Overcoming the incumbency and barriers to sustainable cooling

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ABSTRACT

This article examines cooling in the built environment, an area of rapidly rising energy demand and greenhouse gas emissions. Specifically, the status quo of cooling is assessed and proposals are made for how to advance towards sustainable cooling through five levers of change: social interactions, technology innovations, business models, governance and infrastructure design. Achieving sustainable cooling requires navigating the opportunities and barriers presented by the incumbent technology that currently dominates the way in which cooling is provided—the vapour-compression refrigerant technology (or air-conditioners). Air-conditioners remain the go-to solution for growing cooling demand, with other alternatives often overlooked. This incumbent technology has contributed to five barriers hindering the transition to sustainable cooling: (1) building policies based exclusively on energy efficiency; (2) a focus on temperature rather than other thermal comfort variables; (3) building-centric design of cooling systems instead of occupant-centric design; (4) businesses guided by product-only sales; and (5) lack of innovation beyond the standard operational phase of the incumbent technology. Opportunities and priority actions are identified for policymakers, cooling professionals, technicians and citizens to promote a transition towards sustainable cooling.

POLICY RELEVANCE

The priority actions that can overcome key barriers to a sustainable cooling pathway are as follows. (1) Moving building policies beyond energy efficiency to address climate mitigation and adaptation for improving the heat resilience of the built environment. Building indicators are needed to measure the passive survivability to heat. (2) Conventional cooling control

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and related regulations based exclusively on air temperature require expansion in scope to consider a wider range of thermal comfort variables, thus stimulating technological innovation. (3) Shifting building-centric cooling control to an occupant-centric design, downsizing centralised cooling requirements and enabling adaptive environments integrating personalised environmental control systems. (4) Business models moving from product-oriented to service-based businesses. (5) Environmental cooling considerations that address the humidity influence, the role of energy storage to support renewables through energy flexibility in cooling, and the impact of F-gases. Regulation and citizen empowerment through better environmental labelling can play an important role.

1. INTRODUCTION

Global warming reached approximately 1.09°C (ranging from 0.95 to 1.2°C) above pre-industrial levels in 2011–20, increasing by 0.2°C per decade (IPCC 2022a, 2022b). There is a large likelihood that global warming will reach or exceed 1.5°C between 2030 and 2040 (IPCC 2022a). Many regions are experiencing greater warming than the global average, with extreme and prolonged heat events occurring more often and lasting longer. Together with population growth and economic development, heat is indirectly driving an unprecedented energy demand for cooling, specifically for air-conditioning (AC), which is expected to more than triple between 2016 and 2050, mainly in the residential sector (IEA 2018).

Along with being fundamental to achieving thermal comfort in the built environment, cooling is also critical to achieving the United Nations' (UN) Sustainable Development Goals (Khosla *et al.* 2021b). As such, the topic of sustainable cooling has risen on the agenda of international development and climate policy, targeting the provision of cooling through an adequate balance between natural and human-made capital in order to maximise beneficial societal and environmental outcomes (Costanza & Daly 1992; Khosla *et al.* 2021b).

At the 26th and 27th Conferences of the Parties (COP26 and COP27) in 2021 and 2022, respectively, multiple commitments were made by governments, businesses and civil society in support of sustainable cooling transitions. As of early 2022, 53 governments included sustainable cooling in their nationally determined contributions (NDCs), 25 countries committed to develop National Cooling Action Plans (NCAPs), 14 countries committed to doubling the efficiency of ACs and refrigeration appliances, and 16 cities made a commitment to tackle extreme heat. In the private sector, 14 cooling suppliers and manufacturers—28% of the global residential AC market—joined the Race to Zero (a UN-led campaign to achieve net zero emissions) and the EP100 (global corporate energy efficiency initiative of 120 businesses, including cooling manufacturers and buyers) doubled its membership (Cool Coalition n.d.). While these commitments represent clear progress, challenges remain to tackle cooling sustainably, and to transform the sector into one that offers accessible, affordable and non-polluting cooling solutions to all.

The need for the existing built environment to adapt to impending warmer temperatures requires deploying the best available cooling approaches. A wide portfolio of techniques and technologies is already available to address cooling efficiently (Bhamare *et al.* 2019; Cabeza & Chàfer 2020; Hughes *et al.* 2011; Miranda *et al.* 2021; Renaldi *et al.* 2021; Song *et al.* 2021). These cooling solutions can be classified using five key concepts, aligned with the 'avoid–shift–improve' approach (Creutzig *et al.* 2018): solar protection, heat prevention, heat modulation, heat dissipation and heat removal (Figure 1):

- Solar protection refers to avoiding solar gains in the built environment. These can be applied to opaque building envelope surfaces (roofs or walls) and building openings.
- Heat prevention consists of mitigating or avoiding external and internal heat gains in the building. External heat gains arise from ambient temperature transferring heat through the building envelope, whereas internal heat gains are due to human activities, appliances or lighting.

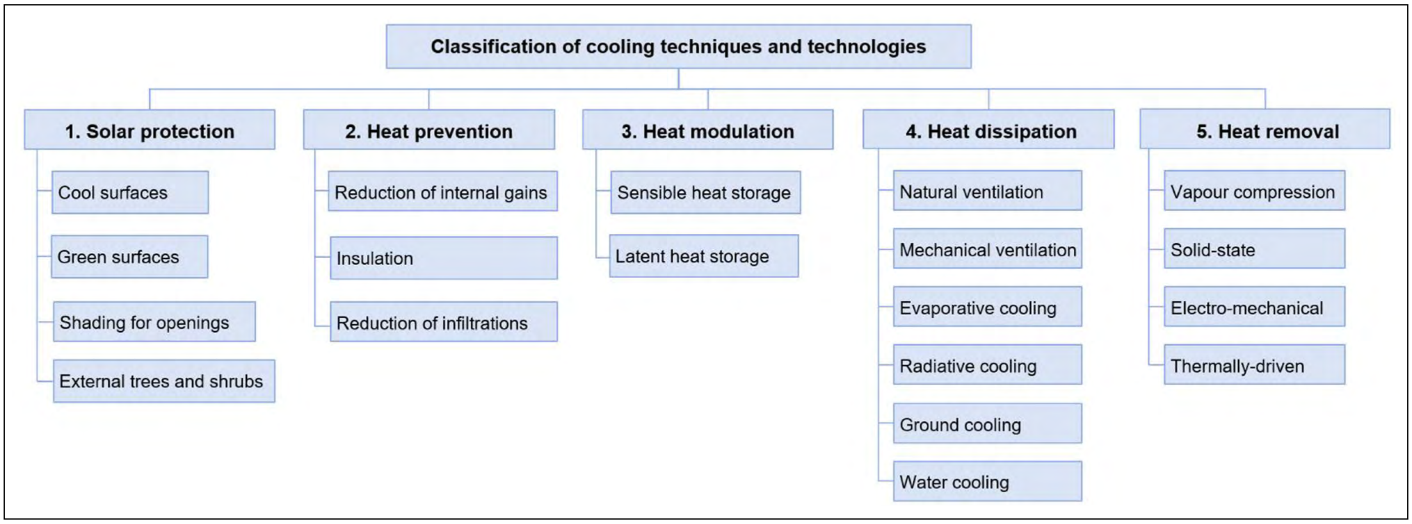

Figure 1: Classification of cooling techniques and technologies for buildings.

- Heat modulation consists of using the building thermal mass to store heat gains and release at optimal times. This technique depends on the thermal storage capacity of the building materials and the natural heat sink available to receive the excess heat.
- Heat dissipation is based on heat rejection from the building through passive or low-energy techniques, with the support of a suitable environmental heat sink at a lower temperature, such as ambient air, water, ground and the sky. Heat dissipation solutions are ventilative cooling, evaporative cooling, radiative cooling, ground cooling and water cooling.
- Heat removal consists of technologies that usually require high-energy input to absorb and reject heat from indoor space to outdoor, without necessarily having a heat sink (*i.e.* lower temperature heat source). Technologies can be grouped into vapour-compression, solid-state, electro-mechanical and thermally driven solutions.

Additionally, a wide range of occupants' behaviours can be mentioned here, such as avoiding heat exposure by wearing light or wet clothing, staying hydrated, and avoiding physical activities or going out in the hottest hours of the day (Hendel *et al.* 2017; Khoukhi & Fezzioui 2012; Monroe *et al.* 2015). Other practices involve cooling down the body by drinking and showering more often than usual (Brager & De Dear 1998). Moreover, a usual activity during the hottest periods is going to blue/green areas or AC spaces, such as movie theatres and shopping malls (Alberini *et al.* 2011).

Despite this extensive portfolio of cooling options, the easiest and fastest response to address increasing temperatures still lies with the installation of AC units, commonly regarded as the sole technological solution (Murtagh *et al.* 2022).

The dominant market technology—the vapour-compression refrigerant system—has become a long-standing incumbent in the cooling industry (Mori 2021). Since its market inception in 1933, it has been the leading cooling technology (Ackermann 2002), taking a significant portion of the market share (Basile 2014). In the process, it has created obstacles to innovation and transition since cooling solutions are largely understood to take this particular form around the world.

An incumbent technology, in economic research, describes the situation where the early specialisation of a given technology, in this case, vapour-compression refrigerant systems, may create a technological lock-in (see Aghion *et al.* 2019 for a general discussion of the case of other clean technologies). Specialisation in vapour-compression refrigerant systems over the past 90 years implies that companies have become continuously better at producing them. Research efforts have focused on this technology, so any new technological solution must face fierce competition from the incumbent. Moreover, new buildings have been built with the idea that this technology is available at scale for providing cooling, with little room to consider alternatives. Overall, ACs have limited competition, and the trend is to overlook additional opportunities to improve comfort, reduce cooling demand, and downsize or even eliminate cooling systems (Lovins 2018).

This paper, first, examines the origin of the incumbent dominance of AC in the cooling sector and identifies key barriers that limit a transition to sustainable cooling. The barriers have been grouped into five priority areas, which consist of:

- building energy policies based only on energy efficiency
- ACs considering only temperature rather than other thermal comfort parameters
- building-centric design instead of occupant-centric design
- businesses-guided exclusively by-product sales
- lack of innovation beyond the standard operational phase of incumbent technology

Second, the paper proposes discussions on how to 'knock out these barriers' by triggering levers for change using an analytical framework for transitioning toward sustainable cooling (Khosla *et al.* 2021a) (Figure 2). These levers include social interactions, technology innovation, business models, governance and infrastructure design. Finally, steps to move towards sustainable cooling are outlined.

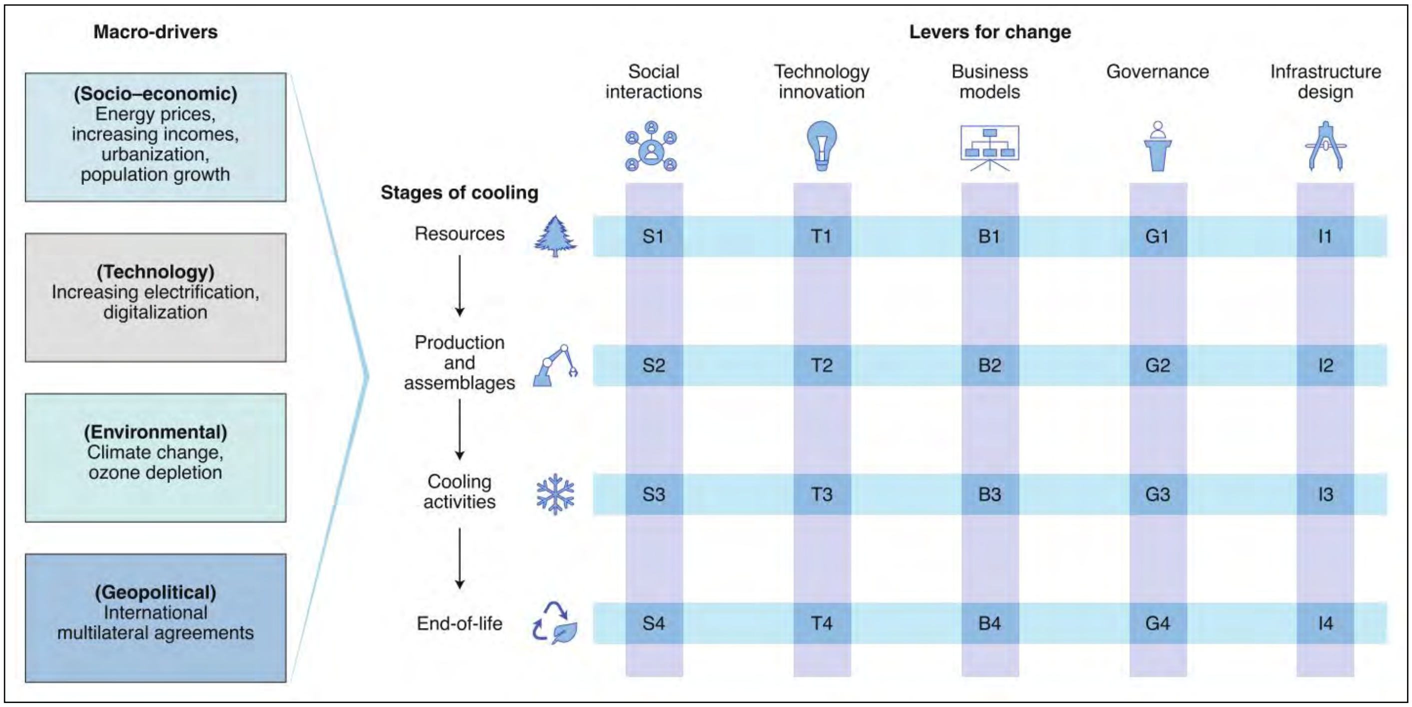

Figure 2: Analytical framework for transitioning towards sustainable cooling.

Note: The framework consists of macro-level drivers (right blocks), the different stages of cooling delivery, and the levers which act on the cooling system to influence the trajectory of the future of cooling. The intersections between levers and stages are intervention points, named accordingly to the lever of change that may trigger a change: S = social interactions, T = technology innovation, B = business models, G = governance and I = infrastructure design.

Source: Khosla *et al.* (2021b).

The scope of the article is on cooling for the global built environment, and it provides an overall understanding of the most important obstacles created by the dominant AC technology, while offering recommendations to overcome them. These obstacles are highlighted through a critical and interdisciplinary revision of the state of the art in the cooling sector by analysing the scientific literature, commercial cooling solutions, research trends and patent development. It was also supported by experts in the area, involving technicians, architects and engineers. The insights provide several potential priority actions by different actors.

2. INCUMBENCY IN THE COOLING SECTOR

The history of human adaptation to hot weather conditions has generated extraordinary knowledge of passive cooling solutions and practices. These non-energy-intensive cooling techniques are supported by architectural design, choice of materials, spatial orientation and individual behavioural coping strategies (Dean Wilson 2021). However, since the appearance of a machine that is capable of cooling indoor spaces within minutes, this cultural heritage has gradually been lost (Short 2017).

Vapour-compression refrigeration has been used for over a century since its invention in 1902 by Willis H. Carrier, and its marketing in 1933 (Ackermann 2002). Its fundamental mechanism

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has remained unchanged, given its good efficiency, scalability, safety and affordability. However, the large-scale deployment of this technology has generated a 'dependency' and 'incumbency' at multiple levels, promoted by different drivers such as businesses, institutions, governments, finance, infrastructure, building industry, thermal control standards, technology, culture and user practices (Shove *et al.* 2014a).

The first large-scale employment of vapour-compression refrigeration occurred in niches across American society, including the textile, creative and tobacco industries, which needed humidity control and ventilation to improve the quality of their products (Basile 2014). AC was then tied to higher economic profits for an increasing number of industries, hence becoming a normalised practice (Banham 1969).

The time it took from industrial use to implementing the technology across offices, and the domestic sphere was short. Workers in offices seemed to increase their productivity when optimal thermal conditions were available, especially during the summer (Banham 1969). This became of interest to entrepreneurs and corporations aiming to expand their profits. The invention also affected how businesses offered their services and how residential and commercial buildings were designed, built and allocated in space, introducing the fashion of deep-plan buildings and glazed facades, among others (Banham 1969). Even standards of social relations were shifted, from meeting in piazzas and green public spaces to meeting in conditioned environments (Dean Wilson 2021).

Indoor thermal comfort moved from the responsibility of the architects (who knew how to enhance passive cooling through building design) to the responsibility of the engineers, who would propose energy-intensive technical solutions (Banham 1969; Barber 2017). The principles of passive adaptability to different temperatures, and relying on residents' resiliency to different thermal variations, became peripheral criteria (Barber 2017). Passive adaptability was replaced by the notion that humans' indoor comfort zone is set between 20 and 27°C, ignoring the fact that comfort bands do vary across cultural groups (Brager & De Dear 2003) and geographies (Wilhite 2009). Even good practices and requirements promoted by building codes and thermal standards started to be written by engineers, reflecting the preponderant role taken by heating and cooling equipment over building design (Brager & De Dear 2003). This is likely one of the main drivers of the diffusion and persistence of mechanical space cooling at the expense of low-carbon passive design (Seppänen & Fisk 2006).

Along with businesses, industries and the increasing involvement of engineers, cultural adaptations also contributed to the incumbency of the so-called AC culture—intended here as:

> the set of values, conventions, or social practices associated with a particular field, activity, or societal characteristic[1]

was a powerful enabler through which space cooling was normalised (Ackermann 2002; Cooper 1998; Osunmuyiwa *et al.* 2020; Shove *et al.* 2014b). At first, ACs became a symbol of status and social power, similar to what can be seen in other industries, such as fashion or automobile (Wilhite 2009). However, ACs became widely adopted and generalised thanks to the creation of desirability and dependency supported by the advertising industry (Ackermann 2002; Basile 2014). The advertising industry promoted the marvels of ACs, tying-in messages about gender roles, emotions and relationship values (Robbins 2003). For instance, Figure 3 provides examples of how a couple was shown to be happier because of AC, or how a housewife could cook a hot meal and look glamorous regardless of the heat.

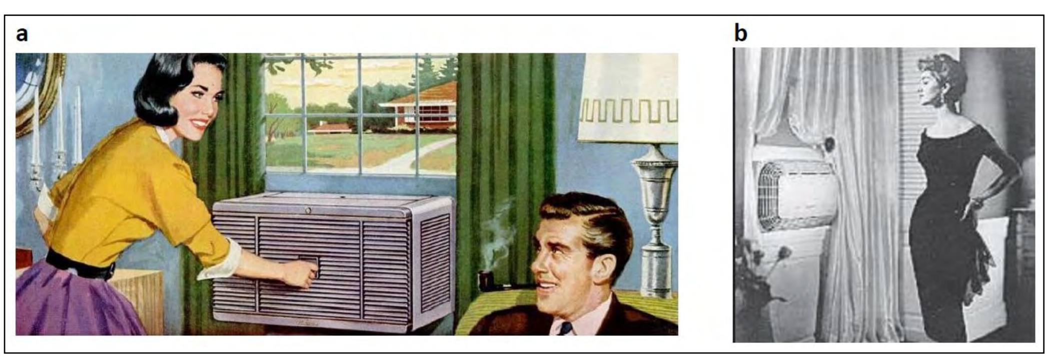

Figure 3: Examples of the advertising industry of air-conditioning (AC): **(a)** AC for marital bliss promoting happy couples thanks to the cooler environment (*Source:* Air-Tro n.d.); and **(b)** an advertisement assured housewives that they could cook a hot meal for their husbands and look glamorous while serving it if they owned an AC (*Source:* Robbins 2003).

This was further fostered by pop culture, movies and music (Needham 2019). The demand for, and satisfaction from, this technology were also fundamentally influenced by other people's experiences. Whyte (1954), Ackermann (2002) and Wolske *et al.* (2020) highlighted that the reliability of AC, communicated by neighbours through word of mouth, further influenced technology adoption. Similarities have been drawn to the five-star review mechanisms on online platforms influencing purchasing behaviour (Chevalier & Mayzlin 2006).

The widespread use of AC rapidly consolidated its addiction across society (Brager & De Dear 1998). For instance, a physiological acclimation where AC rapidly teaches the body to change the perception and expectations of unconditioned spaces and the outdoors (Brager & De Dear 2003). In this case, the expectation of conditioned air is more pervasive as it generates a new obstacle by changing people's physiological and psychological resilience to thermal variations (De Vecchi *et al.* 2012).

This socio-cultural and technical dependence has transformed AC technology into an incumbent pillar in the cooling sector, reinforced by assemblages of actors, institutions, infrastructures and governments (Newell & Johnstone 2018). As Stirling (2019) discusses, incumbency is typically behind persistent war, inequalities, ecological disasters and nuclear risks because of configurations of power which have interests in such events. However, science, research, innovation and technology are not immune to incumbency (Stirling 2019). In light of the established negative externalities of the 'cooling industry', from the global warming potential (GWP) of its refrigerant gases to the fossil fuel-based manufacturing and consumption, it is clear that mechanical cooling can be considered a 'socio-material' incumbency, especially when viable alternatives have always been available. This dominance has created and promoted different obstacles or barriers to the entry of new cooling alternatives into the market. These barriers have been grouped into five areas, detailed in the next section.

3. BARRIERS TO NEW COOLING ALTERNATIVES

This section contextualises the longstanding key obstacles in the cooling sector, centred around the incumbent vapour-compression technology (Figure 4). The identified priority barriers and their consequences have been grouped into five areas.

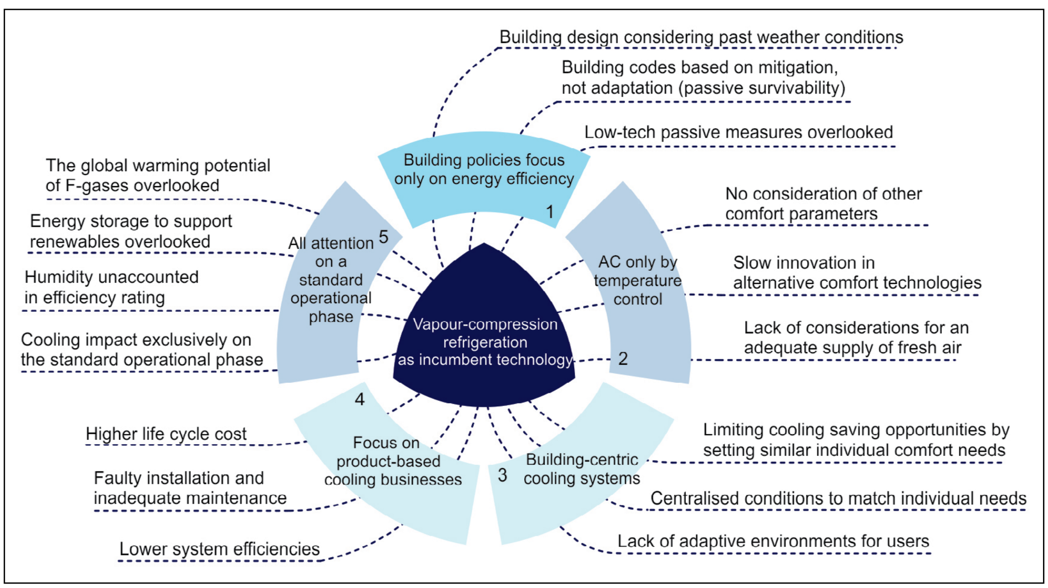

Figure 4: Incumbent and barriers (inner circles) in the cooling sector and their consequences (outer text).

3.1 BARRIER 1: BUILDING ENERGY POLICIES WITH AN EXCLUSIVE FOCUS ON ENERGY EFFICIENCY

The considerable uptake of ACs has catalysed higher energy consumption in the built environment. Aiming to reduce increasing energy demand in the 1970s and 1980s, the initial emphasis of energy policies was on the security of energy supply as a result of the oil price shocks in the 1970s (Sorrell *et al.* 2020). Subsequently, following the first Intergovernmental Panel on Climate Change (IPCC) assessment report and the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) (1992), the mitigation of climate change impacts became a key component of European Union (EU) energy policy along with the security of energy supply (Economidou *et al.* 2020).

Since then, mitigating climate change impacts through policies supporting energy efficiency has become a key component of the building sector and appliances (IEA 2018). From the SAVE Directive to the recently updated Energy Performance of Buildings Directive (EPBD) and Energy Efficiency Directive (European Union 2018) in Europe, or from the first version of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1 published in 1975 to the updated version of 2019 (ANSI/ASHRAE/IES 2019) in the US, energy efficiency policies have driven building design through building codes and labelling (Economidou *et al.* 2020). These building codes have guided the minimum thermal requirements for buildings. Additionally, Minimum Energy Performance Standards (MEPS) and energy labels have shaped the efficiency of refrigeration technology (Schleich *et al.* 2021). MEPS have facilitated the removal of low-efficiency appliances and lowered AC costs through a cycle of innovation and economies of scale (IEA 2021). Energy labelling has promoted consumer awareness of the energy efficiency of appliances and buildings through Energy Performance Certificates (EPCs),[2] enhancing informed consumer choice (IEA 2017). However, despite these policies being able to mitigate the energy demand and associated greenhouse gas (GHG) emissions of buildings and appliances (including AC), they still present obstacles.

From an infrastructure point of view, the policies promoted highly insulated buildings and airtightness by assuming that most buildings use heating, ventilation and air-conditioning (HVAC) systems. However, in scenarios without HVAC (or not frequently used HVAC) systems, studies have shown that insulation and airtightness prevent the release of heat when dissipation through ventilation is not adequate, increasing overheating (Chi *et al.* 2020; Samuelson *et al.* 2020a; Zhang *et al.* 2021). The mechanisms commonly found to dissipate heat from an indoor environment are heat fluxes through the building envelope (managed by thermal mass and insulation), infiltrations (air leakage) and ventilation. If insulation and airtightness are improved without promoting better ventilation, less heat is dissipated and consequently overheating increases (López-García *et al.* 2022). Fosas *et al.* (2018), Samuelson *et al.* (2020b), Lizana *et al.* (2022) and Mehmood *et al.* (2022) demonstrated how energy efficiency measures through insulation and airtightness could reduce overheating in well-designed buildings. However, if left unchecked, such measures create trade-offs in building performance, increasing overheating by more than 5%. Such a scenario, often prevalent in socio-economically deprived areas, highlights the inefficiency of current policies to improve the *passive survivability*[3] or *heat resilience* capacity of cities (Samuelson *et al.* 2020b; Sanchez-Guevara *et al.* 2019).

3.2 BARRIER 2: AIR-CONDITIONING WITH A SINGLE FOCUS ON AIR TEMPERATURE TO CREATE THERMAL COMFORT

The invention and dominance of vapour-compression technology have also promoted the understanding that cooling can be addressed solely through air temperature control (Figure 5a). This classical approach has disregarded different cooling opportunities based on other *thermal comfort variables* involving humidity, radiant temperature, air velocity, clothing insulation or metabolic rate—the hybrid approach (Figure 5b) (BCA 2015; Ma *et al.* 2021). As a result, people tend to rely more on thermostat settings than alternative cooling options (Lovins 2018). This issue has prevented innovations of alternative comfort devices that go beyond temperature regulation to meet indoor thermal comfort requirements. Other alternatives based on dehumidification or radiant cooling to create thermal comfort are scarce (Khare *et al.* 2021).

Moreover, such default configuration with exclusive temperature control combined with promoting insulation and airtightness can have additional adverse health consequences, *e.g.* through the presence of indoor air pollutants when minimum *ventilation* or *air renewal* is not adequate (Becerra *et al.* 2020; Lizana *et al.* 2020). This is very important in most AC installations based on split AC since they do not include any fresh air supply. López-García *et al.* (2022) showed how CO_2 concentrations frequently increase in spaces with these split AC above 3000 ppm during long periods.

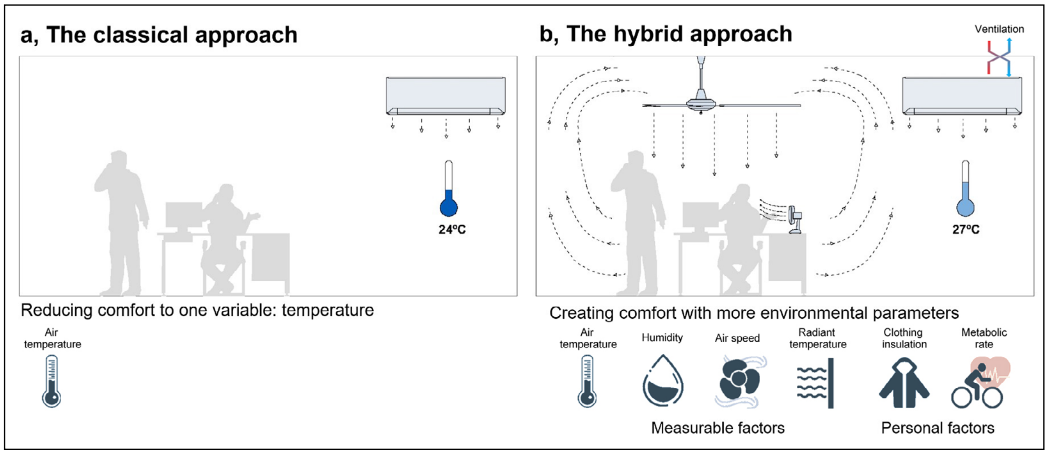

Figure 5: Differences between the classical and hybrid approaches to promote thermal comfort.

As a result, the infrastructure sector accepts (and by default promotes) the installation of off-the-shelf add-on technologies, such as vapour-compression units, focusing on temperature control.

3.3 BARRIER 3: BUILDING-CENTRIC AC TEMPERATURES (OR THERMOSTATS) DO NOT ACCOUNT FOR INDIVIDUAL COMFORT NEEDS

Another barrier, derived from ACs being used as a blanket solution for cooling, is the disregard for the role of individual cooling needs (Jay *et al.* 2021; Schiavon *et al.* 2010). AC lowers the temperature of spaces and occupants, regardless of how requirements can differ by cultural background, gender or other aspects. Khosla *et al.* (2021a) analysed 2092 surveys and identified how preferred AC thermostat temperature settings in India can differ from 18 to above 26°C, with half the households setting their AC temperatures between 24 and 26°C. Parkinson *et al.* (2021) demonstrated how uncomfortable temperatures are more likely to be cold than hot, regardless of the season. Moreover, they showed how this pervasive overcooling existed predominantly for women. This *non-personalised* and *building-centric cooling* control has also affected building design for cooling, assuming that all cooling needs are the same (Brager & De Dear 2003). This is the case with current building codes and EPCs, which limit cooling consumption and carbon emissions through average climate conditions and fixed set-point temperatures (ADENE 2015).

Studies have also highlighted the lack of *adaptive environments* with operable windows, movable shadings, integrated fans or personalised cooling alternatives, partially because of this cultural and building-centric regulatory framework focused on centralised indoor temperature control (Hoyt *et al.* 2015; Malik *et al.* 2022; Schiavon & Melikov 2008).

These criteria miss out on additional energy-saving opportunities related to an occupant-centric building design. Cooling design combining all comfort parameters through centralised and individualised systems (Figure 5b) can harness a larger comfort range in which people feel comfortable, downsizing the cooling system capacity and decreasing operating and environmental costs (Lovins 2018). Here, the most straightforward example is the introduction of air velocity to increase the upper threshold at which people start feeling discomfort. But many other combinations can be explored and designed, *e.g.* using the CBE Thermal Comfort Tool (CBE n.d.; Tartarini *et al.* 2020). As a result, it seems that the main objective of having ACs (*i.e.* achieving the thermal comfort of people) has been overlooked through building-centric temperature focus.

3.4 BARRIER 4: FOCUS ON PRODUCT-BASED COOLING BUSINESSES

Product-based business models have primarily driven the cooling sector by commercialising off-the-shelf vapour-compression appliances (Kurpiela & Teuteberg 2022). Product-oriented companies, namely AC manufacturers and distributors, have dominated the market and shaped the sector. With this approach, end-users are the owners of the cooling assets, while producers only manage a small part of the life cycle of the appliance (*i.e.* resourcing and manufacturing). For end-users, ownership is first constrained by initial investment cost. Once acquired, issues arise related to a lack of technical competencies leading to faulty installations and inadequate maintenance. Hence, higher operating costs, potential refrigerant leaks, drainage problems and electric control failure can occur. These problems can promote *lower system efficiencies* and *higher life cycle costs* (LCC). Moreover, *lack of maintenance* reduces the durability of AC products. An AC lasts about 20 years as long as it is installed and maintained correctly, but not always (Fox Family Heating & Air n.d.). Planned obsolescence is a fact in the HVAC technology industry and is well supported by product-based business models (Allehaux & Tessier 2002; Takakusagi 2021). For the manufacturer, product-based cooling inherently presents a conflict of interest, where producing long-lasting technologies could result in fewer units sold. Companies have therefore tended to innovate in the manufacturing processes to increase the number of units sold and hence profits rather than increase the durability and longevity of products (Jensen *et al.* 2021). Efforts to improve product durability and longevity, however, will require that AC companies explore new business models to cope with the anticipated decrease in product sales as the transition to a circular economy continues (Nishijima *et al.* 2020). This circular economy for cooling will decrease the environmental and social burden on all stages of the consumption process (*e.g.* production, use and end of life), whilst retaining economic growth from an efficient adoption of policies, business models and technologies (Khosla *et al.* 2022).

3.5 BARRIER 5: FOCUS ON A STANDARD OPERATIONAL PHASE

With the incumbent technology operating at a high energy intensity, the life cycle of cooling technologies is neglected. Although the combination of MEPS and energy labels has transformed and improved the cooling technology market, they are both still based on efficiency ratings based on a standard operational phase (ADENE 2015; Schleich *et al.* 2021). Hence, the environmental impacts of the appliances' life cycle are excluded or overlooked. Analysing all life cycle stages for the case of ACs, despite the emissions of the manufacturing stage being important, these are a relatively small amount compared with the real operational use and end-of-life stages which account for the greatest emissions (Karkour *et al.* 2021; Zhao *et al.* 2015). Here, there are some essential aspects to consider.

In the operational stage, the energy efficiency policies based on standard operating conditions have led to efficiency indicators being outdated and not fit for purpose. The indicators do not account for the impact of humidity on system performance or the efficiency of removing moisture. In fact, this is the case of the most common energy efficiency indicators of cooling systems: the energy efficiency ratio (EER) and the seasonal energy efficiency ratio (SEER) (Pérez-Lombard *et al.* 2012). First, the EER is based on the electrical power input and cooling capacity at a defined outdoor temperature (35°C) and indoor conditions of 27°C with a constant humidity level of 50%. Second, the SEER rating is the proportion of an AC's cooling efficiency over a regular cooling season, taking into account a range of operating conditions with air temperature from 20 to 35°C at full and partial-load operations (AHRI 2020). Both indicators are incomplete because they do not account for humidity influence (Warwicker 2010). For example, in cases where humidity is controlled, such as in hot–humid locations, buildings are typically over-cooled due to the dehumidification process (Fukawa *et al.* 2021). Removing water from the air with an AC requires cooling the air until it hits the dewpoint to condensate water. This process usually involves fixed-capacity ACs that cannot avoid overcooling. In other cases, after the condensation process, air temperature is too low, and post-heating is sometimes implemented to ensure an appropriate air supply condition. This second step to remove latent heat is normally not accounted for in the system efficiency. These problems could be avoided by improved design and/or advanced control to separately handle the sensible and latent loads (Kalanki *et al.* 2021).

The incumbent implementation of AC systems also limits its capability to promote renewable energy sources for cooling during the operational phase. Sustainable cooling would require the integration of cooling with energy storage technologies (thermal or electrical batteries) in order to align energy demand with renewable generation while decreasing peak power and carbon emissions (Lizana *et al.* 2017). At the same time, electricity markets should move beyond flat rate prices to deploy effective demand-side response alternatives while increasing renewable generation.

For the end-of-life stage of AC systems, the most important environmental contribution is related to high global warming potential (GWP) fluorinated gases (F-gases) used in vapour-compressor cooling equipment (Wu *et al.* 2021). F-gases, particularly hydrofluorocarbons (HFCs), are widely used for ACs and can leak from units and quickly exacerbate global warming, up to 14,800 times more than CO_2 in the short term (UK Government n.d.). HFCs used for ACs and refrigeration are responsible for more than 1% of global GHG emissions over the last 20 years (Zhao *et al.* 2015) and are projected to be 9–19% by 2050 if emissions continue business as usual (Velders *et al.* 2009). Their wide use came as a negative consequence of the Montreal Protocol, which by banning ozone-depleting chlorofluorocarbons (CFC) refrigerants, led to increased use of HFCs. Product-based sales of ACs have incurred uncertainties surrounding the end of life of AC appliances as there are unclear responsibilities for the appropriate collection, disposal or recycling (and of their refrigerants). Expectedly, leakage of F-gases has been reported as the highest during this final stage of their life cycle due to mishandling (Zhao *et al.* 2015). HFCs currently account for 94% of F-gas emissions, sulphur hexafluoride (SF_6) for 4% and perfluorocarbons (PFCs) for 2%. In the UK alone, F-gas emission levels were 15 $MtCO_2e$ in 2018, equating to 3% of national GHG emissions (CCC 2020). The Kigali Amendment to the Montreal Protocol, agreed by UN countries in December 2016 and ratified by over 100 countries by COP26 extended the targets to phase down F-gases and aims to phase-down HFCs. Technology-wise, natural and/or ultra-low warming refrigerants to replace HFCs are surging. For example, R-290 (propane, GWP < 1) has been used for single-split AC units in China, India and Europe, and R-718 (GWP = 0) in Europe for commercial chillers (EIA 2021; EPA 2016). More research is needed to understand if trade-offs exist between more environmentally friendly refrigerants and the energy performance of the appliances using them, concerning commonly used HFCs (UN/IEA 2020). Moreover, special consideration should be considered around the embodied emissions with new very low GWP refrigerants, such as R1234yf, since they can be more complex and require energy-intensive manufacturing, increasing embodied emissions during the manufacturing stage (Sherry *et al.* n.d.).

4. OVERCOMING THE INCUMBENCY AND BARRIERS: THE PATHWAY FOR SUSTAINABLE COOLING

Vapour-compression ACs are, and will likely be, core to the technological solution to address cooling needs in a warming world—but they do not have to be positioned as the only solution to the warming crisis. There are a large number of robust alternatives available to address cooling (Figure 1). These solutions, implemented following the right order as shown in Figure 6, can increase the heat resilience of the built environment, downsize cooling systems and cooling needs, decrease resource consumption, and mitigate the environmental impact of cooling. These steps should be implemented considering current and future weather conditions, heating and cooling as a whole in building design, and socio-cultural factors. Moreover, these steps require overcoming all these previously discussed barriers towards sustainable cooling (red text in Figure 6).

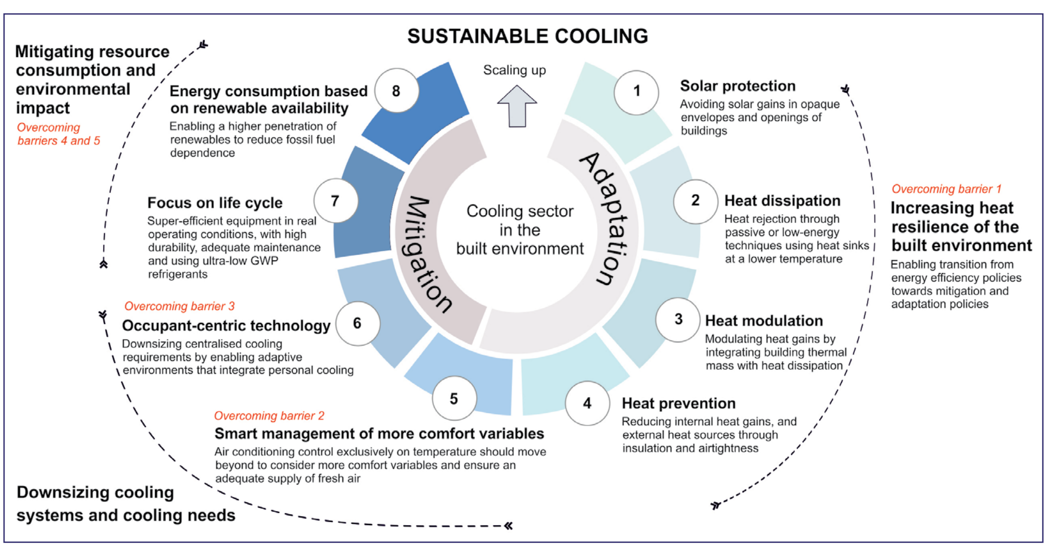

Figure 6: Recommended steps to address the incumbency towards sustainable cooling in the built environment.

This section considers the changes that can be promoted through the specific levers for change to tackle existing barriers and enable this pathway to sustainable cooling (Figure 7).

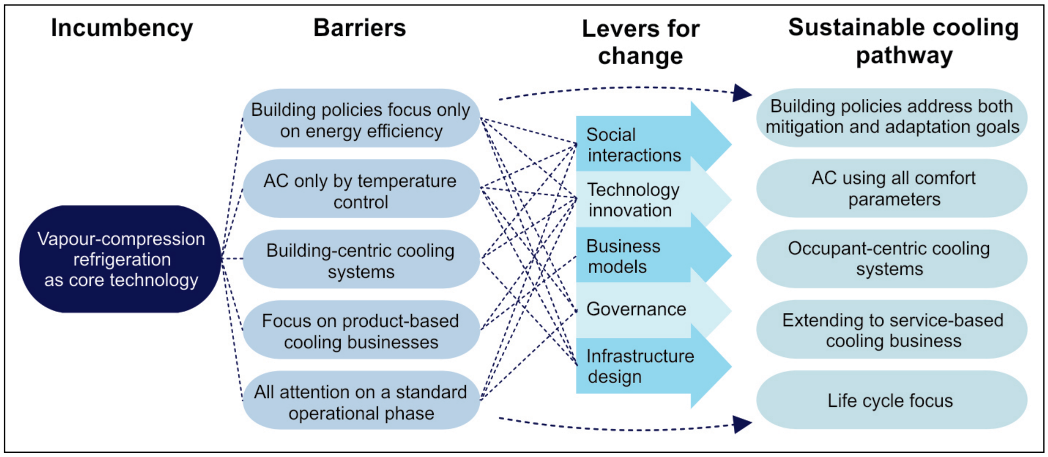

Figure 7: Knocking out the incumbency and barriers in the cooling sector through levers for change.

These levers can support the development of new sustainable and efficient cooling solutions and push forward the progress and maturity of other less-known mechanical and less energy-intensive alternatives, such as traditional or ancient approaches for keeping cool.

4.1 POLICIES BEYOND ENERGY EFFICIENCY: ADDRESSING CLIMATE CHANGE MITIGATION AND ADAPTATION

Current energy efficiency policies in the cooling sector have much scope to move beyond mitigation targets by including adaptation criteria to climate change. These policies would require the consideration of *future weather conditions* and *metrics to measure passive survivability*.

For adaptation-based policies, it is important to promote tools that focus on future climate conditions and not only on average historical weather data, known as typical meteorological year (TMY) weather (Crawley *et al.* 2019).[4] Currently, existing procedures promoted by building regulations to calculate and size thermal systems of buildings do not match future, even existing, thermal needs (Siu & Liao 2020). For example, Lizana *et al.* (2021) and Goncalves *et al.* (2022) demonstrated the importance of practitioners considering expected overheating in the building design process.

The metrics or indicators that guide building design are key elements in creating synergies between mitigation and adaptation targets. However, currently, most metrics target mitigation exclusively, calculating energy and carbon emissions assuming all buildings have AC or HVAC systems and a fixed set-point air temperature for cooling at 25°C.[5] Future building design decisions would benefit from being based on two heat-related indicators, namely, energy use/CO_2 emissions (with AC) and passive survivability (without AC). The target would be to maximise synergies between passive and active building performance, reducing trade-offs and indoor overheating situations (Samuelson *et al.* 2020b). Here, the implementation and improvement of steady-state models[6] for building analysis with AC systems or adaptive comfort models[7] for building analysis without AC systems can play an important role since they consider human adaptability involving all thermal comfort parameters. International thermal comfort standards, such as ASHRAE 55-2020 (ANSI 2020), ISO 7730:2005 (2005), EN 16798-1:2019 (European Standards 2019a) and other scientific publications provide methods to implement these thermal comfort indices. The influence of all these models on thermal comfort can also be better understood using the new online tool created by Tartarini *et al.* (2020): the CBE Thermal Comfort Tool (CBE n.d.)

The consideration of these aspects can be supported through relevant regulatory agencies, designing and implementing new policies according to each geography and governance system. For example, at the EU level, new reporting requirements on national energy and climate plans (European Commission 2022a) associated with the passive survivability of buildings and projected cooling demand would influence the requirements requested by building regulations across the EU. At the national level, infrastructure design can be better adapted by updating building codes. The consideration of future climate conditions in building design, more thermal comfort variables in energy demand analysis and passive survivability analysis could help to address better adaptation to climate change (Lizana *et al.* 2022; Zhang *et al.* 2021). At the city level, appointing chief heat officers with the capacities to work across urban departments to put in place locally contextualised extreme heat plans and support urban solutions for sustainable cooling can enhance urban adaptation to increasingly frequent extreme heat (WEF 2021).

4.2 ACS TO CONSIDER MULTIPLE THERMAL COMFORT PARAMETERS

The barrier of a fixed set-point temperature for ACs, often at 24–25°C to ensure comfort, could be overcome through the levers represented by technological innovation and governance shown in Figure 6. AC should be designed considering *more thermal comfort parameters* and *minimum ventilation requirements*.

Deep changes in consumers' demand and suppliers' offers are required to shape the market of cooling, moving towards considering more variables which directly impact thermal comfort, including temperature, humidity, radiant temperature, air velocity, clothing and metabolic rate (BCA 2015). It is suggested to eliminate the criteria of a fixed AC set-point temperature to fulfil building regulation requirements and calculate EPCs for buildings (Amirkhani *et al.* 2020; CREDS 2018; IDAE 2009; Ministerio de Fomento del Gobierno de España 2020; UK Government 2021). For example, integrating fans to increase airspeed with ACs can also increase the set-point temperature from 25 to 27°C without sacrificing thermal comfort, reducing energy consumption by more than 21% (Hoyt *et al.* 2015; Luo *et al.* 2021; Malik *et al.* 2022; Schiavon & Melikov 2008). However, this integration does not provide a better rating for EPCs. Khare *et al.* (2021) have also proved the benefits of radiant cooling in reducing energy use by 20% in comparison with a conventional AC system. To promote the use of other thermal comfort parameters, new evaluation procedures to meet building requirements would need to be designed and implemented, exploiting more variables.

The implementation of a steady-state approach[8] or adaptive comfort models[9] for building analysis can play an important role in the transition to eliminate fixed set-point temperature criteria for certain contexts (Carlucci *et al.* 2018). These models, created for buildings with and without AC, respectively, consider more environmental variables to define the temperature range in which people feel comfortable, enabling the implementation of commonly overlooked solutions for cooling, such as those based on airspeed, radiant temperature or clothing level. They use operative temperature to measure comfort, something already implemented by the new set of Energy Performance of Buildings standards developed by the European Committee for Standardization (CEN) under mandate M/480, which defines an accurate methodology to calculate the overall energy performance of buildings supporting the EPBD (EPB Center n.d.; ISO 2017). For example, in the case of cooling, EN 16798-2:2019 (European Standards 2019b) considers the possible installation of fans (such as table fans, ceiling fans or personal ventilation systems) to create comfort through an elevated airspeed at their work stations, permitting an increase of the set-point temperature by 1.2, 1.8 and 2.2°C for an average airspeed of 0.6, 0.9 or 1.2 m/s, respectively. However, these criteria are still not implemented in national mandatory procedures (CREDS 2018).

Such criteria could efficiently downsize cooling system requirements and their associated energy and environmental impacts (Lovins 2018). Moreover, higher demand for cooling solutions using more comfort parameters can enable the growth of innovative cooling integrations moving away from fixed set-point temperature considerations. Additionally, *minimum ventilation requirements* are a necessary part of the solution to guarantee appropriate indoor air quality (including adequate levels of CO_2 concentrations and indoor air pollutants) (Becerra *et al.* 2020; Lizana *et al.* 2020; Serrano-Jiménez *et al.* 2020).

4.3 RECOGNISE INDIVIDUAL COOLING NEEDS THROUGH OCCUPANT-CENTRIC DESIGN

Centralised systems have been proven not to be efficient since they may pervasively overcool people more than is needed (Parkinson *et al.* 2021), or even cool empty spaces (Khare *et al.* 2021).

This requires distinguishing between *centralised cooling configurations* and *individual adaptive environments* for user adaptability according to different cooling needs.

Many studies have demonstrated how combining a centralised cooling system with adaptive personal cooling environments can provide energy savings without sacrificing comfort. Khare *et al.* (2021) evaluated the performance of different building- and occupant-centric cooling solutions and observed how the combination of centralised and personalised radiant cooling could mitigate consumption by 38% compared with a conventional AC system. Even the use of personalised radiant conditioning systems alone was able to reach the thermal comfort criteria reducing energy consumption by 69%. Teufl *et al.* (2021) showed how personalised radiant cooling could provide acceptable comfort levels at an ambient air temperature of 28°C. They also highlighted that air movement was key in influencing the subject's preference for radiant cooling (Aryal *et al.* 2022; Teufl *et al.* 2021). Pasut *et al.* (2015) demonstrated how the use of heated/cooled chairs provided comfortable conditions for 92% of the subjects in a range of temperatures from 18 to 29°C. All these findings highlight the importance of recognising the role of individual cooling needs for sustainable cooling (Jay *et al.* 2021). Centralised cooling systems in the building infrastructure could focus on the minimum percentile of people's basic needs; and meet the different individual cooling requirements through adaptive environments that integrate personal cooling alternatives[10] such as personal/desk fans, radiant panels, cooled seats or wearable AC devices (ASHRAE 2017; Hoyt *et al.* 2015; Jay *et al.* 2021).

Additionally, Murtagh *et al.* (2022) showed how regulations and social behaviour change interventions regarding AC settings can focus on acclimatisation to heat. Changes in societal patterns, such as work hours, and behavioural adaptations, such as informed use of shading, can help mitigate heat impact. Drury *et al.* (2021) also proposed providing safe havens in dwellings as an alternative solution to ACs. They show how the housing stock may use well-oriented living rooms or alternative bedrooms, if available, as a cool retreat for sleeping when the main bedroom overheats.

It is important to recognise the levers for change in infrastructure design and technology innovation with which companies can start demanding occupant-centric technologies in order to obtain high economic and environmental benefits without losing productivity. The role of architects and engineers in properly advising and implementing these criteria can also play an important role. This can encourage growth in technology alternatives for personal environmental control (PEC) systems and centralised smart control based on, for example, room occupancy patterns. Also, it is important to recognise the role of social interactions in disseminating and promoting this occupant-centric cooling-related behaviour (Wolske *et al.* 2020). Peer and cultural preferences and experiences highly influence technological adoption.

4.4 FROM PRODUCT-BASED COOLING BUSINESSES TO SERVICE-BASED COOLING BUSINESSES

Business models can move beyond product-based business to *servitisation*, *e.g.* cooling as a service (Blomsma *et al.* 2022; Fernandes *et al.* 2020). The future of cooling would be well based on these product-service systems where the product is joined by more features or service contracts, such as maintenance, repair or replacement (Kurpiela & Teuteberg 2022). Because ownership is not fully transferred, there is potential for a large circular economy. Agrawal & Bellos (2017) and von Delft & Zhao (2021) showed how service-centric models and hybrid models that combine product sales and service options are more profitable and environmentally superior to product-centric businesses. In these business models, manufacturers or service-providing companies are incentivised to use a longer lasting product, maintain it effectively during its operational phase and reuse materials at the end of its life cycle. Servitisation does not need extremely high re-engineering processes for entering the market (Annarelli *et al.* 2018). Moreover, this may promote higher system efficiencies and reduce common problems related to oversizing, faulty installation and inadequate maintenance, reducing the LCC of cooling (Palafox-Alcantar *et al.* 2022).

Despite reported benefits, there are also some obstacles to adopting servitisation. For example, manufacturers risk becoming subcontractors and not partners in the business model, decreasing their control over the system. Also, customers might experience lower cost savings than expected, with a lack of control and trust, and transaction costs that are hard to account for (Huikkola & Kohtamäki 2018). Further research is required to understand better the differences between a business model adopted by manufacturers or service providers and how product-service systems might develop.

This market change requires a shift in procurement strategies and market forces, which could also tie into regulation. Adding extra taxes/duties to exclusively product-based cooling businesses could enable a lever for change in business models. Governance could support product-service systems through subsidies. Moreover, it is important to demonstrate the advantages and benefits for real estate owners to make them aware of the economic and environmental benefits of service-based business models. Novel insurance products or bank products based on these requirements could minimise economic risks for banks and insurance companies while maximising economic, social and environmental benefits for owners and users.

4.5 FROM A STANDARD OPERATIONAL PHASE FOCUS TO LIFE CYCLE ATTENTION IN COOLING SYSTEMS

The focus of the standard operational stage of cooling technology is proposed to move to a full life cycle vision in order to mitigate the environmental impact in its whole life cycle. Here, the *humidity influence*, *implications of energy storage* and environmental impact of *F-gases* are key aspects to be considered.

In the operational phase, humidity influence on technology performance is another important parameter to include. To achieve a comfortable humidity level, ACs on the market will typically overcool the space, leading to suboptimal thermal comfort levels and excessive energy consumption. None of the existing efficiency metrics of cooling systems accounts for humidity influence (Pérez-Lombard *et al.* 2012), which underestimates the effectiveness of cooling solutions. New test standards to measure the performance of AC systems in consideration of humidity could promote more efficient cooling technologies to address latent heat, which is highly important in determining the cooling energy load in hot–humid regions (Kalanki *et al.* 2021).

Cooling systems' operation should also enable higher penetration of renewable energy sources to reduce fossil fuel dependence. In this case, the consideration of energy storage (electric batteries or cool batteries[11]) for cooling integration can play an important role in cooling decarbonisation. Cool batteries have recently attracted much attention for energy storage in cooling applications. Thermal batteries are claimed to be 60–90% cheaper, being a much more cost-effective solution for providing energy for heating/cooling than the most affordable Li-ion alternative (IRENA 2020; Lizana *et al.* 2023). The most common choice is based on water/ice storage. However, additional options based on other phase-change materials (PCMs) or thermochemical processes have been proposed and tested (Lizana *et al.* 2018a, 2018b). Lizana (2019) demonstrated how combining a heat pump with a cool battery, and smart demand-side response could reduce energy consumption by 27% and decrease energy cost by 51% in a case study in Seville (Spain). These benefits were achieved thanks to the combination of higher seasonal efficiency based on night operation with lower temperatures, and operating periods with lower electricity prices.

In the end-of-life stage, the most important implications are related to refrigerants (F-gases) since they can have the highest direct emissions (Zhao *et al.* 2015). By shifting the ownership of technologies away from end-users (as proposed previously), the regulation of safe disposal becomes more feasible (Dehoust & Schuler 2007). This would add to the efforts of moving toward lower GWP or natural refrigerants (Wu *et al.* 2021), which would benefit from being promoted across all cooling sectors and appliances to reduce GHG emissions (EIA 2021). The governance lever may not just limit F-gases but also phase out and penalise them so as to promote the transition to alternative low-GWP gases. Moreover, environmental labelling would allow citizens to make better purchase choices. Shifting the labelling regimes beyond the operational phase in key leading jurisdictions such as the US, EU or India, considering the whole life cycle impact of products, could drive this change. Here, the influence of institutions and international organisations plays an important role (Clasp 2020; European Commission 2022b).

5. LOOKING AHEAD

This perspective examines the existing barriers in the cooling sector promoted by the dominant cooling technology—the *vapour-compression refrigerant technology*—and proposes interventions through levers for change to achieve sustainable cooling. The levers for change are represented by social interactions, technology innovation, business models, governance and infrastructure design, and together they can help overcome barriers in the transition towards sustainable cooling through different actions.

Key actions have been grouped into five areas. They include moving from building policies focused only on energy efficiency to policies considering mitigation and adaptation targets. This involves the consideration of future climate conditions in building design and the implementation of passive survivability metrics to better address adaptation to climate change. Second, moving from air-conditioning (AC) based only on temperature control to AC using more thermal comfort parameters that integrate minimum ventilation requirements. New evaluation procedures to meet building codes' requirements by exploiting more comfort variables may help to overcome the fixed set-point temperature barrier. This can enable the growth of innovative cooling alternatives combining temperature, humidity, radiant temperature, air velocity and ventilation. Third, building-centric cooling control needs to change, recognising individual cooling needs through an occupant-centric building design. Centralised cooling systems can be downsized by allowing adaptive environments that integrate personal environmental control (PEC) systems (*i.e.* personal cooling devices). Occupant-centric cooling through operable windows, personal fans, cooled seats or wearable cooling systems can help to meet personal cooling needs while increasing centralised set-point temperature, *e.g.* from 24 to 27°C, essentially cooling people, not buildings. Fourth, businesses would benefit by moving from product-oriented to service-based models to promote low-carbon economies, ensuring that the product life cycle is extended, and its performance improved by the associated services. Finally, environmental considerations need to be extended beyond the standard operational phase to the whole life cycle in real operating conditions. This would increase the efforts to move towards the integration of humidity influence in cooling efficiency rating, the role of energy storage in the operational phase to promote renewables, and the use of ultra-low global warming potential (GWP) refrigerants through new constraints or even empowering consumers to make a better sustainable purchase through environmental labelling.

There is a limited window to shape the fast-growing trajectory of cooling, with rising temperatures driving cooling emissions and hampering progress towards zero-carbon targets. Overcoming barriers from the incumbent technology will enable a sustainable future of cooling for all, including those most vulnerable and with the least access—an issue that must become a present-day priority for actors across all levers of change.

NOTES

1 Merriam-Webster dictionary definition of culture.

2 Energy Performance Certificate (EPC) is an energy labelling that informs about the formal rating of the energy efficiency of a building.

3 Passive survivability refers to the ability to maintain safe thermal environments in the absence of a functional AC system.

4 A TMY is a set of hourly meteorological data in a year for a given geographical location. It is used for energy simulations to support building design. The weather data are created from hourly historical weather data by selecting the most 'typical' months normally considering a period of 10 years or more.

5 Tools to simulate the energy demand of buildings in order to fulfil building codes, emit EPCs or size AC systems use a fixed set-point temperature to calculate cooling needs. For example, in the case of Spain and the UK for cooling, the set-point temperature for EPCs is defined at 25°C (Amirkhani *et al*. 2020; IDAE 2009; Ministerio de Fomento del Gobierno de España 2020).

6 The steady-state approach (or PMV/PPD method) proposed by Fanger (1970) predicts the mean thermal sensation and percentage of dissatisfaction of a given group of people in the environment considering all comfort parameters. It is represented through the indices predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) following a seven-point thermal sensation scale. It is used for AC buildings and was incorporated into the international standard ISO 7730, then subsequently in ASHRAE Standard 55. The last version was published in 2020 (ANSI 2020).

7 The adaptive comfort model defines linear regression that relates acceptable indoor operative temperature to outdoor temperature or outdoor meteorological variables. The principles of adaptive comfort are typically applied to non-AC buildings since it considers physiological, psychological and behavioural factors in thermal adaptation. This model was proposed as an alternative to the PMV-PPD model in buildings without AC systems since PMV-PPD overestimated occupant discomfort in both cold and warm seasons. De Dear & Brager (1998) proposed the first adaptive comfort approach that was integrated into an international standard (ASHRAE 55:2004). It is currently available in many international standards such as the last version of ASHRAE 55:2020 (ANSI 2020) or EN 16798-1:2019 (European Standards 2019a).

8 See note 6.

9 See note 7.

10 Personal cooling alternatives refer to cooling devices specifically designed for personal environmental control (PEC). They focus directly on specific body parts and may offer an energy-efficient means for improving comfort in indoor environments. These targeted body parts are the head and hands in warm conditions, and the feet and hands in cool conditions (ASHRAE 2017).

11 Cool batteries are thermal energy storage solutions to store cool for cooling applications. These batteries can be based on three thermal storage methods: sensible, latent or thermochemical. Sensible heat storage consists of the heat/cool stored and released by modifying the temperature of the storage medium. Latent heat is associated with the heat stored or released in a medium undergoing a phase change. Thermochemical heat storage is related to reversible sorption and/or chemical reaction processes. A complete review of thermal energy storage materials and building applications was reported by Lizana *et al.* (2017, 2018a).

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COMPETING INTERESTS

The authors have no competing interests to declare.

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