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Sustainable Cooling in a Warming World: Technologies, Cultures, and Circularity

Radhika Khosla,[1,2] Renaldi Renaldi,[2,3]
Antonella Mazzone,[1,2] Caitlin McElroy,[1,2]
and Giovani Palafox-Alcantar[1,2]

[1] Smith School of Enterprise and the Environment, School of Geography and the Environment, University of Oxford, Oxford, United Kingdom; email: radhika.khosla@smithschool.ox.ac.uk

[2] Future of Cooling Programme, Oxford Martin School, University of Oxford, Oxford, United Kingdom

[3] School of Water, Energy and Environment, Cranfield University, Cranfield, United Kingdom

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Abstract

Cooling is fundamental to quality of life in a warming world, but its growth trajectory is leading to a substantial increase in energy use and greenhouse gas emissions. The world is currently locked into vapor-compression air conditioning as the aspirational means of staying cool, yet billions of people cannot access or afford this technology. Non–vapor compression technologies exist but have low Technological Readiness Levels. Important alternatives are passive cooling measures that reduce mechanical cooling requirements and often have long histories of local use. Equally, behavioral and cultural approaches to cooling play a vital role. Although policies for a circular economy for cooling, such as production and waste, recovery of refrigerants, and disposal of appliances, are in development, more efforts are needed across the cooling life cycle. This article discusses the knowledge base for sustainable cooling in the built environment and its significant, interconnected, and coordinated technical, social, economic, and policy approaches.

Contents

1. THE MULTIDIMENSIONALITY OF COOLING

Cooling is becoming a fundamental demand in a warming world. It is critical for maintaining thermal comfort and health and enabling productivity. The need for cooling is projected to rapidly increase in the coming decades due to a combination of factors such as increasing frequency and intensity of extreme heat from climate change; rapid urbanization across countries; and growing economies, household incomes, and populations, especially of the hottest parts of the world. Under current conditions, three-quarters of the world's population will face health risks from deadly heat (1), and approximately two to four billion people will need space cooling solutions to avoid these risks (2). By 2070, 3.5 billion people will be exposed to mean annual temperatures $\geq$29.0°C, a situation found only in 0.8% of global land surface at present but projected to expand to 19% of global land, affecting not only traditionally hot regions (3). In 2020 alone, record temperatures resulted in a new high of 3.1 billion more person-days of heatwave exposure among older people (>65 years), and 626 million more person-days affecting children younger than 1 year, compared with the annual average for 1986–2005 (4).

Air conditioning is widely accepted as the immediate technological space cooling solution for warming weather and thermal comfort. Given the projected rise in cooling needs, the energy required for space cooling is estimated to triple by 2050, which will require electricity capacity larger than the combined generation capacity of the United States, European Union (EU), and India in 2016 (5). However, owning a cooling device does not only depend on exposure to climatic conditions (particularly the combined effect of temperature and humidity) but also on socioeconomic and cultural factors, such as an ability to afford and access cooling. Despite the exponential rate of air conditioning increase that is projected, there is estimated to be a staggering cooling gap of 2–5 billion people in 2050 who are exposed to heat stress but do not have the capacity to adapt to it with an air conditioner (AC) (6, 7), making equity a central issue to the future of cooling. Furthermore, although air conditioning is likely to be the world's primary heat reduction strategy,

Air conditioning: the process of modifying air temperature, humidity, and/or air quality to primarily achieve thermal comfort

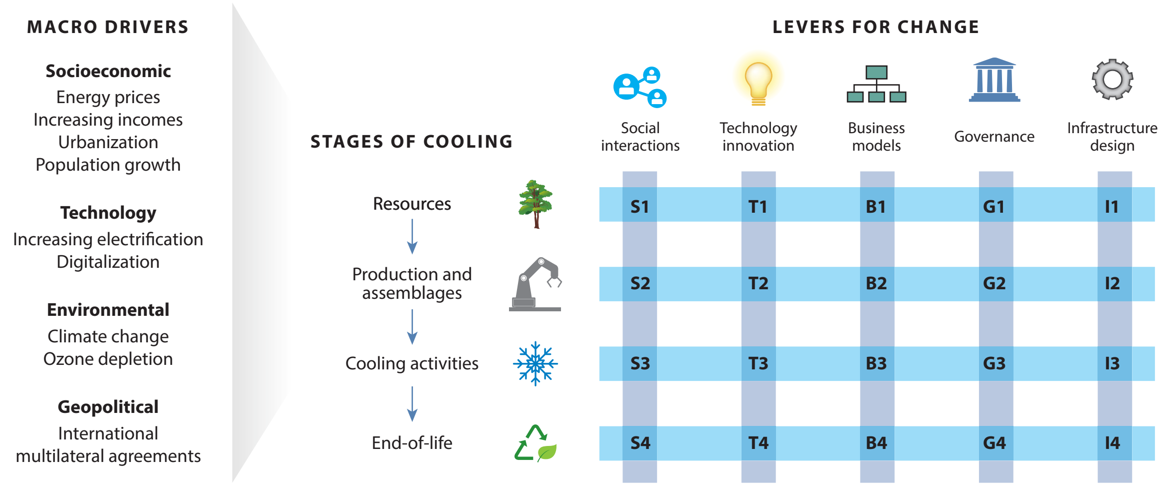

Figure 1

Analytical framework for transitioning toward sustainable cooling. Figure adapted with permission from Reference 8.

it exacerbates global warming and fuels further extreme heat events, resulting in a vicious cycle that increases the need for more ACs.

Although the immediate links to and opportunities from cooling are made with heat, thermal comfort, and energy consumption, evidence shows that cooling is in fact directly linked to all 17 Sustainable Development Goals (SDGs) (8). For instance, the goals of zero hunger (SDG 1) and good health and well-being (SDG 3) are supported by satisfying cooling demand through cold chains for food and medicine. The provision of domestic space cooling for thermal comfort is also related to SDG 3, quality education (SDG 4), and reduced inequalities (SDG 10). Such links with cooling have been charted for each of the SDGs and illustrate the pervasive and multidimensional nature of cooling and its challenges. The solution space toward sustainable cooling is thereby equally multidimensional, drawing from studies of and actions within governance, social cultures, technology, business models, and infrastructure (**Figure 1**).

Despite its relevance to sustainability, cooling has remained relatively understudied in the academic literature. This article helps to fill the gap by providing an interdisciplinary overview of the multiple dimensions of the cooling challenges and opportunities. The article approaches cooling as a sociotechnical system comprised of technologies and social elements that are interlinked and reflective of the way cooling trajectories are influenced and shaped. It focuses on space cooling within the built environment, which is the largest contributor to cooling-related greenhouse gas (GHG) emissions (9). Starting with a focus on technologies, and lock-ins to incumbent cooling modalities, the article traces alternatives to energy-intensive cooling, particularly the role and significance of passive cooling measures. It then discusses the role of the individual, society, and culture in determining how technologies get embedded into everyday life and how people are active agents with varied local responses to pursuing relief from hot temperatures. Following this, the article looks to the future for integrating the delivery of sustainable cooling technologies and approaches within a circular economy, including discussing supportive policy and business models. In addressing these various dimensions of cooling, the article brings forth the interacting technical, social, economic and policy elements of this global issue and identifies central research themes for the future of cooling, climate change, and sustainable development.

Passive cooling: cooling mechanisms that require low or no mechanical energy input to achieve thermal comfort

Circular economy: a set of principles and tools that contribute to planet sustainability by minimizing resource extraction, promoting conservation, and driving regeneration

2. COOLING TECHNOLOGIES AND ALTERNATIVES

We begin by discussing how global cooling demand is both currently and projected to be largely met by electricity-driven vapor-compression cycle ACs. This section provides an overview of the cooling technological lock-in, and other not-in-kind or non–vapor compression cooling technologies. It also highlights the significance of passive cooling measures for thermal comfort, improved energy efficiency, and cooling energy demand reduction.

2.1. Global Technological Lock-in

Global space cooling demand is currently fulfilled almost exclusively by electric-driven fans and ACs. Residential electric fans in use were estimated at 2.3 billion worldwide, and the global sales of ACs have been growing steadily in the past decades, with an estimated 1.6 billion installed in 2016 (5). Electric fans are especially vital to maintain thermal comfort for populations in hot and humid regions with poor access to quality electricity supply and with limited affordability of more expensive technologies (10). Although there is scope for improving typical fans' efficiency, for example, through motor and blade design improvement, the corresponding cost increase can be high without market scale (11). Furthermore, the fans-over-AC ownership ratio is expected to fall rapidly as AC ownership continues to rise with growing incomes and urbanization in many hot climates, and in other regions with increasing extreme heat.

The energy and climate challenge of ACs lie in their high energy consumption. ACs are estimated to have used 2,000 TWh/year of electricity in 2018 and projected to triple use by 2050 (9). Global CO_2 emissions from space cooling are expected to double from 1,135 million tonnes (Mt) in 2016 to 2,070 Mt in 2050 (12). This significant emissions rise is projected despite the declining carbon intensity of global power generation. The overall GHG emissions from ACs are both direct and indirect (13): Indirect emissions are related to power generation activities that supply electricity to the AC system, and direct emissions stem from escaping refrigerant from the AC system into the atmosphere during charging, maintenance, leakage, break-down, and end-of-life disposal.

This current ubiquity of ACs can be traced back to the postwar period in the United States, which saw a rapid growth in commercial air conditioning, such as in retail and movie theatres (14). Combined with the approach of standardized building design, which is cheaper but disregards the local climate, air conditioning systems shifted from being viewed as an amenity to a necessity (15). This transformation has now happened worldwide, risking a global lock-in for space cooling applications—technologically, institutionally, and behaviorally (16). Technologically, the vapor-compression cycle has been the most dominant technology for more than six decades. The technology is thriving due to its low cost, high efficiency, good safety records, and high scalability. It also has wide-ranging applications including in domestic refrigerators and ACs, commercial chillers, automotive ACs, and refrigerated containers. The lock-in for cooling is different from that of heating, which is present on a national level rather than globally and has a variety of different technologies in use (17). For example, domestic heating in the EU has been fueled by a combination of natural gas, oil, coal, electricity, and biomass. The United Kingdom is mainly reliant on natural gas for its domestic heating systems due to the rapid expansion of gas boilers and the corresponding distribution pipelines since the 1960s. Furthermore, hot water–based central heating systems are common in Europe, whereas warm air–based systems are more prevalent in the United States. We discuss the details of the dominant vapor-compression cooling technology next.

2.2. Current Dominant Cooling Technology: The Vapor-Compression Cycle

AC units around the world use a standardized scientific principle. A cooling effect from the vapor-compression cycle is produced by modifying the phase of the working fluid, the refrigerant,

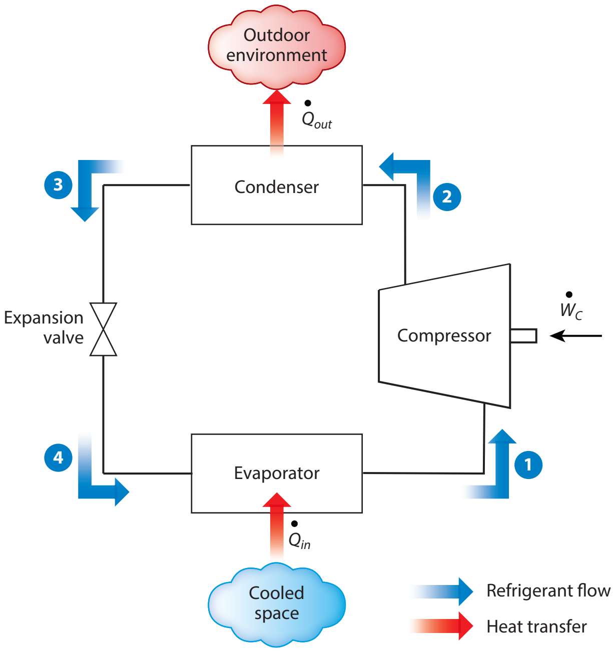

Figure 2

Illustration of a vapor-compression cycle. Heat from the cooled space (Q_{in}) is transferred to the working fluid in the evaporator and rejected to the ambient air (Q_{out}) in the condenser. During the evaporating stage, the thermal energy from the cooled space, Q_{in}, is transferred to the refrigerant (Process ④–①). The electrical energy input, W_c, is required in the compressing stage where a compressor increases the pressure of the saturated vapor refrigerant (Process ①–②). During the condensing stage, the thermal energy is transferred from the refrigerant to the environment, Q_{out} (Process ②–③). The cycle is closed as the refrigerant is throttled to a two-phase liquid-vapor mixture before entering the evaporator (Process ③–④).

through compression, condensation, expansion, and evaporation (**Figure 2**). The electrical energy input, W_c, is required in the compressing stage where a compressor increases the pressure of the saturated vapor refrigerant (processes 1 and 2 in **Figure 2**). During the evaporating stage, the thermal energy from the cooled space, Q_{in}, is absorbed by the refrigerant. This stage occurs in the indoor unit of a typical split-type AC. During the condensing stage, the pressurized refrigerant transfers the thermal energy, Q_{out}, to the environment. This stage typically happens in the outdoor unit of a split AC. The cycle is closed as the refrigerant is throttled to a two-phase liquid-vapor mixture before entering the evaporator (processes 3 and 4 in **Figure 2**). The performance of a vapor-compression cycle is measured by its coefficient of performance (COP), which is defined as the ratio between the thermal load and the work input, i.e., COP $= Q_{in}/W_c$. These fundamentals have driven the cooling industry since its initial rise. And as a result, the incumbency of this vapor-compression technology also introduces boundaries around how dramatic energy and GHG reduction can take place within the technology's core thermodynamic structure.

Improving the energy efficiency of ACs is one option to decrease their indirect emissions by ensuring the same cooling load can be served by lower electricity supply. Specifically, a vapor-compression cycle has inherent thermodynamic losses that are to be minimized to increase its COP. Despite being a mature technology, modifications to improve the COP of vapor-compression cycles are still widely investigated, including subcooling, expansion loss recovery, and multistage cycles (18). Typical ACs have a COP of 2.3–3.5, with many minimum energy performance standards (MEPS) prescribing threshold levels between 3.0 and 3.5. For example, China's MEPS thresholds for fixed-speed drive room ACs with capacity less than 4.5 kW are 3.6 (Grade 1), 3.4 (Grade 2), and 3.2 (Grade 3) (19).

A step forward to improve AC efficiency was the 2018 international Global Cooling Prize, which resulted in a cooling system with five times lower climate impact at not more than twice the cost of the standard AC units sold in the market (20). The advancements included several key improvements to the standard vapor-compression cycle that tackle both temperature and humidity: variable-speed compressor, improved evaporator design and controls, direct evaporative cooling at the condenser, integrated photovoltaics and direct current components, and the use of low-GWP (global warming potential) refrigerants (20). Variable-speed compressors improve AC performance by modulating operations according to load conditions and avoid frequent on-off switching (21–23). Improvements on the evaporator design and controls avoid overcooling by separating the sensible and latent cooling load in the space, and have an energy savings potential between 7 and 12% (24). Integrated photovoltaics can directly power approximately 50% of global cooling demand in the twenty-first century, reducing indirect emissions (25). Although this resulting "gold standard" of the routinely used AC is an important step in moving the technology to higher levels of efficiency, pathways to scale the product and support its testing facilities are yet to be determined.

Another pathway to improved energy performance of vapor compression–based cooling is through MEPS (mentioned above), which are prevalent across countries. For instance, the room AC MEPS in China have the potential to reduce cumulative CO_2 emissions by 12.8% between 2019 and 2050, with cost savings of more than 2,500 billion RMB (Chinese yuan) (19). In practice, the energy efficiency of marketed ACs depends highly on country-specific legislations and their implementation in the field. Furthermore, refrigerants remain key to the global cooling technological lock-in. In the early refrigeration technology of the twentieth century, refrigerants were flammable or toxic, confining their use mainly to industrial systems (26). Safer refrigerants, based on chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), were then developed to satisfy the demand for residential and commercial space cooling. After recognizing their high ozone depletion potential (ODP), CFCs and HCFCs have been phased down with the Montreal Protocol treaty in 1987 (27). They are mainly replaced by hydrofluorocarbon (HFC)-based refrigerants, short-lived gases which have no ODP. However, the GWP of HFCs is still high, ranging between 1,340 GWP_{100} for R134a and 3,940 GWP_{100} for R404a. In 2016, the Kigali Amendment to the Montreal Protocol was initiated to phase down these high-GWP HFCs (27). We discuss policies for cooling in Section 4.

Finally, district cooling is another option to improve the efficiency of delivering cooling by centralizing the main cooling equipment. A district cooling system distributes thermal energy in the form of chilled water from a central source to consumers for space cooling and dehumidification application (28). The system typically consists of four parts: the central chiller plant, the heat rejection system, the distribution system, and the end users (29). In addition to energy efficiency, district cooling systems can include more sustainable heat/cold sources, such as the combination of waste heat and renewable heat with thermally driven cycles (absorption or adsorption), and the direct use of deep or surface water and liquid natural gas regasification as a cold source (30). Furthermore, in climates where both cooling and heating are required, fifth generation district heating and cooling can be a promising solution. Here, a thermal network is able to supply and extract heat at relatively low temperatures, and heat pumps are installed with end users to satisfy the heating and/or cooling demand (31).

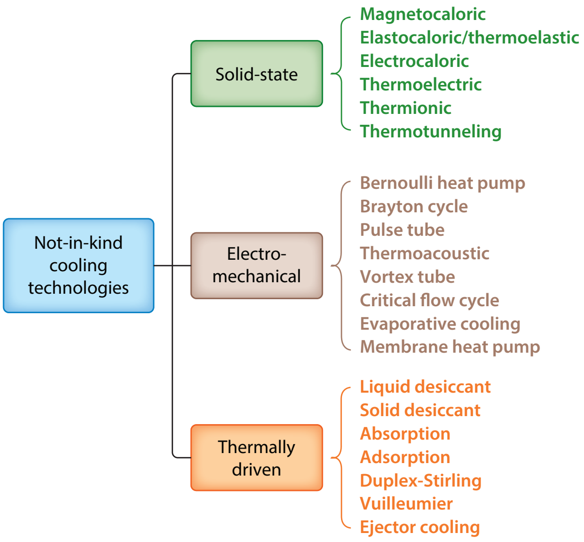

Figure 3

Classification of not-in-kind cooling technologies based on primary energy input and working material. The technologies are divided into three major categories: solid-state, electromechanical, and thermally driven cooling. Figure adapted with permission from Reference 35.

2.3. Alternative Cooling Technologies

Another important option to minimize the environmental impacts of ACs is to use non–vapor compression (or not-in-kind) cooling technologies, most of which use no or low-GWP refrigerants. Such technologies have been developed in the past decades and can be categorized based on different characteristics. **Figure 3** shows a classification based on primary energy input and working material (32).

Comparative reviews of not-in-kind technologies conclude that most of these technologies are still in low Technological Readiness Levels, and technical progress on some of them has been slower than expected (33, 34). Lower energy efficiencies and higher costs are often cited as the main limitations of alternative cooling technologies, with significant technical breakthroughs required to improve their market potentials. A patent-based study shows that absorption, evaporative, thermoelectric, magnetocaloric, and adsorption are emerging technologies with potential applications in space cooling (35) (**Figure 4**). Although more research is required to improve the performance of technologies of low–moderate maturity, supportive deployment-oriented policies are necessary to increase the installation of cooling technologies with moderate–high technical maturity.

With regards to alternative refrigerants, the search for low-ODP and low-GWP refrigerants presents challenges to balance the trade-offs between energy efficiency, safety, cost, availability, and environmental considerations of new refrigerants (26). HFCs have been the fastest growing GHG in response to the success of the Montreal Protocol (36, 37). Hydrofluoroolefins (HFOs) have been identified as one replacement for HFCs (being a subcategory of them) (38). Even though HFOs have GWP_{100} values of less than 1, HFOs typically still need to be mixed, for example with HFCs, in order to obtain a nonflammable blend or for direct substitution in existing equipment. Naturally, this practice will result in a higher GWP_{100}. Another option for low-GWP

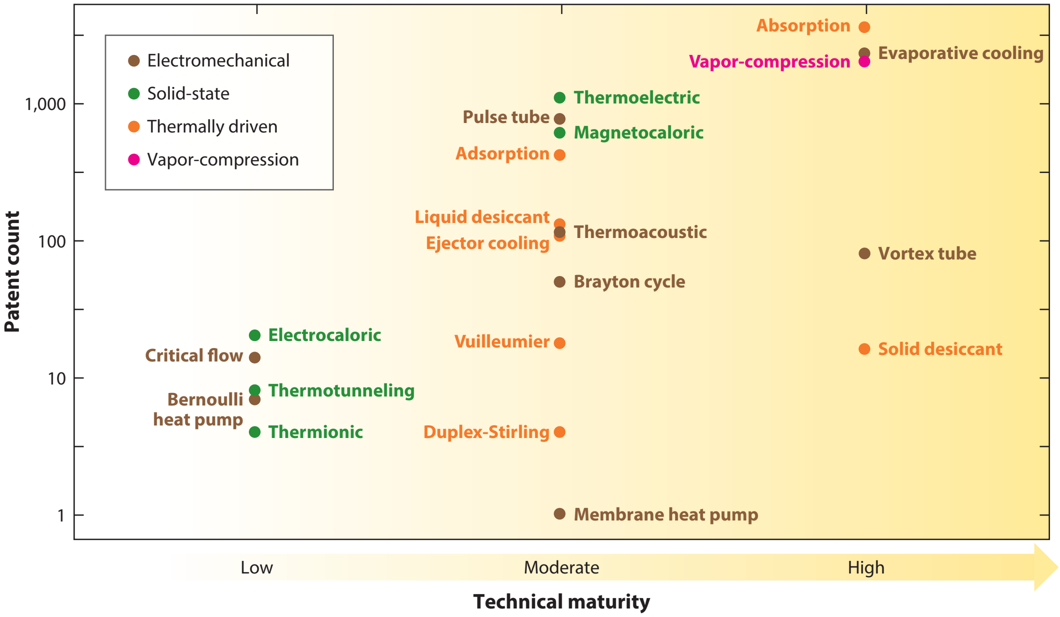

Figure 4

Maturity level and patent number counts of not-in-kind cooling technologies. The *y*-axis (patent family count) is in logarithmic scale. The technical maturity levels are based on qualitative evaluations of the technology. The clusters of cooling technologies are expected to follow a diagonal trend line; i.e., mature technologies will have higher patent family counts. There is approximately an order of magnitude patent count threshold between technical maturity levels. Figure adapted with permission from Reference 35.

refrigerants is to use natural refrigerants, such as ammonia and hydrocarbons. Their use is commonplace in industrial systems where large equipment size is less of an issue and flammability and toxicity can be more readily managed. Nevertheless, the use of natural refrigerants in residential space cooling is a debated subject due to size suitability, lifecycle emissions, and increased safety measures.

Energy efficiency improvements, alternative refrigerants, and not-in-kind cooling are all important measures in limiting the environmental impacts of increasing AC uptake worldwide. However, the relatively limited near-term alternative options to vapor-compression ACs highlight the importance of space cooling demand reduction. Ultimately, passive measures that limit the need for mechanical cooling—discussed next—are core to scaling a more sustainable approach to cooling.

2.4. Cooling Demand Reduction by Passive Measures

Passive cooling measures, which use minimum or no electric energy, have been used across geographies and cultures to deliver thermal comfort long before the advent of the AC. They are low maintenance, have lower running costs, and do not use refrigerants. Unlike quick-fix AC solutions, buildings' passive cooling measures are mostly integrated deeply in building design. Furthermore, passive cooling measures span multiple spatial levels, e.g., buildings, neighborhood, and cities. Although societies have long used passive cooling techniques to protect themselves from extreme heat, their wide application and integration in modern urban built environments is complex, as it involves multiple actors: architects, engineers, policy planners, real estate developers, and end users, among others. Passive cooling measures are also widely studied as the main strategies to mitigate urban heat islands (UHIs) (39). For example, using a highly reflective coating on roofs can contribute to 0.2–0.6°C of cooling for every increase of 0.1 in neighborhood albedo (fraction of light reflected) (40).

Passive cooling measures that operate at the building level can be structured into three categories (41, 42). The first category is heat gain prevention/protection measures to avoid heat gains by blocking or minimizing incoming solar irradiation. These include using vegetation, water bodies, shading, and glazing to minimize solar heat gain. For buildings, heat gain can be reduced by modifying the thermal and optical properties of the building's interface with the environment. Green roofs and cool roofs are also widespread examples of roof-based heat prevention measures (43). Green roofs involve covering the rooftop of buildings, either partially or completely, with vegetation and growing medium (44–46), and their benefits include reducing building energy consumption, mitigating the UHI effect (combining building level and other microclimate-scale passive measures), increasing urban biodiversity, improving water management, and reducing noise pollution (45–47). Cool roof measures minimize solar heat gain by increasing the roof solar reflectance (48), leading to energy savings and peak demand reductions (49, 50). Cool roofs are also found to have the potential for reducing heat-related mortality during heatwaves (51). In one example, a cost-benefit study of implementing smart surfaces, including cool and green roofs, in the city of Baltimore estimated significant reductions in peak summer temperature and reduced structural inequality in lower-income areas through improvement in air quality, employment, and lower energy bills (52). Other examples of heat prevention include preventing solar heat gain from windows by modifying the glazing properties and implementing shading techniques. Relevant glazing properties are U-value, solar heat gain coefficient, and visible transmittance (42). The need to balance energy performance and other important aspects, e.g., vision, ventilation, and daylight, has led to the development of numerous glazing technologies, such as multilayer glazing, low-emittance coatings, spectrally selective coatings, and smart glazing (53). More recently, an ultrawhite paint and film has been developed to achieve high performance in solar reflectance (approximately 97.6%) and reach an average cooling power of 117 W/m^2 (54).

The second category of passive cooling measures is heat modulation, which aims to delay or displace peak temperature. This can be achieved, for example, by using the building thermal mass to retain heat during the day before releasing it to the ambient environment at night. Structural materials of buildings also act as thermal storage that retains thermal energy from solar irradiation and internal heat gain. The thermal capacity of building materials can be enhanced by implementing phase change materials (PCMs) in different building components, such as walls, ceilings, and roofs (55, 56). The appropriate types and installation locations of PCMs are found to be highly dependent on climatic conditions, building type, and the overall building cooling systems (42).

The third passive cooling category is heat dissipation—the transfer of thermal energy from buildings into the surrounding air, water, ground, or sky. Heat dissipation techniques can be organized into ground, convective, evaporative, and radiative cooling (41, 42). Examples include natural ventilation, evaporative cooling, and radiative cooling. Each of these has been reviewed in the literature (41, 42, 57–59) with a notable surge in ventilation studies (60). Ground cooling exploits the low and constant temperature of the ground at a very shallow depth up to 3 m. It employs earth-to-air heat exchangers that connect the indoor air of the building with the ground. Convective cooling transfers the heat from the building to ambient air through natural ventilation, such as, wind-driven, buoyancy-driven, Trombe wall, and solar chimneys. For example, night ventilation techniques use the colder night air to dissipate the daytime heat gains (41). Evaporative cooling utilizes the evaporation of water when it encounters nonsaturated air, resulting in reduced temperature and increased humidity. Depending on the nature of the air-water contact, evaporative cooling is categorized into direct and indirect evaporative cooling (41). Radiative cooling uses the relative coldness of the universe to reduce the temperature of a sky-facing surface. The temperature of the surface can drop below ambient temperature by minimizing its heat gain while maximizing thermal radiation within the atmospheric window of 8–13 μm (61). Traditionally, this technique relies on a clear night sky as the heat sink. Recently, the development of new photonic materials allows subambient cooling under direct sunshine (61). Another recent example shows the potential of membrane-assisted radiant cooling without mechanical treatment of the air (62), effective in hot-humid conditions with desiccant packs used to dehumidify the air.

Cooling demand reduction using passive measures and technological improvements through energy efficiency are necessary to achieve sustainable cooling. Nevertheless, as in any energy system, the users of these approaches are central in determining the adoption of future pathways. For this, behavioral and cultural approaches to cooling, and the hard and soft infrastructures which enable them, play a vital role (63).

3. COOLING BEHAVIORS AND CULTURAL APPROACHES TO COOLING

Moving beyond technology, this section focuses on the role of individual, societal, and cultural knowledge of how to keep the body cool, with people as active agents pursuing relief from uncomfortable temperatures. This includes vernacular strategies, those from local and traditional practices. We unpack these across geographies with a view to multi-objective, nature-based, and low-carbon adaptive solutions to rising temperatures that are complementary to other sustainable approaches to cooling.

Humans adapt to warming temperatures by dissipating heat by convection, conduction, evaporation, and radiation. The body loses excessive heat via conduction if it is in touch with another surface that has a lower temperature, or via evaporation and conduction when the body sweats and air movement evaporates water on the skin. However, when the body is unable to exchange heat with the external environment, such as during high temperatures and humidity, several physiological issues occur (4). Normal core temperature at rest varies between 36.5 and 37.5°C (97.7–99.5°F). An increase of the body temperature beyond 37.5°C can have devastating effects on the body. According to Universal Thermal Climate Index, safe ambient air temperatures should range from 17°C to 24°C. However, people in different climates and geographies have also adapted and acclimatized to a range of temperatures beyond this upper end. The relativeness of human thermal comfort is also determined by people's physical, health, and socioeconomic characteristics (64). For example, vulnerable groups such as the elderly, children (65), pregnant women, or people affected by long-term health conditions such as obesity and diabetes, or those with occupational heat exposure, have higher vulnerability to heat stress (66, 67). For these groups, access to controlled temperatures is essential. Moreover, in fast growing cities, vulnerable groups, in particular street vendors and those in informal settlements, risk losing longstanding cooling practices such as accessing green and shaded spaces and water bodies as high-rise buildings replace public areas.

For nonvulnerable groups, and within limits, repetition and prolonged exposures can also modify the physiological and psychological responses to thermal comfort. The body tends to adapt, in moderation, to different temperatures, leaving thermal imprinting (also known as thermal adaptation) (68) on bodily-perceived thermal comfort. Scientists summarize the physiological exposure to temperatures as metabolic adaptation, localized adaptation (for specific parts of the body, generally the extremities), isolative adaptation, and hypothermic/hyperthermic adaptation (69, 70). Psychological responses to prolonged exposure to high or low temperatures can also manifest through stronger preferences, routinized activities, and alteration of psychological states. There is evidence that people's prolonged exposure to air conditioning, such as professional office workers, or people with conditioned homes and cars, have a preference for wanting more space conditioning (with variations depending on thermal histories and physical characteristics) (71). Some studies also discuss a trend toward air conditioning addiction in urban office, hospitality, or educational settings, which influences cooling preferences and discourages adaptive comfort principles in buildings, for instance, using more natural ventilation (72–74).

In addition to individual preferences, thermal comfort is informed by sociocultural determinants, such as by government guidelines, architectural trends, urban planning, and building standards. Media, advertising, and other cultural influencers also play a role in shaping people's attitudes toward thermal comfort and cooling needs. Cooper (75) argues that the social construction of comfort and the need for cooling has been charged by a political agenda of modernity and materially executed by building industries and technology producers with capital interests. The author shows how owning an AC was a prerogative *sine qua non* in the United States and the need for cooling was created by industry and supported by a neoliberal governmental agenda (75). For Wilhite (76), the expansion of AC use for cooling was the result of a cultural ideology of comfort created by technicians and media (77), and advertising (78) influenced consumers' preferences toward space conditioning (79). Repetition of certain messages, combined with the constructed idea of comfort contribute to generating mental hooks and preferences for certain technologies (e.g., the AC) (72, 79). Others discuss how AC-based cooling in climates that are not dangerously hot is the result of social practices and habits entrenched in ephemeral ideas of hygiene and cleanliness (80, 81), social etiquettes, and conventions (82). In the rest of this section, we discuss the different sociocultural influences on and adaptive behaviors for cooling.

3.1. Cooling Behavioral Adjustments for Thermal Comfort

Brager & de Dear's (83) work on behavioral adjustments put humans at the center of thermal decisions by suggesting three main strands to classify actions for thermal comfort. The first is personal adjustment, which refers to drinking or eating hot or cold food and beverages, physical activity, and posture adopted during the day. The second is how humans use the technology available (e.g., fans, heaters) or passive strategies such as closing and opening windows. The third are changes of commonly accepted routines such as taking siestas (after-lunch naps) or changing dress codes. Personal, technological, and cultural adjustments differ in different geographies. For example, in India (Hyderabad), Indraganti (84) found that people preferred to adapt with behaviors such as opening and closing windows, doors, and curtains to maintain comfortable conditions indoors, or increasing room ventilation as seen in Japan (82).

Other common indoor behavioral strategies include sleeping on roofs, moving to the coolest area in the house, or reducing daily activities, as has been found in several hot tropic and arid (85–92) as well as temperate regions (93, 94). Other strategies include changing working and sleeping times (95, 96) and making lifestyle changes. For example, the practice of wetting clothing and taking several cold showers during the day has been found in Australia (92). Although preferences for the AC are reported in all regions (hot/dry, temperate, and hot/humid) (65, 93, 97–100), activities such as visiting shopping malls or other public buildings to seek cooling is noted in hot/tropical (92, 101) and temperate climates (102). Other reported local behavioral adaptive strategies are walking barefoot on cold stones, as in Bangladesh (103), or keeping clay pots filled with water to cool the ground and roof, as in India (63, 104).

Finally, adaptive cooling strategies in hot temperatures include the frequent consumption of thermogenic food. Thermogenic food can alter the metabolism and aid processes of thermoregulation[1] (106). In hot geographies such as in Northern Africa and Asia, studies show a more frequent consumption of capsaicin and other herbal stimulants such as teas to enhance cooling thermosensation (106). Foods that alter the balance of total body water can also influence thermoregulation; hypohydration can reduce sweating rates and skin blood flow responses to a given temperature exposing the body to hyperthermia (107). The cooling potential of food and beverages are used in folk practices and traditional medicine; for example, in China, "xi gua" [watermelon (*Citrullus lanatus*)] is used during summers to increase fluids in the body (108). Similarly, the consumption of chrysanthemum flowers (*Chrysanthemum morifolium*) in combination with peppermint leaves has been reported as a common heat-relieving strategy in China and Northern Africa (109). In some cases, Chinese herbs were found to delay the sensory neural response to heat in elevated temperatures (110), whereas in other instances, the thermogenic properties of food and herbs could contrast so-called hot syndrome [heat stress, fever, delirium (111)]. More research is needed to unpack and validate the function and properties of such compounds and understand their effects on thermal comfort.

3.2. Cooling, Clothing, and the Social Context

Clothing is an important factor determining thermal comfort (112). Thermal comfort attributes of textiles comprise water vapor resistance (breathability), thermal resistance, air permeability, liquid wicking rate, water resistance, and water repellence (113). These attributes are important in specific environments; for example, thermal resistance is crucial for firemen and people working in metallurgy because of their exposure to high temperatures, and breathability is important for sportswear. Thermal insulation is affected by the fabric's physical and structural properties, such as fiber type, which can be natural (originated from plants or animals, such as silk, wool, cotton, and linen), synthetic (polyester, nylon, acrylic fabric), and smart textiles [PCMs that improve the thermoregulatory effect of clothing, particularly moisture management fabric, infrared responsive materials, and water-responsive materials (114)]. The latter are used to produce personal protective equipment such as cooling vests, which are able to temporarily maintain microclimate temperatures of at least 5° below outdoors temperatures[2] (113). Li & Luo (115) demonstrated that wool and cotton are perceived as cooler than polyester due to the different textile hygroscopic properties, and Davis & Bishop (116) also point out that fabric construction, the design characteristics of the clothing, air velocity, and the movement of the body during exercise all play a role in pumping air in and out of the microenvironment.

To determine the properties of clothing, the American Society of Heating, Refrigerating Air-Conditioning Engineers (ASHRAE) and the International Organization for Standardization (ISO) have established a common measurement called clo-unit, where 1 clo = 0.155 m^2°C/W. The clo-value ranges between 0 and 1, where 0 is the naked body and 1 is the clothing insulation property during winter (117). Based on this, ASHRAE (118) and ISO 7730 (**https://www.iso.org/standard/39155.html**) have compiled a list of garments with an assigned clo-value. For

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[1] According to Osilla et al. (105), thermoregulation is a "mechanism by which mammals maintain body temperature with tightly controlled self-regulation independent of external temperatures. Temperature regulation is a type of homeostasis and a means of preserving a stable internal temperature in order to survive."

[2] More detailed information is at ASTM F2300 - Standard test method for measuring the performance of personal cooling systems using physiological testing (established 2010; **https://www.astm.org/f2300-10r22.html**).

example, ankle socks (thin) have a clo-value of 0.02, and a long-sleeved sweater (thick) has a clo-value of 0.36 (118). Typically, a summer material clo-value is considerably lower than winter, as it is assumed that people would wear lighter clothing; however, socioeconomic, environmental, and cultural variables can influence expected clothing preferences. A comparative study on indoor thermal comfort conducted in Korea (119) in two different periods showed that in 1980 people were wearing clothing during winter with a clo-value of 0.95 (warm garments), and in the summer it was 0.5 (light garments). Two decades later, these values changed to 0.58 clo and 0.24 clo respectively, pointing to the influence of economic development leading to improved regulation of indoor temperatures, and a change in thermal comfort perceptions resulting in differing clo-values (119).

Sociologists have drawn similar links between the material culture embedded in clothing and how they are linked with perceptions of the self. Numerous studies conducted in Brazil (120), Singapore (101), Malaysia (121), and Japan (93) show how office wear culture is shaping the way air conditioning is used during the summer. In many hot-humid countries, people wear a combination of garments that do not facilitate air circulation or evaporative cooling with a high clo-value, typical of the northern hemisphere's office wear. This norm of dressing in Western styles, especially in offices, has been found in cultures across the world (101, 121–123). As Lundgen et al. (124) show, the adoption of Western-style clothing in hot geographies such as West African countries resulted in an increase of air conditioning usage, whereas non-Western clothing can improve thermal comfort standards without energy wastage. Furthermore, the recent phenomenon of fast fashion can also hinder the achievement of thermal comfort from clothing, as most textiles used are made with synthetic polymers, such as polyester (125), which reduces air permeability, moisture management, and thermal conductivity (126). This is particularly important given its growing use in typically hot and humid countries in Africa and Asia (125).

Social conventions, such as dress codes, uniforms, and cultural traditions, too, can influence the achievement of adaptive thermal comfort through clothing adjustments. Kwok & Chun (127) observe that students in Japan could not offset heat loss through adaptive strategies because of the uniform required by schools, resulting in perceived discomfort. Similar findings by Shrestha et al. (128) in Nepal show how dress codes negatively influence thermal comfort and adaptive adjustments through clothing. At present, the clothing thermal insulation values database compiled by ASHRAE is based on Western-style clothing. Only recently, Havenith et al. (129) started to integrate broader garments into the study of thermal comfort, especially traditional clothing from Pakistan, India, Indonesia, Kuwait, China, and Nigeria; however, more research is needed to understand the relation between clothing insulation and thermal comfort in non-Western countries.

3.3. Vernacular Architecture

Vernacular or traditional architecture[3] is driven by local knowledge and traditionally available materials, and it accounts for local environmental and climatic conditions. Vernacular architecture uses the internal and external spatial organization of dwellings, design, proportions, and orientation of buildings to optimize comfort while inheriting traditions and ancient knowledges. There are several parameters that reinforce the passive cooling potential of vernacular buildings for thermal comfort, namely, room structure, ceiling shape, roof materials, wall materials, geometric orientation in the space, shading, shape and number of windows, and infiltration (130). All these elements contribute to the passive qualities of vernacular buildings across different

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[3] Vernacular architecture is a genre of regional construction that uses traditional materials and resources indigenous to the area.

geographies. Sturdy building envelopes can protect against outdoor weather conditions, given that heat transfer occurs slowly in thick walls, and keep indoor temperatures cooler during the day and warmer at night. In both deserts and cold climates, vernacular dwellings have a thick envelope, whereas in tropical climates the envelope of the buildings are lightweight (130). In hot and tropical climates, vernacular buildings usually have larger windows and fissures in the walls (such as in wood stilt houses in tropical riverside localities), allowing natural ventilation and air circulation. Furthermore, vaulted ceilings allow hot air to gather above while occupants can enjoy a cooler environment below (130). Notable examples of cone-like structures are the ice houses called "yakhchāl" in Iran (131) and the domed houses referred to as "trulli" in Alberobello, Italy (132). The yakhchāl, in particular, were so efficient that they were used as ancient "refrigerators" (131). Traditional architectural designs in Central Asia and the Middle East, such as the windcatchers, are also vernacular examples of how to improve thermal comfort by increasing indoor ventilation of cooler air (133). Among many Amazonian riverine societies, houses are built on stilts due to seasonal inundation of the vegetation, and the design allows cross-ventilation beneath and on top of the dwelling (99).

Special importance is also attributed to the local materials used in vernacular architecture. It is well established that soil, especially if used as wall cover, has high thermal inertia that reduces heat transmission (131). Several types of stones have also been tested for their thermal conductivity, thermal diffusivity, thermal capacity, and thermophysical properties. Experiments conducted in the Western Desert of Egypt show how sandstone, limestone, and Karshif (local rock rich in sodium chloride) are viable vernacular solutions capable of regulating moisture behavior (134). In southern Italy, vernacular buildings built with tuff (calcareous material) provide thermal insulation. In rural tropical areas, such dwellings are usually built with easily available natural materials (such as wood, palm straws, and natural ropes). Some studies show that use of such materials can provide better ventilation and protection from radiative heat than nonindigenous building designs and materials (99, 135, 136). As discussed throughout this section, a range of cultural and social factors mediate the need for cooling without using technologies and building materials that require large amounts of embedded energy and resources. Next, we turn to examining the larger production network and lifecycle of the provision of cooling.

4. CIRCULARITY OF COOLING

This section looks to the future for integrating the delivery of the most sustainable cooling technologies within a global array of cultural and behavioral practices. It does so through an exploration of opportunities that place cooling systems within a circular economy.

4.1. Production of Circular Cooling

A circular economy for cooling embraces both technological innovation and individual behavior to reduce the carbon intensity and GWP of cooling equipment, facilitate the reuse and recycling of equipment materials, and help make affordable, environmentally safe options more accessible. The production of cooling is global, and an active understanding of the geography of its production and consumption is a necessary precursor to altering its current economic models for delivery and production toward circularity and increased access and equity of its use. This also requires changes to the technical design of cooling equipment as well as the business models for its sale, use, reuse, and disposal. This section examines the ways in which the production of cooling can change toward a circular system and the effects of these changes.

There are several established hierarchies for approaching a circular economy. The most well-known is a hierarchy of waste (137), applied ubiquitously to rethink the entire use of materials

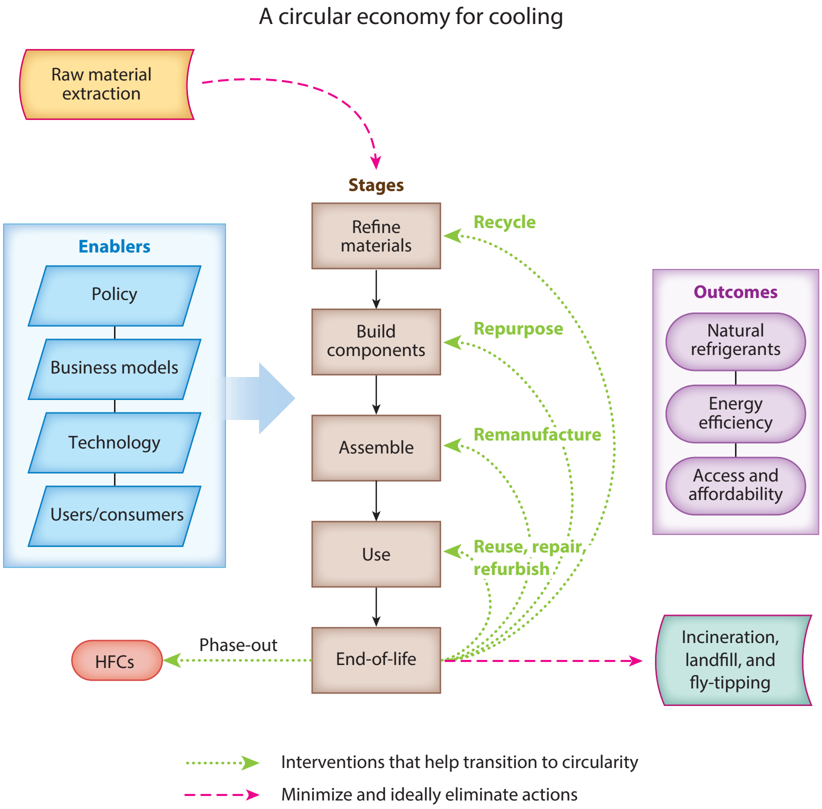

Figure 5

Enablers, stages, and outcomes of a circular economy for cooling. Abbreviation: HFC, hydrofluorocarbon.

in any aspect of the economy. Potting et al. (138) have built on this conceptual hierarchy to create a framework that is more aligned to the hierarchy of decision making toward circularity in a production chain. This is inclusive of both manufacturing and smarter policy, and we apply this framework to present an analysis of production networks for circular cooling. The framework prioritizes smarter production processes by refusing, rethinking, and reducing the production of a new product. Building on the ways to refuse or avoid the use of mechanical cooling discussed in the sections above, this section focuses on changes related to the necessary production that remains. It includes reusing, repairing, and refurbishing products; then remanufacturing and repurposing the products and their parts; and finally recycling.

Figure 5 illustrates a circular production network for cooling and shows the integration of the waste and decision-making hierarchy. It includes consumer behavior and technology innovation as two of the four main enablers that shape circular cooling production and use. The diagram shows how circularity is planned at each stage of production and how parts re-enter their original or another production system. Industry, particularly manufacturers, is leading the development of the circular production of space cooling. However, there is a significant gap in the academic literature for the circular production of space cooling equipment. This review of the circularity of the lifecycle stages and physical components of cooling has thereby required drawing on literature for similar manufactured goods to space cooling, for instance, input materials and waste products of concern for refrigeration, which highlights many of the key material concerns for space coolers as well.

One of the changes toward circular cooling that requires the fewest shifts and is thus prioritized is reuse. Using products longer, while maintaining their efficiency, extends the life span of a cooling product and its parts. In practice, however, consumers prefer to purchase a cheaper cooling product with lower efficiency even if future energy savings are relinquished, given the preference for lower upfront costs and high discount rate for future savings. One option is for manufacturers and retailers to adapt their revenue models to include the resale and reuse of units that are still in good operational condition and continue to fulfil their original function, as has existed for decades in other white goods industries such as washing machines (139). But even though efficient reuse is possible for many old ACs, it is very cost ineffective due to components and parts being part of the equipment's integrated design. Another impediment to increasing the inclusion of reuse in the production network of cooling is the prevalence of informal markets for resale. These markets are more common in developing countries and present challenges for intervention similar to those of the informal plastics economy (140). Although informal markets for cooling units do keep their materials in use longer, the separation from retail or manufacturer oversight fails to create the opportunity to remove or repair units no longer operating efficiently or safely.

The next and slightly more resource-intensive level of circular production concerns repair or refurbishment and maintenance. Refurbishing cooling appliances means bringing an old product to a condition of functioning with the best environmental standards. There are currently no studies in the peer-reviewed literature that assess the costs of refurbishment for cooling units. However, the cost of refurbishing electronic products in other sectors allows for a reduced sale price. For example, refurbished smartphones are on average 30% cheaper than new ones (141). In addition to lower cost, customers are incentivized to purchase these smartphones with guarantees for software updates, continued performance, and battery life. For cooling units, the parallel advantages would be lower operating costs due to improved energy efficiency. Similar studies are urgently needed given the exponential increase of cooling need and demand that is fast approaching.

Critical to enabling repair, refurbishment, and maintenance is the recovery of cooling units. The location of collection centers for the recovery of units, as well as sites where repair and refurbishment can occur to maximize product returns and decrease the transportation costs of moving recovered units to repair sites, is most efficient when close to consumers (142). Studies on the more established recovery networks for refrigeration units (143) found that transportation costs are the most important consideration for optimizing profits and enabling manufacturers' participation in repair, remanufacture, and recycling activities. Once recovered, products designed with modularity for their parts can most easily be repaired and utilized in remanufacturing, as Kremer et al. (144) demonstrated with modular design of refrigeration units that could be adopted for space cooling units. Finally, Muranko et al. (145), referring to the more established research on refrigeration, found that remanufactured refrigerated display cabinets (RDCs) can have an extended life and perform the same function as new ones. Although the higher costs of such refrigeration units have incentivized repair and remanufacture faster than lower-cost space cooling units, the incentives for repairing and refurbishing space cooling units will likely increase as demand increases and lower-cost units are desired in different markets.

In addition to incentivizing repair and remanufacture, changes in consumer behavior and confidence toward repaired products is also required (146). Muranko et al. (146) experimented with the best ways to raise consumer awareness about circularity, including presenting facts, photos, and demonstration of the quality of refurbished refrigeration units. They found that marketing campaigns raised consumer awareness and led to regulation and behavioral changes. Similar approaches can be explored to change consumer perceptions of space cooling units.

The production of circular cooling moves onto the end-of-life management of cooling products when all other strategies have been exhausted. End-of-life product use reduces products otherwise considered waste to their component parts and finds further value and use. Because of its high content of mechanical components and motors, as well as a small amount of electronics (i.e., equipment that processes large amounts of data and has circuit boards), cooling end-of-life waste classifies as electrical waste in the Waste Electrical and Electronic Equipment (WEEE) categorization of the European Commission (147). The most comprehensive global WEEE monitor report is attributable to Forti et al. (148), which states that a total of 53.6 Mt of WEEE was generated in 2019 globally, of which 10.8 Mt is comprised of cooling equipment, and only 9.3 Mt (17.4%) of the total WEEE was documented and collected properly. However, there is no evidence in the literature about the environmental impacts of disaggregated cooling WEEE components. This is a vital research gap, which makes it difficult to account for the impacts of cooling waste at the end-of-life. Risks of other poorly managed WEEE are known to include illegal approaches to end-of-life such as through burning. For example, Gangwar et al. (149) studied the concentrations of heavy metals in the atmosphere in case study sites with illegal burning of WEEE in India. The main purpose of incinerating WEEE is usually to separate metals from plastics and other complex components (150). The reclaimed metals are then available for reuse, but the process of retrieving them is highly polluting, as it releases heavy metals (lead, copper, zinc, nickel, and chromium), which can be found in dangerously high concentrations in local inhabitants (149). WEEE will increasingly contain more cooling units if demand is not met and managed through greater circularity of cooling units.

Although a coherent literature on the circular economy of cooling is sparse, there is emerging literature on managing cooling products at their end-of-life for some specific component parts. Briones-Llorente et al. (151) studied how processed insulating foams from old and obsolete refrigerators can be recycled as insulating materials in the construction of buildings that require specific thermal comfort capacity, such as hospitals. However, the most attention has gone to the risks posed by cooling waste as sinks or banks for CFCs and HFCs, which respectively cause severe damage to the ozone layer and are potent short-lived GHGs. CFC banks have been decreasing since 2010 after their production phaseout (152), but there is no real or estimated quantification for HFC banks. The banks are expected to increase with the phasing out of these gases in newly manufactured products. Safe recycling or destruction of HFC gases must occur under controlled thermal processes (153) and is only possible if discarded cooling units are recaptured into a formal circular production process. Beyond insulation and HFCs, there is no measurement of other components within cooling units (e.g., heavy metals, plastics, etc.); these are all materials that present future possibilities for reuse and closing loops in the cooling production chain (154).

Finally, with environmental and regulatory pressure increasing, there is a push to develop net-zero and circularity aligned cooling technologies and services (155). The main parameters currently used for identifying net-zero aligned manufacturers are developing cooling units that are accessible, energy superefficient, and based on ultralow-GWP natural refrigerants. These types of refrigerants are easily recovered and recycled, and unlike synthetic ultralow GPW refrigerants, they do not create concerns over by-products from their production. An assessment of 54 cooling manufacturing companies concluded that 90% of companies are still in an early stage in the "Race to Zero" emissions, and cooling suppliers are more likely to commit to developing these technologies if they are geographically located in countries with strong, binding net-zero commitments (156). However, robust inclusion of cooling in the net-zero debate, including the perspective of both short- and long-lived gases and their impact on and solutions to warming, is currently missing.

Given the limited available research on the circular production of cooling, there is value in understanding current practices from other electricals industries where it is possible to translate and extrapolate knowledge on substantial reductions in raw material and energy demand. This knowledge provides a foundation for more work and research to reduce the costs of cooling units of all varieties and reduce environmental pollution from cooling production and discarded units. However, there is currently inadequate literature directly assessing these features for the circular production of cooling. What is clear from the available literature is that cooling manufacturers will not be the sole responsible agents of change toward a circular economy. A systemic change includes many stakeholders and changes to business models, consumer behavior, regulation, and industrial symbiosis, i.e., collaboration across productive industries to use the outputs of cooling production as inputs to their own processes (157). In the following section we look more closely at the enabling factors for circular cooling production.

4.2. Enabling Circular Cooling: Policy and Business Models

There is a fast-growing literature related to cooling and climate policy concerned with both improving the energy efficiency of cooling and ending the use of HFCs in cooling units. The global GHG emissions across all cooling sectors is estimated at ~7% (158), and 15% of these come from cooling buildings (159), whereas cold chains (mainly food and vaccines) alone account for 2–4% of the total GHG emissions in the United Kingdom (160). International climate policy has led to an uneven national and regional policy landscape for reducing cooling energy demand and creating energy efficiency standards (161). However, the Montreal Protocol and subsequent Kigali Amendment have been the major multinational agreements that are affecting the use of refrigerant gases for cooling. If achieved, the HFC CO_2eq metric tonnes avoided by Kigali will be approximately 53 billion, reducing 80% of HFC production by 2050 (152, 162) on top of the Paris Agreement, which pledged to avoid 7 billion CO_2eq metric tonnes by 2030 (163).

Even though the production of cooling is a global industry, changes to production and consumption practices are strongly influenced by regional and national policy environments (164). For example, the EU's 2014 F-gas Regulation was an important legislation to ban the use of F-gases in a more proactive and accelerated way than the Kigali phase-down schedule (165). Relatedly for materials use and reuse, the EU's extended producer liability legislation, part of the EU's Green Deal, is a mechanism intended to push manufacturers (including for space cooling) to produce long-lasting and easily repairable and recyclable products (166). The EU policy to treat WEEE aims to contribute to circularity given the complex and sometimes hazardous mix of materials used in equipment (147). National regulations are also expanding to address other sustainability failures in the production of cooling (and other electrical appliances), including bans on premature and programmed obsolescence of cooling appliances, new incentives for remanufacturing and life extension strategies (167), and WEEE management. These policies operate at the complex intersection of manufacturing practice and consumer behavior. For example, policy to extend product life span leads to a product price increase response by manufacturers (168). Consumers must then evaluate if the costs of running their old, and potentially less efficient, unit are high enough to justify the expense of a new efficient, but costly, unit (168). Furthermore, Baxter et al. (142) highlight that in order to enable circular production, disposal policies and collection systems must exist at a local level. Forti et al. (148) estimate WEEE (including discarded cooling appliances but not disaggregated figures) account for ~8% of landfills in developed economies where nearly all waste management engages consumers through a local system.

An emerging area of gray (nonacademic) literature looks at legislation to address the illegal use and trade of HFC gases and WEEE across Europe, which emerged after the 2016 EU legislation that banned F-gases in certain cooling equipment and other products (165, 169). One study finds that weak enforcement in EU border countries resulted in F-gases still being accessible for old cooling units throughout the EU, and although operations to seize these illegal HFCs are impactful, further systemic changes to reduce their demand would be significant in combatting their illegal trade (165). Literature addressing the illegal global trade of WEEE has been growing over the past decade, but it has yet to specify illegal cooling waste within peer-reviewed literature (170–172).

Complementing the enabling effects of policy is the work of business models for circularity and sustainability (173). For example, the major manufacturer Daikin Europe is building a circular economy for refrigerants by embracing a "loop – recover, reclaim, reuse" approach, which aims to avoid an annual production of 250 tonnes of virgin refrigerants (174). An emerging business model tied to facilitating circular business promotes servitization (175) or a shift to a Product-as-a-Service System (PSS) where businesses focus on meeting needs rather than creating products (176). The servitization business model has expanded widely and particularly within the interconnected systems of cities (177). There are a few examples of servitization for cooling, for instance, the growing use of the business model Cooling-as-a-Service (CaaS) (178–180). Servitization of cooling entails businesses providing the service of keeping a space at a particular temperature. Users pay a service or subscription fee for the provision of this temperature, but they are not responsible for the equipment or energy used to achieve it. The advantages include customer savings on the cost of investing in cooling equipment; external incentives for service providers (e.g., subsidies by governments, tailored equipment from manufacturers) to use the most efficient, space-appropriate, and well-maintained cooling equipment; incentives for businesses to participate in the circular use of cooling units across their portfolios of clients; and increased access to cooling (178). CaaS examples include district cooling in Singapore's Marina Bay where multiple residential, office, and commercial buildings benefit from constant and reliable cooling by sharing a water chiller providing air conditioning, with on-demand flexibility to individually adjust temperature and intensity of use (178). Another example is a mixed commercial precinct in India installed by Kaer, who provide cooling with highly efficient AC units and monitor indoor air quality (181). Initial studies indicate that CaaS business models can save up to 23% of costs for customers and avoid 49% of carbon emissions as a result of efficient electricity use and minimized refrigerant leakages (179).

Other business models for cooling make use of new technologies in cooling equipment itself, and through the expansion of the internet of things use remote monitoring and embedded sensors to monitor and improve the performance and efficiency of cooling appliances (182). These innovations are well matched to the demands of rapid global urban development (183) as many features of a circular economy, from CaaS to industrial symbiosis, operate most effectively when coordinated within a dense ecosystem of users. As has been noted, more and better policy and business models to incentivize and facilitate circularity are needed, including increased access to financial instruments for sustainable cooling provision, marketing campaigns to raise awareness, and economic rewards to customers of sharing and service models (184, 185).

This section has illustrated how policy and business model innovations are interconnected in their effects to enable a transition to circular cooling inclusive of both circular production and cooling use. Regulatory and business environments are at the leading edge of these changes and peer-reviewed literature is yet to catch-up with practices specifically related to the production of circular and sustainable space cooling. Expanded and ongoing research in this area is needed to address this literature gap and inform progress on how a circular cooling economy can deliver cooling that has minimal material intensity, reduced GHG emissions from refrigerants and energy use, and is more accessible and affordable globally.

5. CONCLUSION: SHIFTING TOWARD SUSTAINABLE COOLING FOR ALL

Cooling consumption is growing fast and gaining visibility in energy and climate debates. Evidence shows that cooling sustainably is linked to the achievement of each of the 17 SDGs. However, under present climate and socioeconomic conditions, three-quarters of humanity will face health risks from deadly heat, with approximately two to four billion people requiring domestic space cooling to avoid these risks. Currently only a fraction of the global cooling demand is met, providing both challenges and an opportunity to work toward sustainable cooling for all. As this review lays forth, cooling in the built environment is comprised of various interacting social and technical dimensions, and the solutions for sustainable cooling also draw from different disciplinary and practitioner lenses.

An important reason for the concern for space cooling's trajectory is the lock into energy and GHG-intensive air conditioning technology, which is widely seen as an agent of modernity and progress. Air conditioning benefits from economic and technical efficiencies and its global technological ecosystem, institutional backing, and supporting behavioral practices have led to path dependence making it mainstay in future cooling projections. Unfortunately, the affordability of such cooling is not commensurate with the rapid growth in its projected need, and billions of people exposed to heat stress (often aggravated by humidity) will not have equitable air conditioning access. Alternative passive forms of cooling that have no or substantially lower environmental externalities and lower long-term costs have been widely used across countries for many decades, and preserving and enhancing access to such approaches for all remain important to a sustainable cooling future. Passive forms often require deep integration with building and urban design and thereby require inclusion at the design stage that is more tenable for new construction. Green and reflective white roofs, shading, glazing, insulation, PCMs, natural ventilation, and evaporative cooling are all extremely well-evidenced forms of such passive cooling across geographies. Promoting such approaches as a key part of the cooling portfolio requires a strategic shift in energy, climate and infrastructure related decisions. Although implemented in discrete pockets in urban centers and through local forms of vernacular cooling, more research and action are needed for adequate policy strategies and instruments to foster passive cooling as a complementary approach to active cooling at scale, particularly to protect vulnerable communities.

The lifestyle and social contexts in which technology choices are embedded are also key determinants of future cooling patterns. How people use, adjust to, and reinvent their cooling needs are perpetually changing, and these choices and habits can be beneficial or determinantal for environmental goals. Behavioral changes, for instance, changing temperature set-points, dressing codes, times of work, and prioritizing passive cooling activities can be fostered to trigger social tipping points. However, this requires further research to develop a greater understanding of the mechanisms and influences that underlie cooling needs, access, and thermal comfort in different contexts.

Finally, changing economic models for production and consumption are needed to move toward an equitable and circular economy for cooling. Circularity will require changes to the technical design of cooling equipment (and refrigerants) as well as policy and business models for sale, use, reuse, and disposal. Although there is a substantial literature on circularity, its application to cooling is largely unaddressed, pointing to the important need for further research that connects all stages of the cooling (and refrigerants) lifecycle. In sum, this review provides the state of knowledge on the relatively overlooked issue of space cooling. It points to several areas where research is limited and in need of much deeper examination and lays forth the evidence base of the scope of activities, innovations, and interventions that can contribute to a sustainable cooling future.

SUMMARY POINTS

1. The ubiquity of ACs risks a global technological lock-in for space cooling applications across the world with multiple negative implications for affordability and access to all.
2. Highly energy-efficient ACs are not mainstreamed across markets, and their large-scale uptake, often highly dependent on country-specific legislations, is important to mitigate the climate impacts of fast increasing cooling demand.
3. Alternative cooling technologies need significant improvements through research and development, as well as supported strategic deployment in the market, to compete with the conventional AC.
4. Passive cooling measures are critical components of sustainable cooling and can reduce cooling demand at the personal, building, and city level, but their deployment at scale is limited.
5. Material culture and social values are strong influences in the choices people make to keep their bodies and environments cool and in the creation of cooling habits. Local cooling cultures, depending on geographical and socioeconomic contexts, can lead to high-carbon AC use or to the complementary use of low-carbon passive and vernacular cooling strategies that reduce energy-intensive cooling demand.
6. Drawing from the rich history of vernacular cooling solutions and applying them in new constructions, particularly in hot and humid conditions, can bring useful benefits to communities.
7. Both technologies and behavior are key enablers to a full circular economy for cooling production and use, along with policy and business models.
8. Policies across cooling waste (e.g., recovery of refrigerants and disposal of appliances) are in development, but more efforts are needed to boost alternative business models.
9. Servitization of cooling saves energy, costs, and material utilization and also improves efficiency and technology innovation as a sustainable cooling option.

FUTURE ISSUES

1. Research on scaling integrated approaches to cooling demand (building design, passive measures, improved efficiency, and control systems) and cooling energy supply is needed for new built and retrofit scenarios.
2. Supportive mechanisms need to be identified to foster the development and deployment of alternative cooling technologies with relatively high Technological Readiness Levels.
3. The equity implications of different cooling scenarios and approaches are yet to be examined for vulnerable communities in different geographical contexts.

4. Studies are needed on the feasibility of recovering and scaling vernacular architecture for reintegration into urban contexts for thermal comfort.
5. Unpacking the clothing thermal insulation of fast fashion and non-Western garments can help enrich global knowledge on adaptive strategies for thermal comfort.
6. Understanding the availability and affordability of local beverages and foods for hydration and other passive cooling practices of people in different geographies and occupations to provide adaptive cooling can bring visibility to different cooling approaches.
7. The broader systems of circular resource management are not yet expanded to support the production of circular cooling, from the availability of recycled materials to consumer engagement with circular products and behavior.
8. International regulation particularly tied to climate change appears to have great potential to change the trajectory of cooling production in terms of efficiency and the use of HFCs and short-lived gases, but more research and policy are needed to understand how this will be enacted across different regional and national scales of production and cooling use.
9. The illegal activities related to cooling are not sufficiently documented, such as illegal trade of HFCs, illegal dumping and trade of less efficient and high-GWP appliances (especially from the Global North to the Global South), and illegal disposal of cooling waste (fly-tipping and landfill).
10. There is the need to consider business models that embrace new and innovative technologies, including for new delivery of cooling through servitization business models. This includes further studies that assess the efficiency improvements, broader environmental benefits, and scalability of these new business models in the cooling sectors.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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