# Cooling for Sustainable Development

*Radhika Khosla*[1,2], Nicole D. Miranda[1,3], Philipp A. Trotter[1,2,4], Antonella Mazzone[1,2], Renaldi Renaldi[1,3], Caitlin McElroy[1,2], Francois Cohen[1,2,6], Anant Jani[1,5], Rafael Perera-Salazar[1,5], Malcolm McCulloch[1,3].*

*[1] Future of Cooling Programme, Oxford Martin School, University of Oxford, UK.*

*[2] Smith School of Enterprise and the Environment, School of Geography and the Environment, University of Oxford, UK.*

*[3] Energy and Power Group, Department of Engineering Science, University of Oxford, UK.*

*[4] Chair for Operations Management, RWTH Aachen University, Germany.*

*[5] Nuffield Department of Primary Care, University of Oxford, UK.*

*[6] Institute for New Economic Thinking at the Oxford Martin School, University of Oxford, UK*

**corresponding author (radhika.khosla@smithschool.ox.ac.uk)*

**Abstract**

The unprecedented rise in cooling demand globally is a critical blind spot in sustainability debates. We examine cooling as a system comprised of active and passive measures, with key social and technical components, and explain its link to all 17 Sustainable Development Goals. We propose an analytical and solution-oriented framework to identify and shape interventions towards sustainable cooling. The framework comprehends demand drivers; cradle-to-cradle stages; and system change levers. By intersecting cooling stages and levers, we discuss four specific, exemplary interventions to deliver sustainable cooling. We propose an agenda for research and practice to transition towards sustainable cooling for all.

## Introduction

Cooling has been fundamental to shaping society in the twentieth century[1–3] and will be even more so in the coming decades. It enables thermal comfort of societies at high temperatures and is critical for industrial production and for the preservation of food and medicine. Air conditioning is widely considered to be an agent of modernity and a driver of the changing nature of life in the tropics, yielding deep associations between cooling and civilization's progress[4]. The trajectory of cooling is currently undergoing an extraordinary change: as the economies and populations of the hottest parts of the world grow, the demand for cooling for well-being has the potential to drive one of the most substantial increases in energy and greenhouse gas (GHG) emissions known in recent history[5]. Under current climate and socio-economic conditions, three-quarters of humanity will face health risks from deadly heat[6], with approximately two to four billion people requiring domestic space cooling to avoid these risks, a number that exceeds the energy poverty gap indicated in the Sustainable Development Goals[7]. The energy needed for space cooling alone is projected to triple by 2050, an equivalent of adding 10 new air conditioners (ACs) every second for the next 30 years[8]. This will require electricity generation capacity akin to that of the US, EU and Japan today, implying myriad socio-economic, environmental and political challenges[8].

Despite the extraordinary projections for its growth, cooling is a blind spot in today's sustainability debates[8]. No cooling-related term (such as "cool", "cooling", "cold", "refrigeration", "freeze", "ozone", "heat" or "thermal") features in the text of the UN's 2030 Agenda for Sustainable Development, the 17 goals, or their 169 targets. Two gaps in the literature are particularly salient. First, beyond selected evident links to energy[7,9], the extent of the relationship between cooling and the SDGs is neither well understood nor systematically mapped. This is within the larger context of recent work acknowledging the importance of describing the interrelationships between SDGs to design cross-cutting interventions[10–12]. Secondly, there is a paucity of literature on cooling and a narrowness in its scope. The literature that does exist is either limited to a technological[13–15], behavioural[16] or an extreme heat impact focus[17;] or confines sustainability analyses to the environmental impact of refrigerants[18,19], and does not consider a holistic and systemic view to the provision of cooling. By contrast, extant studies on heating buildings are orders of magnitude more numerous than those of cooling them[20,21]. As a consequence, in order to structure the challenges and solution space to achieve sustainable cooling, we argue that a novel, whole system perspective is needed.

In this Perspective, we first examine the linkages between each of the 17 SDGs and the provision of cooling by assessing the literature. Second, to respond to the absence of considering cooling as a multi-faceted system[22], we develop an encompassing analytical framework that accounts for the interlinkages between cooling and the SDGs with the objective of identifying, understanding and shaping intervention pathways and cross-cutting solutions towards sustainable cooling. By 'sustainable' we mean striking an adequate balance between natural and human-made capital, to maximise beneficial societal and environmental outcomes[23]. Finally, we demonstrate how the framework can be used to categorise, identify and distil a set of specific, high-potential interventions and propose an agenda for research and action to facilitate the transition towards sustainable cooling for all. The framework and agenda are solution-oriented by design and help respond to the urgent call for developing actionable transformations to achieve the SDGs,[24,25] especially the significant opportunities that are at risk of path-dependent trajectories[26].

## Cooling and the SDGs

We review the academic literature to identify the type and nature of relationships between cooling and each of the 17 SDGs. We define a structured topic search query for each SDG and apply it to 12,000+ peer-reviewed journals across disciplines. Search words were selected using a consensus-based expert elicitation method and from SDG indicators and targets, combined with a common set of terms that capture the literature on cooling (Supplementary Information). From 5.3 million documents (articles, reviews, patents, and others) identified to contain SDG related topics, we find 0.43% or 23,093 documents to have mentioned cooling-related terms in their title, abstract or keywords (Figure 1). The ratio of the total number of identified SDG documents compared to those which also include cooling-related terms ranges from below 1.5 orders of magnitude for SDG 7 and SDG 12 to over 3 for SDG 4 and SDG 17.

The identified papers yield concrete and evidence-based examples of how cooling facilitates the achievement of the SDGs (Table 1), demonstrating that cooling is directly linked to all 17 SDGs.

***Table 1. Indicative examples of linkages between each SDG and the provision of cooling***

| **SDG** | | **Exemplary linkages between the SDG and cooling (see Table B.1 for references)** |
|---|---|---|
| SDG 1 | No poverty | Increased extreme heat without cooling provisions is linked to lower productivity from land and income, exacerbating poverty especially in developing countries. Reduced cooling from decreased urban green spaces is also linked to increased income poverty. |
| SDG 2 | Zero hunger | Cooling enables food production and delivery via the cold chain as well as from cooling techniques that support food production in greenhouses and aquaponic systems. |
| SDG 3 | Good health and well being | Cooling reduces the health burden of severe exposure to heat, especially with climate change impacts of rising temperatures. In addition, heat has an impact on infant wellbeing. |
| SDG 4 | Quality education | Cognitive faculties are impaired by extreme temperatures, and heat has a negative effect on productivity and learning outcomes which are mitigated by cooling. |
| SDG 5 | Gender equality | Household food-related activities are often women's responsibilities, and the opportunities from cooling and refrigeration enable women to undertake small businesses and reduce time spent on daily food provision. |
| SDG 6 | Clean water and sanitation | Industrial processes (e.g. thermoelectric power plants) require vast amounts of water for cooling with important implications and choices for water availability and quality. |
| SDG 7 | Affordable and clean energy | Active space cooling and refrigeration have a very large electricity demand and influence clean energy system design (including via solar cooling technologies). Cooling is also required to generate clean energy, for instance via solar concentrated power. |
| SDG 8 | Decent work & economic growth | Cooling reduces the negative health impacts on the economy and on worker productivity, especially in light of negative climate change impacts. |
| SDG 9 | Industry, innovation & infrastructure | Cooling in large quantities is vital for maintaining the resilience and sustainability of infrastructures, such as power plants and data centres, and creating adaptive infrastructures in response to increasing urban heat island and population impacts. |
| SDG 10 | Reduced inequalities | Sustainable cooling has the potential to reduce inequalities among and within countries and is proposed as a recipient of climate finance via multilateral funds for clean energy and climate investments, especially from OECD to developing countries. |
| SDG 11 | Sustainable cities and communities | The provision of active and passive cooling is key to the habitability and sustainability of communities and cities in areas such as public and private transport, in homes, and in urban design and planning. |
| SDG 12 | Responsible consumption & production | Cooling consumption seriously burdens energy resources, and production of cooling technology has significant sustainability impacts across its life cycle (extraction to disposal). Cooling from cold chains and refrigeration are also vital to reducing food waste. |
| SDG 13 | Climate action | Cooling consumption drives large increases in GHG emissions driving climate change. Further, F-gases are a key by-product of refrigeration and air conditioning, which have amongst the highest global warming potential. |
| SDG 14 | Life below water | Cold chains and refrigeration practices are central to the fishing industry. Further, industrial cooling processes affect underwater biodiversity (e.g., coastal water intake for cooling in nuclear plants affects jellyfish population). |

| SDG | | Exemplary linkages between the SDG and cooling (see Table B.1 for references) |
|---|---|---|
| SDG 15 | Life on land | Refrigeration at very low temperatures enables cryopreservation of endangered land-living species. Furthermore, sustainable urban land use mitigates urban heat islands through evaporative cooling. |
| SDG 16 | Peace, justice and strong institutions | Cooling is a focus of international agreements such as the Montreal Protocol, and with rising visibility of its potential for Agenda 2030 and the Paris Agreement, which aim for peace and justice across institutions. |
| SDG 17 | Partnerships for the goals | Cooling and refrigerants are part of the portfolio of global climate finance to developing countries and plays a role in enhancing countries' financing, technologies, and capacities for sustainable development. |

*Note: Exemplary references for each link are provided in Table B.1 in the Supplementary Information B*

As illustrated in the non-exhaustive list of examples in Table 1, the goals of zero hunger, good health and wellbeing, and climate change are fostered by delivering cooling through cold chains for essential food and nutrition, the supply of vaccines and protection against extreme heat, and reduction of GHG emissions respectively. Performance of pupils in schools reduces considerably where hot weather cannot be offset by the availability of cooling[27]. The reduction of inequalities (including gender) is a social challenge that benefits from more just access to well-being-related resources such as cooling. The evidence across the goals makes clear that how cooling is provisioned for is critical to SDG outcomes. It also suggests how overlooking the links between cooling and the SDGs poses risks to sustainability outcomes. For example: meeting the growth in cooling energy demand with inefficient technologies can pose severe burdens to the availability of clean and affordable energy (SDG 7) and to global temperature rise from refrigerants and fossil-fuel based power (SDG 13); unsustainable cooling technology production can seriously stress energy resources and have significant sustainability impacts from extraction to disposal (SDG 12). Furthermore, often there are positive and negative feedbacks between cooling and the SDGs, thereby enabling the delivery of some goals, while undermining others. For instance, cooling has been essential to protect good health and well-being (SDG 3)[28], and will continue to be critical in this regard as extreme temperatures rise, but the manner in which it is predicted to grow comes at the serious cost of climate action (SDG 13). Recognizing the absence of cooling through the SDGs is a critical first step in addressing the missed opportunities, and potential perils, that arise from this gap.

## Framework for transitioning towards sustainable cooling

Given the scale, pace, and complexity of growing cooling needs, how can the solution space for transitioning cooling towards sustainable development be identified? There are promising disciplinary frameworks that can help answer this question. While not addressing cooling specifically, the wider sustainability transitions literature provides alternatives, particularly with the lens of the Multi-Level Perspective which combines technological, systemic and exogenous macro-level landscape elements to place socio-technical systems at the centre of analysis[22,29]. However, frameworks proposed in this literature explain how transition happen, not how they can be directed, and typically focus on technological novelty, overlooking changes in the deployment and the mechanisms of uptake of technologies[30]. Frameworks in the transition management literature focus on interventions for sustainability, but are mostly confined to governance levers[31]. The Energy Cultures approach provides another alternative, anchoring system dynamics in interactions between people and technologies, behaviours and norms[16]. At the same time, it refers less to institutions, governance and market arrangements which are important in shaping consumption trajectories. The literature on Technology Innovation Systems provide yet another related line of enquiry[32], and while valuable in tracing the arc of technology growth, it is less applicable to non-technological scenarios which can be relevant especially in the context of passive cooling.

To enable a systemic transdisciplinary approach to cooling as a system within the context of sustainable development[29], we draw from the different literatures discussed above and propose a solution-oriented framework that integrates across analytical silos (Figure 2). The framework consists of macro-level drivers that impact cooling demand dynamics. We also categorise the different stages of cooling delivery across the value chain. Further, we identify five levers which act on the cooling system, specifically on each of the stages of cooling delivery, to influence the trajectory of the future of cooling. The intersection of stages and levers yields a set of twenty interconnected intervention points for system change[33]. We elaborate on each of these framework components below.

***Macro-drivers of cooling as a system.*** Macro-drivers or trends are key to understanding the external conditions which shape the required output and operation of the cooling system. These drivers are characterised as being external to the cooling system but with an influence over how it evolves. These are illustrated on the left-hand side of Figure 2.

First, *socio-economic trends* of urbanization, economic development, population growth, especially in developing countries with hotter climates, as well as changing energy and appliances prices[34,35] are leading to shifting and unprecedented demands for cooling. This is observed, for example, in Mexico where increased income and heat exposure have driven a sharp rise in air conditioning demand[5]. Second, *technological trends* influence the demand for new cooling systems, their availability, configuration and controls. The increased access to cooling technologies, rise in data centres for increasing internet traffic and data loads, and expanding electrification (aligned with SDG 7) especially in South and South-East Asia and sub-Saharan Africa are materially influencing the uptake of cooling[7]. Third, *environmental trends* driven by climate change are altering cooling demand, particularly in cities with urban heat island effects. Increasing extreme temperatures are changing global requirements of thermal comfort, increasing GHG emissions and the use of ozone-sensitive refrigerants (i.e. phase-out of Hydrofluorocarbons (HFCs) and Chlorofluorocarbons (CFCs)). Fourth, *geopolitics trends* reflected in international multilateral agreements, such as the Paris Agreement, Kigali Amendment to the Montreal Protocol, the UN Urban Agenda, among others, comprise a global geopolitical governance driver, which has bearings on how countries and the private sector develop cooling technologies and design related policies. Each of these macro global trends directly and indirectly influence how the future trajectory of cooling evolves.

***Stages of cooling delivery.*** We conceptualize the cooling value chain in four distinct stages (Figure 2) to isolate the different constituents of the cooling system. The initial stage, *resources*, relates to the provision of natural raw materials including their extraction and pre-processing. This includes the metals which comprise cooling equipment, or the materials which passive cooling technologies are made of, and the refrigerants used in ACs. The *production and assemblages* stage describes how resources are combined into a passive or active form of cooling, for instance the process of manufacturing fans and air-coolers, or that of creating high-insulation bricks. This stage also entails technology design and deployment (e.g. installation). The third stage, namely *cooling activities*, encompasses purchasing, operating and maintaining the service of cooling to meet demand. This stage is defined in broad terms, ranging from large-scale, industrial cooling to individual-level activities such as wearing lighter clothes to stay cool. *End-of-life* as the final stage includes the removal or decommissioning of forms of cooling, often leading to reuse (e.g. upcycle, full or partial recycle), elimination or disposal. Examples of how active and passive technologies may pass through the different stages of cooling are presented in Table 2.

**Table 2. Examples of cooling delivery stages for active and passive technologies**

| | **Active cooling examples**[36] | | **Passive cooling examples**[37] | |
|---|---|---|---|---|
| **Stages of cooling** | *Split mode room air-conditioner (AC)* | *District cooling neighbourhood network with centralised chillers* | *Plants in and surrounding buildings for shading and providing cooling*[38] | *Transparent phase-changing window material to reduce heat gains* |
| **Resources** | Metals, refrigerants, petrochemicals, and water required to produce ACs components | Metals to produce chillers, metal or plastic pipes for network and water as heat-transfer fluid | Seeds/cuttings, soil, nutrients and water | Phase-change material (PCM), glass and frame (e.g. metal & wood) |
| **Production and assemblages** | Manufacturing processes of AC in a factory, distribution and installation in internal and external walls | Laying underground network pipes, installing chillers and building cooling plant | Planting vegetation in adequate location and orientation to shield heat (e.g. next to windows/tree canopies on walls) | Manufacturing glazed windows with phase changing material in a factory, distribution and installation in building envelope |
| **Cooling activities** | People's AC purchase decisions, and people's AC use decisions (e.g. controlling the temperature set point) | Operating and maintaining chillers and the cooling plant; and people's temperature and timing settings | Maintaining the vegetation in indoor and outdoor environments with support of the building administration (e.g. pruning) | People's window purchase and installation activities; smart window systems that maximise thermal comfort |
| **End-of-life** | Remanufacturing and recycling of viable AC components; safe disposal of refrigerant gases | Decommissioning of cooling plants and distribution network | Removing of vegetation for building refurbishment purposes; or sustainable disposal of vegetation, e.g. biomass for heat | Once PCM windows reach the end of use, disposal is carried out or re-manufacturing |

***Levers for change.*** We identify an encompassing set of five levers capable of driving sustainable system change. Viewing cooling as a system comprised of interacting social and technical constituents, we argue that cooling demand is defined by socio-cultural behaviours[16,39] and satisfied by a set of technological solutions[22] which enable the delivery of cooling-related value in accordance to companies' business models[40], forming markets that are governed by policies and set in the context of wider physical and intangible infrastructures[29]. We therefore identify five interconnected levers as social interactions, technology innovation, business models, governance, and infrastructure design.

The first lever concerns *social interactions.* With new technologies available to consumers, people frequently readjust and reinvent their needs and priorities, and new behavioural patterns are perpetually created[41]. Collective values resulting in pro-environmental behaviours shape technological adoption, which indirectly have an impact on cooling resources and production and assemblages. The systematic repetition of specific behaviours creates 'cultures of cooling,' which differ across geographies and time. Recurring behavioural choices and habits can be environmentally beneficial (e.g. nature-based/zero-carbon practices) or detrimental, with the ability to be a powerful lever for large-scale impact on global resources and the environment.

*Technology innovation*, the second lever, influences ways of generating sustainable cooling through new technologies and by responding to dynamic cooling needs. Technological advancement can foster energy-efficient and affordable passive and active cooling. For instance, this lever can significantly change the impacts of cooling by improved efficiency of the incumbent AC technology, i.e. vapour compression cycle[42]. Similarly, improved phase change materials and radiative cooling can fulfil or reduce space cooling demand. Technology innovation occurs across the stages of cooling and applies to space, food and processes to meet changing cooling needs in a sustainable fashion.

The third lever, *business models,* shapes companies' key business processes and how these are linked internally and with external actors to provide cooling. Business models are critical to adopt and implement both established and new cooling technologies, connecting technological innovations and/or regulatory changes with user needs to deliver on their cooling demand. They consist of three critical dimensions[40], namely the firm's value proposition, its value capture approach (how the value proposition is realised and monetised), and value networks to support the value proposition. Sustainable cooling-based value propositions could entail, for example, a socially responsible way of extracting raw materials required for cooling, delivery of a food cold chain with net-zero emission or guaranteeing high recycling rates of AC components.

The fourth lever of *governance* is key to align the multitude of actors and steer the direction of the cooling transition via policy design and implementation. This lever comprises overarching policy strategies for the future of cooling which are guided by the SDGs and individual actors' objectives; economic, regulatory and information instruments which implement the policy strategies; and associated multi-level governance processes[43]. Sustainable cooling policies can comprise international agreements as well as national guidelines and local, adaptation-focused instruments[8]. Deep decarbonisation is likely to require a broad set of policy instruments[44]. For example, regulations are key to effectively encouraging the deployment of the more efficient ACs which are often subject to energy performance standards[45]. Expanding carbon pricing creates financial incentives to support efficient ACs. A growing number of national cooling action plans provide an integrated policy vision towards cooling across sectors.

Finally, the lever of *infrastructure design* for cooling encompasses both the broader context in which cooling services are supplied and demanded. Infrastructures, such as the physical built environment and the electric power system (or hard infrastructures), and equally, the degree of spatial interconnectedness and human capabilities (or soft infrastructures) shape and enable different solutions for cooling. Cooling and infrastructure need to provide urban resilience in light of climate change and increasing urban populations. We assign a focal role to infrastructures because they predetermine the available action space and provide an opportunity for choices and behaviours that are associated with sustainability[46]. For example, for every ton of milk distributed, twenty times more is lost in sub-Saharan Africa than in Europe as milk transport covers vast rural areas with no access to electricity infrastructure to power cooling[47]. Designing and adjusting infrastructures offers significant potential for reshaping the possibilities of cooling supply and demand. The choice of infrastructures and how they are combined and used create path dependency and lock-in. In this way, careful selection of long-lived infrastructure assets is critical for influencing future patterns of behaviour, organisation and development[12].

Each of these five levers influences each stage of the four stages of cooling, with the potential to trigger interventions that can shift the trajectory of cooling towards achieving sustainability outcomes.

**Interventions to transition cooling towards sustainability**

In this section, we demonstrate how the framework can be used to identify and map the solution space of cooling interventions which have considerable potential to enable sustainable development. Interventions at the intersections of each cooling stage and each lever of the framework are influenced by one or several macro-drivers and can impact the entire cooling system so as to build momentum towards sustainability transitions. By emphasizing the potential for purposeful intervention in complex and inter-connected systems, our approach builds on the studies of social transitions and sensitive intervention points[33]. Changes induced by any one of these interventions can be non-linear, path-dependent, amplificatory, or recursive. We discuss four interventions with the potential to shift the balance between natural and human-made capital towards more sustainable outcomes. While these exemplify different intervention points in Figure 2 (namely, in turn, B3, I2, G1 & G4, and S3), the interconnected nature of the cooling system implies that the realisation of the interventions' full potential can depend on supportive actions across adjunct intervention points. Table C.1 in the Supplementary Information C lists the respective relevant drivers, stages of cooling and levers of these four interventions.

***Cooling as a Service (CaaS) business model (intervention point B3).*** Only a fraction of global cooling demand is currently met, with climate change driving the need for more cooling globally in general, and in many hot and low-income countries in sub-Saharan Africa and South Asia, specifically. This is likely to exacerbate the cooling access gap. The "Cooling as a Service" (CaaS) business model innovation is an approach to overcome these challenges. Its value proposition is to make environmentally sustainable cooling more broadly accessible. Rather than pursuing the traditional way of selling AC units, CaaS companies capture value by retaining ownership and operation of cooling assets and charge customers for ensuring thermal comfort in their homes[48]. Critically, the often times prohibitively large upfront investment burden is either shared or entirely taken away from end-users, making access to cooling more attainable for low-income households. While CaaS has not been implemented at scale in low-income countries, its asset ownership retention approach is similar to pay-as-you-go (PAYG) business models for solar home systems which was instrumental in providing first-time electricity access to roughly 30 million people worldwide in 2019 alone[49]. Similarly to off-grid energy regulations in some African countries, CaaS can be combined with government regulations that curb end-user prices for cooling services. Environmentally, deploying highly energy-saving cooling systems, which are more expensive but have lower lifecycle costs per unit of cooling, becomes more attractive, implying its potential for contributing to more sustainable cooling. In addition, the CaaS business model endogenises proper maintenance of cooling systems (which can reduce electricity demand by up to 20%[50]). The Rwandan government is the first to have implemented a financial support mechanism for CaaS operators offering space cooling and food refrigeration services. Early-stage finance is a key barrier for asset bundling at scale. Companies could look to various green finance vehicles as a potential and currently underexplored source. Where CaaS is used for food cold chain applications such as in Rwanda, green finance can save additional, substantial carbon emissions from reducing food waste.

***Embedding passive and energy-efficient sustainable cooling in urban infrastructure (intervention point I2).*** Given that projections of world population living in towns and cities are set to reach 66% by 2050, these will become the epicentre of cooling demand[51]. The production and assemblage of infrastructure locks-in long-term physical assets and types of cooling consumption. Passive and energy efficient city designs[7] provide benefits to large populations by reducing urban heat islands[52], reducing cooling loads and improving thermal comfort in both indoor and outdoor environments. A key means through which city planners can introduce passive cooling is increasing vegetation through street trees, green façades and green roofs[53]. For example, in Xiamen Island, the integration of green roofs reduced average land surface temperature by 0.91°C[54]. Passive technologies have longer lifetimes than mechanic-electrical components of active technologies, hence benefits will be delivered in the longer-term. Urban infrastructures can furthermore be designed to ease the application of energy-efficient bundled cooling networks. However, to apply these multifunctional solutions, it is necessary to overcome political economy complexities, as observed in the green infrastructure planning of New York city[55]. In addition to policy-makers, municipalities, construction sector professionals (e.g. builders, architects), organisations with high cooling demand and individuals are required to agree on the design of infrastructural spaces and technological choices with sustainable cooling strategies such as green and blue spaces and phase changing materials.

***Linking cooling to climate action and refrigerant phase-down across global environmental agreements (intervention points G1 & G4)***. Active space cooling and refrigeration is based on the use of a chemical coolant to absorb and release heat. Hydrofluorocarbon (HFC) functions as an excellent chemical coolant within both; however, HFCs are 10,000 times more potent than $CO_2$ in contributing to climate change. If F-gas use continues on its current trajectory it is estimated to contribute 20% of global climate pollution by 2050[56]. Changing the current HFC trajectory requires coordinated global action -- and global agreements are a key intervention to do so especially when free markets with external environmental costs fail to exert sufficient pressure on producers and consumers. The Montreal Protocol, one of the most successful global environmental agreements[57], reduced nearly 98% of ozone depleting substances. The Kigali amendment to the Montreal Protocol entered into force in 2019 and aims to replicate this success and reduce HFC consumption by 80% by 2047. Critically, the Kigali amendment defines progress as reducing the total tonnes of $CO_2$ equivalent, opening up a multitude of solution avenues while still increasing the provision of cooling necessary for wellbeing. Combining this HFC phase out with improved energy efficiency of cooling has the potential to reduce the global temperature increase in business-as-usual scenarios by up to 1 °C in the coming decades[48]. But achieving this sustainable balance for cooling and climate at scale requires further policy and technological innovations. Greater coordination is required from the institutional frameworks for phasing-out F-gas and improving the energy efficiency of cooling by linking the SDGs to the Montreal Protocol at the global level as well as to regional and national cooling plans. Within this institutional framework there is also scope to address market and technology orientated solutions. Further, such new governance measures that address the cooling-climate interface can also limit end-of-product-life F-gas leakages and enable practices towards a circular cooling economy. This requires a network of aligned policies to address all the stages of cooling: from the production of sustainable cooling (as with the Biarritz Pledge for Fast action on Efficient Cooling from the 2019 G7) to the design of anti-dumping policies to prohibit the import of inefficient technologies.

***The role of lifestyles and behaviours for access to sustainable cooling and resilience (intervention point S3).*** Lifestyle, social and behaviour changes are important determinants of consumption patterns[39]. For cooling, these include using alternatives to active cooling (e.g. achieving thermal comfort through changes in clothing, beverage intake or shading) or by altering habits (e.g. reducing standard AC temperatures for big consumers such as hotels and commercial buildings). Cooling-related lifestyles vary: the average US-American consumes over six times the energy for space cooling compared to people in the European Union, and over 28 times compared to people in India[8]. Further, socio-cultural and psychological factors influence consumption, driving differentiated attitudes towards thermal comfort. In Singapore, the use of ACs is deeply rooted in everyday practices[58], while in Japan, despite most households having AC, people prefer natural ventilation[59]. A deep understanding of cultures and household dynamics is central to driving such sustainably-oriented behaviours. While not always easy to achieve, lifestyle and behaviour changes -- such as changing temperature set-points, changing dressing codes, changing times of work, prioritizing passive cooling activities and infrastructures – can be fostered by anchoring them in shared ideologies such as global wellbeing, environmental protection, as well as social justice movements and moral standpoints[33,60]. Behavioural science and environmental psychology offer key insights on how humans make choices, which can be used for designing sustainability-promoting instruments[61] and triggering social tipping points[62]. When behavioural change occurs, follow-on measures can sustain the change over time[63].

## Transitioning Cooling towards Sustainable Development: Agenda for Research and Practice

The unprecedented predicted growth in cooling, its absence from mainstream sustainable development debates, and the range of potential interventions to transition the system towards the SDGs begs a critical question: Where should cooling research and practice focus to underpin a shift towards sustainability? As this issue swiftly gains prominence, the implications of cooling decisions on other SDGs will gain purchase. Climate change presents one such example: meeting the internationally agreed aspiration of net-zero GHG emissions by mid-century will have serious implications for cooling technological and infrastructure decisions (and vice versa) which are set to rapidly grow in the same timeframe. How should countries, companies, organizations and individuals navigate their immediate and growing requirements of cooling with the much larger and longer-term implications of their decisions? There remains a pressing and unanswered field of enquiry that investigates if, how, and for whom, cooling contributes to the goals of sustainable development.

To advance answers to this question, in analysing the cooling and sustainable development nexus as well as of defining an action-oriented framework to foster sustainable cooling, we define an agenda for research and practice by highlighting three areas of prioritisation. Knowledge, analysis and decision-making around each of these can effectively facilitate a transition towards sustainable cooling over the short and long-term. Connecting the expertise across disciplinary boundaries will be key to addressing these issues and understanding the various inter-relationships that cooling presents. This is especially relevant as the academic literature is limited, as established in this Perspective, whereas professional practice in this area is advancing at a faster pace[14,56]. As a result, the co-production of knowledge by the often-scattered academic and professional communities who are at the frontier of the relevant areas of science and practice will be key to a holistic and integrated understanding of the relationships between sustainable development and cooling. Such inter- and trans-disciplinary approaches that link research with empirically evidenced impact have become an important trend in approaching advancements of science particularly in fields where on-ground experience is crucial for testing and calibrating new findings, such as in urban science and architecture[64]. Equally, the need for a transdisciplinary approach is well identified to establish demand-side climate solutions – to which cooling is central – and investigate their mitigation potential, detail policy measures and assess their implications for human well-being and sustainable development[39]. With this context, we propose three overarching outcome-oriented themes to guide the agenda for research and practice.

***Place planetary stewardship and meeting people's needs at the heart of cooling decisions.*** In order to be compatible with the SDGs, cooling must protect both people and the planet. The provision of cooling, however, can posit trade-offs between people and the planet. There is strong potential for an unintended feedback; for instance, the cycle of higher temperatures leading to increased cooling and energy consumption, which leads to a rise in GHG emissions and, in turn, fuel higher temperatures. Preserving human well-being, along with stability of the environment will be essential to a long-term cooling trajectory that is sustainable. Our framework suggests that doing so will require better understanding context-specific societal needs, innovation and deployment of technologies to enable equitable quality of life, governance practices that account for the externalities to the environment and providing adequate physical and intangible infrastructures for sustainable cooling to be feasible, across the stages of cooling.

***Prepare for and mitigate climate change impacts which will demand cooling in varied geographies.*** There is clear evidence that as the planet warms the negative impacts, vulnerabilities, and risks to life and infrastructure will increase in almost all geographic locations. The frequency and intensity of extreme heat events, for example, is a well identified global trend that is already changing the geographies of cooling. For instance, in Europe with its milder climate, 15% of the increased electricity demand between 1990 and 2016 is attributable to space cooling[65]. A large burden of cooling falls on warm-climate low and middle-income countries with, as this Perspective suggests, considerable bearings on the various SDGs. Other, often cooler climate regions that do not traditionally account for extreme heat events will have to start adapting long-term plans, processes, infrastructure and capabilities. Analogously, warm-weather regions will need to prepare extensively for the likely high costs of such extreme events. Urban heat action plans and early warning systems are gaining prominence as a starting point to reduce the imminent negative impact on people and the planet. Embedding the anticipated economic and non-economic costs of a changing climate and its implications of cooling throughout development and resilience planning, across scales of governance, will be necessary to prepare for the exponential increase in cooling consumption.

***Promote long term sustainable cooling solutions over existing unsustainable business-as-usual alternatives.*** The dominant active cooling technologies are well-established, with large supply chains, high performance and lower upfront costs, but can come with long-term negative impacts on energy demand (e.g. competing for use of renewables) and emissions (e.g. leaks of refrigerants). However, there are numerous passive cooling technologies and designs that deliver thermal comfort with no or substantially lower energy consumption as they harvest local, naturally-occurring and renewable resources (e.g. materials with high thermal mass, wind for ventilation, vegetation for shade, sea and lakes as heat sinks). Their benefits include lower maintenance and longer life-spans, and more flexibility to adopt and adapt to local knowledge in the form of vernacular cooling. Being strongly interlinked with building design, passive cooling may have higher upfront capital costs. However, it is a strategic investment that offers long-term cooling solutions with lower running and planetary costs. More research and more action are needed for adequate policy strategies and instruments to foster passive cooling technologies, as well as context-specific interactions of passive cooling with physical infrastructures and social behaviours.

In this Perspective, we lay forth the multiple inter-relationships between cooling and sustainability, arguing for cooling to be considered as central to achieving all SDGs. We also provide a transdisciplinary conceptual framework to identify, shape and influence the interventions by which the current trajectory of cooling can deliver sustainable development. With a world positioned at the brink of unprecedented cooling demand, this Perspective offers a way forward while being acutely aware of the extraordinary opportunity the current moment provides to use cooling as a lens to look to the sustainability of our future.

**References**

1. Cooper, G. *Air-conditioning America: engineers and the controlled environment, 1900-1960.* (Johns Hopkins University Press, 1998).

2. Ackermann, M. *Cool Comfort: America's Romance with Air-Conditioning*. (Smithsonian Institution Press, 2002).

3. Cox, S. *Losing our cool: Uncomfortable truths about our air-conditioned world (and finding new ways to get through the summer)*. (New Press, 2012).

4. Berger, M. W. Cool Comfort: America's Romance with Air-Conditioning (review). *Technol. Cult.* **45**, 452–454 (2004).

5. Davis, L. W. & Gertler, P. J. Contribution of air conditioning adoption to future energy use under global warming. *Proc. Natl. Acad. Sci. U. S. A.* **112**, 5962–5967 (2015).

6. World Meteorlogical Organization and World Health Organization. *Heatwaves and Health: Guidance on Warning-System Development*. (2015).

7. Mastrucci, A., Byers, E., Pachauri, S. & Rao, N. D. Improving the SDG energy poverty targets: Residential cooling needs in the Global South. *Energy Build.* **186**, 405–415 (2019).

8. International Energy Agency. *The Future of Cooling - Opportunities for energy efficient air conditioning*. https://www.iea.org/reports/the-future-of-cooling (2018).

9. Peters, T. *A Cool World - Defining the Energy Conundrum of Cooling for All*. (2018).

10. Fuso Nerini, F. *et al.* Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nat. Energy* (2018) doi:10.1038/s41560-017-0036-5.

11. Fuso Nerini, F. *et al.* Connecting climate action with other Sustainable Development Goals. *Nature Sustainability* (2019) doi:10.1038/s41893-019-0334-y.

12. Thacker, S. *et al.* Infrastructure for sustainable development. *Nat. Sustain.* (2019) doi:10.1038/s41893-019-0256-8.

13. International Institute of Refrigeration. Research Projects. http://www.iifiir.org/medias/medias.aspx?INSTANCE=exploitation&PORTAL_ID=portal_model_instance__eu_research (2018).

14. Rocky Mountain Institute. Global Cooling Prize. https://globalcoolingprize.org/ (2018).

15. Research Institute of Sweden. *KLIBLOL - Present and future comfort cooling in domestic and commercial buildings.* http://www.sp.se/en/index/research/effenergi/completed/effen_kliblo/Sidor/default.aspx (2018).

16. Stephenson, J. *et al.* Energy Cultures: A framework for understanding energy behaviours. *Energy Policy* **38**, 6120–6129 (2010).

17. Wilhelmi, O. V & Hayden, M. H. Connecting people and place: a new framework for reducing urban vulnerability to extreme heat. *Environ. Res. Lett.* **5**, 14021 (2010).

18. Lunt, M. F. *et al.* Reconciling reported and unreported HFC emissions with atmospheric observations. *Proc. Natl. Acad. Sci. U. S. A.* (2015) doi:10.1073/pnas.1420247112.

19. Myhre, G. *et al.* IPCC AR5 (2013) Chapter 8: Anthropogenic and Natural Radiative Forcing. in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2013). doi:10.1017/ CBO9781107415324.018.

20. Ürge-Vorsatz, D., Cabeza, L. F., Serrano, S., Barreneche, C. & Petrichenko, K. Heating and cooling energy trends and drivers in buildings. *Renew. Sustain. Energy Rev.* **41**, 85–98 (2015).

21. Waite, M. *et al.* Global trends in urban electricity demands for cooling and heating. *Energy* **127**, 786–802 (2017).

22. Geels, F. W. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Res. Policy* **33**, 897–920 (2004).

23. Costanza, R. & Daly, H. E. Society for Conservation Biology Natural Capital and Sustainable Development. *Source Conserv. Biol.* **6**, 37–46 (1992).

24. Elmqvist, T. *et al.* Sustainability and resilience for transformation in the urban century. *Nat. Sustain.* **2**, 267–273 (2019).

25. Sachs, J. D. *et al.* Six Transformations to achieve the Sustainable Development Goals. *Nat.*

*Sustain.* **2**, 805–814 (2019).

26. Seto, K. C. *et al.* Carbon Lock-In: Types, Causes, and Policy Implications. *Annu. Rev. Environ. Resour.* **41**, 425–452 (2016).

27. Park, R. J., Goodman, J., Hurwitz, M. & Smith, J. Heat and learning. *Am. Econ. J. Econ. Policy* **12**, 306–339 (2020).

28. Barreca, A., Clay, K., Deschenes, O., Greenstone, M. & Shapiro, J. S. Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the Twentieth Century. *J. Polit. Econ.* **124**, 105–159 (2016).

29. Markard, J., Raven, R. & Truffer, B. Sustainability transitions: An emerging field of research and its prospects. *Res. Policy* **41**, 955–967 (2012).

30. Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. & Sovacool, B. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Res. Soc. Sci.* **37**, 175–190 (2018).

31. Loorbach, D. Transition management for sustainable development: a prescriptive, complexity-based governance framework. *Governance* **23**, 161–183 (2010).

32. Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S. & Smits, R. E. H. M. Functions of innovation systems: A new approach for analysing technological change. *Technol. Forecast. Soc. Change* **74**, 413–432 (2007).

33. Farmer, J. D. *et al.* Sensitive intervention points in the post-carbon transition. *Science* (2019) doi:10.1126/science.aaw7287.

34. Newell, R. G., Jaffe, A. B. & Stavins, R. N. The induced innovation hypothesis and energy-saving technological change. *Technol. Chang. Environ.* 97–126 (2010) doi:10.2139/ssrn.223777.

35. Biddle, J. Explaining the spread of residential air conditioning, 1955-1980. *Explor. Econ. Hist.* **45**, 402–423 (2008).

36. Werner, S. International review of district heating and cooling. *Energy* **137**, 617–631 (2017).

37. Bhamare, D. K., Rathod, M. K. & Banerjee, J. Passive cooling techniques for building and their applicability in different climatic zones—The state of art. *Energy Build.* **198**, 467–490 (2019).

38. Feyisa, G. L., Dons, K. & Meilby, H. Efficiency of parks in mitigating urban heat island effect: An example from Addis Ababa. *Landsc. Urban Plan.* (2014) doi:10.1016/j.landurbplan.2013.12.008.

39. Creutzig, F. *et al.* Towards demand-side solutions for mitigating climate change. *Nat. Clim. Chang.* **8**, 260–263 (2018).

40. Foss, N. J. & Saebi, T. Fifteen Years of Research on Business Model Innovation. *J. Manage.* **43**, 200–227 (2017).

41. De Vecchi, R., Cândido, C. & Lamberts, R. Thermal history and its influence on occupants' thermal acceptability and cooling preferences in warm-humid climates: A new desire for comfort. in *Proceedings of 7th Windsor Conference: The Changing Context of Comfort in an Unpredictable World* (2012).

42. Park, C., Lee, H., Hwang, Y. & Radermacher, R. Recent advances in vapor compression cycle technologies. *Int. J. Refrig.* **60**, 118–134 (2015).

43. Rogge, K. S. & Reichardt, K. Policy mixes for sustainability transitions: An extended concept and framework for analysis. *Res. Policy* **45**, 1620–1635 (2016).

44. Tvinnereim, E. & Mehling, M. Carbon pricing and deep decarbonisation. *Energy Policy* **121**, 185–189 (2018).

45. Karali, N. *et al.* Improving the energy efficiency of room air conditioners in China: Costs and benefits. *Appl. Energy* **258**, 114023 (2020).

46. Creutzig, F. *et al.* Beyond Technology: Demand-Side Solutions for Climate Change Mitigation. *Annu. Rev. Environ. Resour.* **41**, 173–198 (2016).

47. Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R. & Meybeck, A. Global food

losses and food waste. (2011).

48. K-CEP. *Building momentum for impact - K-CEP Year Three Report*. https://www.k-cep.org/year-three-report/ (2020).

49. World Bank Group. Off-Grid Solar Market Trends Report 2020. 215 (2020) doi:10.1017/CBO9781107415324.004.

50. K-CEP. *Cooling as a Service (CaaS)*. https://www.k-cep.org/wp-content/uploads/2018/07/Cooling-as-a-service-Knowledge-brief-6.7.2018_Final_online_v1.pdf (2019).

51. Bai, X. *et al.* Six research priorities for cities. *Nature* **555**, 23–25 (2018).

52. Santamouris, M. & Kolokotsa, D. Passive cooling dissipation techniques for buildings and other structures: The state of the art. *Energy Build.* **57**, 74–94 (2013).

53. Aram, F., Higueras García, E., Solgi, E. & Mansournia, S. Urban green space cooling effect in cities. *Heliyon* **5**, e01339 (2019).

54. Dong, J. *et al.* Quantitative study on the cooling effect of green roofs in a high-density urban Area—A case study of Xiamen, China. *J. Clean. Prod.* **255**, 120152 (2020).

55. Meerow, S. The politics of multifunctional green infrastructure planning in New York City. *Cities* **100**, 102621 (2020).

56. K-CEP website, accessed 27 of April, 2020.

57. Protocol, M. Protocol on substances that deplete the ozone layer.,’. *Int. Leg. Mater.* (1987).

58. Hitchings, R. & Lee, S. J. Air conditioning and the material culture of routine human encasement: The case of young people in contemporary Singapore. *J. Mater. Cult.* **13**, 251–265 (2008).

59. Fujii, H. & Lutzenhiser, L. Japanese residential air-conditioning: natural cooling and intelligent systems. *Energy Build.* **18**, 221–233 (1992).

60. Cerda Planas, L. Moving Toward Greener Societies: Moral Motivation and Green Behaviour.

*Environ. Resour. Econ.* **70**, 835–860 (2018).

61. Ebeling, F. & Lotz, S. Domestic uptake of green energy promoted by opt-out tariffs. *Nat. Clim. Chang.* **5**, 868–871 (2015).

62. Otto, I. M. *et al.* Social tipping dynamics for stabilizing Earth's climate by 2050. *Proc. Natl. Acad. Sci. U. S. A.* **117**, 2354–2365 (2020).

63. Moloney, S., Horne, R. E. & Fien, J. Transitioning to low carbon communities-from behaviour change to systemic change: Lessons from Australia. *Energy Policy* **38**, 7614–7623 (2010).

64. Ürge-Vorsatz, D. *et al.* Advances toward a global net zero building sector. *Annu. Rev. Environ. Resour.* **45**, (in print) (2020).

65. *The Future of Cooling - Opportunities for energy efficient air conditioning*. https://www.iea.org/reports/the-future-of-cooling (2018).

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**Author contributions**

R.K. led the manuscript conception, design and writing. N.M. led data acquisition and analysis on the links between cooling and the SDGs. R.K., N.M. and P.T. wrote the introduction and the section on cooling and SDG links. A.M. developed the framework visuals. N.M., P.T., A.M., R.R. and C.M. contributed to the framework writing. A.J., P.T. and M.M. contributed to the future agenda. R.K., P.T., F.C., M.M. and R.P.S. revised the manuscript. All authors contributed towards the design of the work and the editing of the manuscript.

**Competing interests**

The authors declare no competing interests.