SCP framework.

We understand 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/humidity. A humidity-adjusted heat vulnerability index intersected with social vulnerability characteristics (low-income dwellers, 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 characterisation (e.g., people in a situation of homelessness).

Health and cooling for nutrition and medical purposes

Cooling is fundamental for health and wellbeing 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 World Health Organisation, cold chain supported vaccinations and prenatal care are key to **prevent 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 also save children and vulnerable people from diseases and mortality linked to improper and/or insufficient food conservation, which leads to food spoiling, intoxications by harmful bacteria, diarrhoeal diseases and malnutrition[71]. Such occurrences may happen because of faulty appliances or lack of appropriate food cooling techniques, which increase food waste[71].

Humans react differently to increasing temperatures based on 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 **Non-Communicable Diseases (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 has been proven to deteriorate during hot and humid periods, with an increase of suicidal rates[76].

Exposure to adequate temperatures throughout the gestational period is also fundamental among pregnant women and unborn babies. Bonell et al[77] in Sub-Saharan Africa, show important changes in foetal heart rates among working mothers. Stillbirths and preterm births were linked with higher temperatures during summers in Quebec[78] Australia[79] and US[80], while foetal growth and birth size were found to be irregular among pregnant women in Bangladesh [81].

We understand people are deprived of cooling for medical purposes and nutrition if space cooling (active and/or passive) is not available to keep children, people affected with NCDs, and pregnant women, and unborn babies 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 identify the severity of cooling deprivation in a particular geography.

Education and Working Standards

Heat can also affect **student performance and cognitive abilities**. Park et al[82] conducted a study in the US showing how heat most likely alters human physiology and cognition impacting on learning abilities and professional outcomes. Similar findings have been gathered by Cedeño Laurent et al[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 United Kingdom 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 affect **outdoor workers** and this is likely to be exacerbated due to climate change[86]. Outdoor workers are more exposed to climate extremes, higher UV radiation, noise and air pollution[87]. A study conducted in Iran showed that 75% of outdoor workers, considered in the study, were exposed to heat stress in the hottest hours of the day (12-3pm)[88]. In such conditions, workers should be given appropriate hydration, and clothing, they should take frequent breaks and should 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 immaterial infrastructure that guides people in effectively protecting themselves during heatwaves. Institutional knowledge plays a significant 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 immaterial capital can result in a deprivation of the tools needed to combat excessive heat.

We understand 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.

Table 1. Systemic Cooling Poverty - key dimensions and variables

Dimensions	Variables	Deprivations in relation to systemic cooling	Ref
Climate	WBT	Deprived if combined temperature/humidity reaches unliveable levels	90
Thermal comfort Infrastructures & Assets	Urban Planning	Deprived if passive and natural cooling is not available (i.e., natural ventilation; shading, public squares, cool pavements, 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.	91
	Housing materials	Deprived if inadequate housing conditions hinder or block the building's passive cooling potential	55
	Clothing	Deprived if appropriate clothing for heat protection is not available (e.g., synthetic clothing trap heat)	32
	Assets	Deprived if appropriate refrigeration and space cooling devices are not affordable Deprived if obsolete highly inefficient cooling technology 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, fans) and food refrigeration	59
Social and thermal inequality	Thermal Justice	Deprived vulnerable populations (by gender, age, ethnicity, race, migration status, disabilities, sexuality, class) are exposed to heat shocks and urban heat island effects	14
Health	Child mortality; Diarrheal diseases; Food poisoning; Elderly mortality & morbidity	Deprived if space cooling (active or passive) is not available to keep children safe from heat-related illnesses	70

		Deprived if refrigerators to preserve food are not available, extreme heat increases enteric pathogens and disrupt intestinal microbiota balance	
	Non-Communicable Diseases	Deprived if space cooling (active or passive) is not available to relief people affected with Non-Communicable Diseases (cardiovascular diseases, chronic respiratory diseases, diabetes, cancers, mental health conditions)	75
	Adverse birth outcome in pregnant women	Deprived if space cooling (active 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 (passive or active) hinders the attendance of educational courses	83
	Working standards	Deprived if appropriate passive, active and personal cooling are not provided for worker's health and wellbeing	88
	Heat adaptation knowledge	Deprived if people do not have cultural capital to mitigate the effects of extreme heat	89

Box 1: Towards the operationalisation of the Systemic Cooling Poverty framework: some initial considerations.

Implementing the proposed Systemic Cooling Poverty (SCP) framework firstly necessitates a consideration of: (i) the **level of the implementation**, which can range from the local scale (e.g. a city), to the country level, up to a globally-relevant assessment; (ii) the **granularity of the implementation**, which can span from the individual or household level up to macro-scale, population-wide analysis. Based on these dimensions, different potential data sources, variables, and measurement and processing techniques can be employed to operationalise the SCP framework.

First, nationally representative or ad-hoc collected **household survey data** are suitable for capturing dimensions of **(i) micro-infrastructure** (housing quality and materials, assets ownership), **(ii) expenditure capacity** in relation to the cost of services (electricity and water prices, AC units and refrigerators upfront cost). Second, **sub-national or national statistics** have the potential to inform about (i) **access to services** (electricity, water) and (ii) **costs and prices** of e.g., utility bills, appliances, and products, as well as (iii) **prevalence of health-related issues** such Non-Communicable Diseases among different strata of a population. Third, **geospatial data and related GIS processing techniques** bear large potential to contribute to measuring **urban infrastructure** and its availability, accessibility, and **distribution inequity and inequality** in relation to different population groups. These include, for instance, the availability of urban green space and shaded areas. Relatedly, **climate reanalysis and earth observation data products** also have a key role to play in operationalising the SCP framework. They allow measuring the values and distribution of different **climate-related metrics**, such as wetbulb (humidity-adjusted) temperature, in terms of both cumulative (long-run average values) and acute values (e.g., peaks). High-resolution, downscaled products (or/and local weather station networks) can then even allow **differentiating** between exposure levels within a city and in relation to the different characteristics of the population living in each area. Fourth, **policy analysis and qualitative methods** are a necessary tool for assessing dimensions such as heat adaptation knowledge, adaptation behaviour drivers and responses (e.g., clothing decisions, or information on how to best mitigate the effects of heat), as well as broader regulatory contexts and the effectiveness of their actual implementation (e.g., temperature exposure-related work regulation, and public buildings infrastructure and regulation).

The scale and granularity of the SCP implementation will determine the level of aggregation of each dimension and the best suited variables to characterise them, spanning from individual household and city-level high-quality data and ad-hoc collected information to country and population-wide implementations increasingly relying on existing nationally representative survey data and big data such as GIS infrastructure archives and earth observation data. In addition, a **mixed-methods approach** is necessary to incorporate the different dimensions of the SCP illustrated in Table 1.

Finally, besides approaches to measure and understand each individual dimension, it is crucial to identify approaches to integrate those into **a systemic index**. This requires careful steps of standardization, weighting, and aggregation. Important references include the Multidimensional Energy Deprivation Index[25] and the Multidimensional Poverty Index mentioned in the main text, the Heat Vulnerability Index[92] with its applications to temperate[93] as well as tropical[94] regions.

While identifying the most evident causes behind systemic cooling poverty, we recognise 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, see [95]. Second, we did not focus on the state of transportation in urban and rural areas and its linkages with cooling poverty, yet we do understand its importance, especially when people need to use affordable and available transport to reach the nearest cooling centres and hospitals. We intend to resolve such limitations in future studies as the concept of cooling poverty develops and gains insights from empirical research.

Discussion and conclusion

The development, measurement and monitoring of multidimensional indices are increasingly recognised as an important tool to inform policy and advance progress in society, and they are particularly useful when incommensurable dimensions co-exist and need to be evaluated simultaneously[96]. Indices have the advantage of facilitating comparison across countries, regions, as well as over time, and can more easily inform policy.

Here we demonstrate how cooling poverty is multidimensional and multiscale, and it is part of a complex system of deprivations and systemic inequalities. In this context, the development of a Systemic Cooling Poverty Index can help raise awareness to the understudied phenomenon of heat vulnerability and thermal safety. As the rise in wet bulb temperatures 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[97]. Chronic systemic cooling poverty 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 geo-political and economic shocks, can challenge temperate regions as well, which are already experiencing more frequent and long heatwaves and ecosystem tropicalization.

This paper lays out a conceptual guidance providing the basis for the selection, measurement, and combination of the single variables that define the concept of SCP. An illustrative empirical execution of two of the defining variables of the SCP concept demonstrates the complexity of empirically calculating the proposed index. Consider housing material and clothing. An individual is deprived of appropriate cooling comfort if inadequate housing conditions hinder or block the building's passive cooling potential. Information about housing materials, specifically with respect to walls and roofs, is often available in nationally representative, large-scale household surveys in many countries. Another easily quantifiable variable that can indirectly inform about a house's passive cooling potential is the expenditure on electricity for low-income households located in warm places. This type of empirical implementation would characterise deprivation with respect to Thermal Comfort Infrastructure and Assets at the macro level, across broad geographical areas. However, these proxies would fail to capture the role of elements such as noise, air pollution, safety, or building orientation. Dedicated surveys on housing conditions are available for selected countries and selected years, but not necessarily with the required granularity. If building-specific elements are to be included in housing materials, a dedicated survey would probably be needed to deepen the characterisation of this dimension. While household budget surveys and international trade data trace the expenditure and imports of goods, including clothing, deprivation is here defined in relation to the ability to shield the human body from excessive heat, requiring an understanding of the actual material used. While income levels are likely to be correlated with clothing quality, this does not necessarily correlate with their protective effect.

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 co-designed and implemented with multi-stakeholder input. The SCP index can help practitioners gain a thorough understanding of the needs of the diverse vulnerable populations suffering from SCP and then incorporate insights from a variety of professionals and practitioners (e.g., community-based groups, architects, geographers, urban planners, health practitioners, engineers, sociologists, historians, and intercultural experts) to inform the co-design of effective solutions. These co-designed solutions will also need to take account of different scales including the individual, building, and landscape-urban level, which are also incorporated in the SCP index. Finally, the implementation of these solutions will require an understanding of the cost-benefit as well as trade-off considerations to ensure the most efficient and effective use of resources, especially in lower- and middle-income countries.

At the policy level, different considerations will need to be made at the regional and country levels. Given the multidimensional and systemic nature of cooling poverty, it is important that there is effective coordination between different sectors (e.g., housing, healthcare, food and agriculture, transport). The SCP Index can help reveal some of the most important and promising areas for intervention, which can serve to inform considerations on reasonable and ethical approaches for prioritisation of the needs of different vulnerable groups and/or regions in the context of limited resources. For example, through the quantification of the chosen variables, the SCP index, could reveal that in tropical and subtropical regions, addressing the issues of sanitation and accessible potable water should be prioritised over reorganising urban infrastructure. The SCP index can help governments to make the most needed cooling intervention in a timely and ethical manner while accounting for important trade-off considerations. We aim to demonstrate the empirical application of SCP framework in future works.

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