UN environment programme

The free degrees

How sustainable, passive-first cooling can save lives, money and food

Cool Coalition
a UNEP-convened initiative

Global Cooling Watch
2025

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List of Abbreviations

°C	Degrees Celsius
BAU	Business-as-usual
CaaS	Cooling-as-a-service
CDD	Cooling degree day
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COP	Conference of the Parties
EV	Electric vehicle
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HVAC	Heating, ventilation and air conditioning
IPCC	Intergovernmental Panel on Climate Change
kW	Kilowatt
kWh	Kilowatt-hour
LRM	Lifecycle refrigerant management
LT-LEDS	Long-Term Low Emission Development Strategies
m^2	Square metres
MEPS	Minimum energy performance standards
MRV	Measurement, reporting and verification
NAP	National Adaptation Plan
NCAP	National Cooling Action Plan
NDC	Nationally Determined Contribution
PFAS	Per- and polyfluoroalkyl substances
SBTi	Science Based Targets initiative
SDG	Sustainable Development Goal
TW	Terawatt
TWh	Terawatt-hour
U4E	United for Efficiency
UNEP	United Nations Environment Programme
W	Watt

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Foreword

As the planet endures record temperatures and unprecedented heatwaves, cooling has become a lifeline – essential for survival, health and prosperity.

From protecting people against extreme heat to preserving food and medicines, from keeping schools open to sustaining economies, cooling underpins nearly every aspect of modern life. It makes our new reality liveable, productive and progressive.

Unsurprisingly, global demand for cooling is soaring, especially in rapidly urbanizing and warming regions. This year's Global Cooling Watch report projects that installed cooling capacity is on a trajectory to triple by 2050, potentially driving emissions to 7.2 billion tons of carbon dioxide equivalent – even with efficiency gains and refrigerant phase-down efforts. Yet billions will still lack adequate protection from heat.

We must reimagine cooling – not as a source of emissions, but as a cornerstone of heat resilience and sustainable development. During heatwaves, access to cooling can mean the difference between life and death. Year-round, it enables thriving communities, food security, continued learning and habitable cities. Sustainable, accessible cooling—from passive design to efficient refrigeration—must be treated as essential infrastructure, as fundamental as clean water, energy and sanitation.

Designing cooler cities should be central to urban planning. Passive and nature-based solutions—shading, natural ventilation, reflective surfaces and green corridors—are our first line of defence. They reduce heat stress, curb urban heat islands and relieve pressure on strained power grids. The time to redesign our urban spaces is now.

Low-energy and renewable-powered cooling solutions—such as fans, evaporative systems and solar-driven refrigeration—can safeguard health and livelihoods, including in off-grid communities. Yet heat resilience requires not just adaptation to heat, but also accelerating mitigation efforts across active cooling solutions. Deeper emission cuts require transformation: scaling hybrid systems that combine fans and air conditioners, super-efficient equipment and next-generation refrigerants.

Taken together, these measures define a Sustainable Cooling Pathway – cutting projected emissions by 64 per cent, protecting three billion more people from extreme heat, and saving up to US$43 trillion in cumulative energy and grid infrastructure costs by 2050. The co-benefits are immense: fewer heat-related deaths, stronger economies, more liveable cities and fewer blackouts.

Achieving this demands ambition and coordination across nations, sectors and scales. Beat the Heat—a joint effort of the UNEP-led Cool Coalition and Brazil as host of COP30—offers a platform to turn these findings into tangible action. We call on governments, cities and partners to join this effort – aligning policy, finance and delivery to ensure that every step to cut emissions also protects those most at risk.

It is human to protect what we value – our homes, our cultures, our communities. These places hold both intrinsic and economic worth, and the instinct to safeguard them runs deep. Adapting them to a hotter, more volatile climate is not just survival, it is a commitment to continuity and resilience. By making sustainable cooling the foundation of heat resilience, we can protect lives and livelihoods today while preserving the places, traditions and futures we hold dear.

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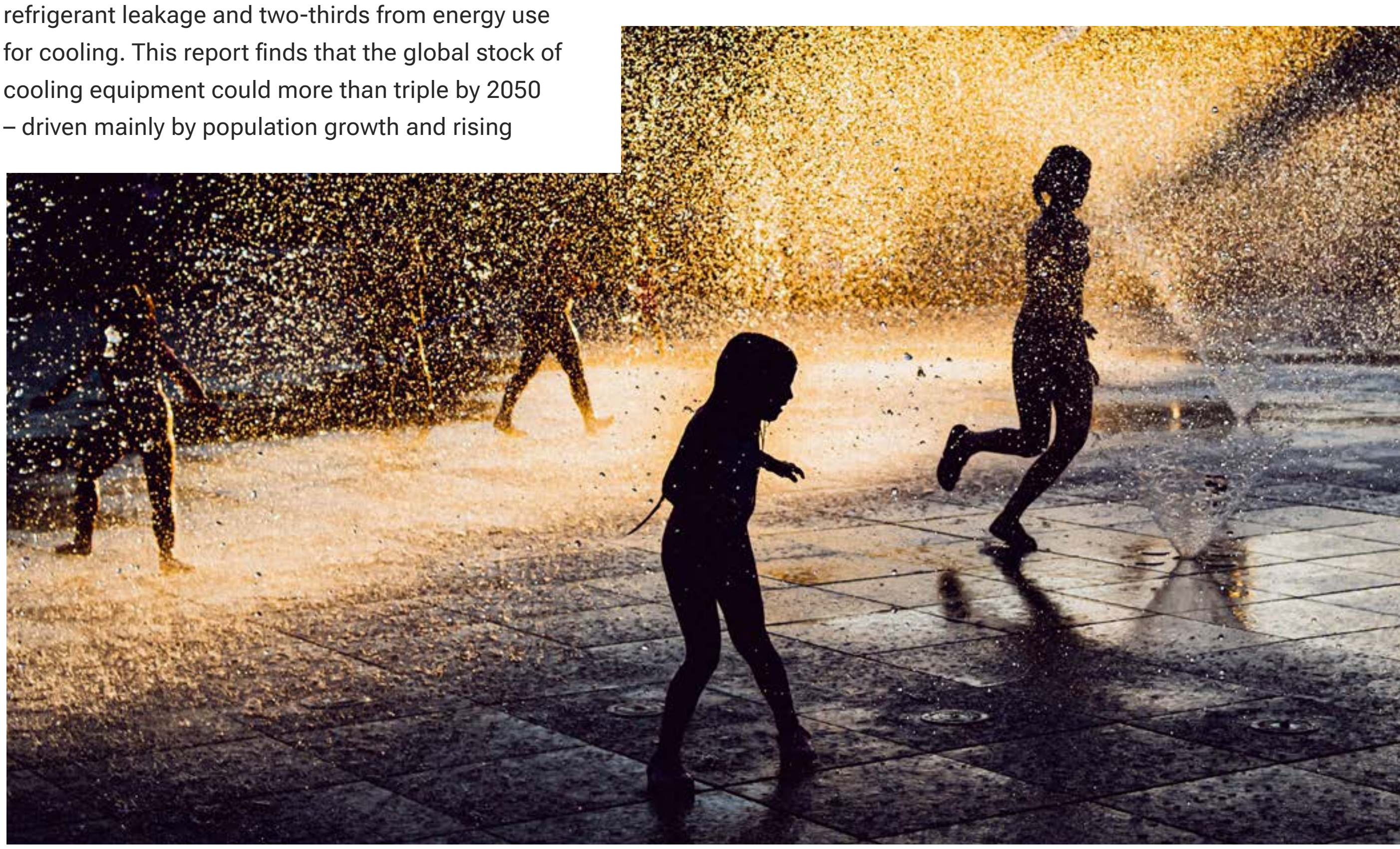
Executive Summary

Cooling is both a lifeline in a rapidly warming world and a major challenge for climate action. It protects people from extreme heat, safeguards food and vaccines, and enhances liveability and productivity in homes, schools and workplaces.

However, surging demand for cooling risks locking in steep increases in energy use and greenhouse gas (GHG) emissions. Inefficient air conditioning is already straining electricity grids, driving power outages and forcing costly investments in new power infrastructure. Cooling's climate challenge is two-sided: to expand affordable, sustainable cooling approaches for adaptation, while cutting the energy and carbon footprint of cooling for mitigation.

In 2022, GHG emissions from refrigeration and air-conditioning equipment totalled an estimated 4.1 billion tons of carbon dioxide equivalent (CO_2e) globally, of which roughly one-third was from refrigerant leakage and two-thirds from energy use for cooling. This report finds that the global stock of cooling equipment could more than triple by 2050 – driven mainly by population growth and rising incomes, but also by more frequent extreme heat events and policies to help the poorest households obtain access to some cooling. This would push cooling emissions to 7.2 billion tons of CO_2e under a Business-as-Usual Cooling Pathway, despite ongoing energy efficiency and refrigerant phase-down policies.

The alternative is a Sustainable Cooling Pathway, which has the potential to slash GHG emissions from cooling to near-zero in 2050, increase access to cooling and result in trillions in economic savings. This pathway consists of passive cooling strategies; low-energy and hybrid cooling that combines fans and air conditioners; rapid adoption of high-



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efficiency equipment; and accelerated phase-down of hydrofluorocarbon (HFC) refrigerants. Modelling shows that the 2050 cooling equipment stock could be cut by around 40 per cent and cooling-related emissions reduced to 2.6 billion tons of CO_2e, or 64 per cent below BAU. When combined with rapid decarbonization of the global power sector, residual cooling emissions could fall to just 0.2 billion tons of CO_2e, or 97 per cent below BAU levels.

Cooling for climate adaptation and mitigation

Practical and integrated solutions already exist to deliver sustainable, equitable and climate-aligned cooling for all. Scaling these measures can deliver deep cuts in cooling emissions, strengthen resilience to extreme heat and unlock trillions of dollars in avoided energy and infrastructure costs. Current trends demonstrate that societies cannot simply "air condition their way out" of escalating heat risks. Instead, adaptation and mitigation must be addressed together, with systemic approaches that integrate passive and active cooling solutions at the national and subnational levels.

The theme of this year's report—bridging extreme heat and access to cooling—reflects the growing recognition of cooling as both an essential adaptation strategy and an integral component of climate mitigation. Extreme heat has emerged as a fast-growing climate risk, resulting in hundreds of thousands of deaths annually, reducing productivity, straining infrastructure and disproportionately affecting vulnerable communities. Over one billion people, particularly women in low-income and marginalized communities, face high risks from inadequate cooling, underscoring the urgent need for reliable, affordable and sustainable access to protect health, livelihoods and food security.

Policy momentum and implementation gaps

Analysis of 192 countries as of June 2025 shows rising recognition of cooling's climate footprint. In total, 29 countries have established specific GHG reduction targets for the cooling sector, with a further 5 developing such targets. Altogether, 134 countries have incorporated cooling into their Nationally Determined Contributions (NDCs), National Adaptation Plans (NAPs), Long-Term Low Emission Development Strategies (LT-LEDS) and/or energy plans.

Policy momentum is strong but uneven. Only 54 countries have policies across all three measures consistent with the Sustainable Cooling Pathway: passive cooling in building energy codes, minimum energy performance standards and rapid refrigerant transition. A further 78 countries cover two of these pillars, 40 cover only one, and 20 have yet to begin.

By embedding passive cooling into building design, energy codes permanently reduce the cooling loads of buildings, enabling smaller and more efficient cooling systems, lowering energy use and cutting GHG emissions. However, critical implementation gaps remain in building energy codes worldwide, particularly in developing regions where regulatory frameworks lag urgent cooling needs.

While 69 countries mandate residential building envelope standards and 58 mandate glazing standards, only 19 require shading features. A similar pattern is observed for non-residential building codes. This is despite research demonstrating that strategic passive cooling measures can achieve average temperature reductions of 2.2 degrees Celsius (°C) and energy savings of 29 per cent.

Reducing growth in global cooling capacity

Without intervention, the global installed capacity of cooling equipment could more than triple, rising from 22 terawatts (TW) in 2022 to 68 TW by 2050. The growth is likely to be particularly steep in low- and middle-income countries in hot regions such as Africa and South-Central Asia, driven by rapid development, expanding urban populations and rising temperatures.

But the growth in cooling capacity will not be confined to developing and emerging economies. As global average temperatures climb by 1.5°C, and possibly 2°C or more, above pre-industrial levels, there will also be strong growth in high-income countries with relatively mild climates. In Europe, for example, more frequent periods of extreme heat are forecast to cause a large increase in the demand for air conditioning.

Applying sustainable cooling load reduction measures—including passive building design; the expanded use of fans, evaporative coolers and hybrid air-conditioning systems; and refrigeration load reduction—could reduce the 2050 installed cooling capacity from 68 TW to 40 TW, a 41 per cent cut. Such measures would yield substantial emission reductions while expanding access to affordable cooling solutions to the most vulnerable populations.

Economic and equity benefits from scaling up sustainable cooling

Implementation of the Sustainable Cooling Pathway could deliver significant economic and social gains. By 2050, annual electricity savings could reach 8,500 terawatt-hours (TWh), equivalent to US$1.3 trillion (2020 US$) – with cumulative savings of 110,000 TWh, worth US$17 trillion between 2025 and 2050. Peak load reductions of 5–10 TW could avoid an estimated US$13 trillion to US$26 trillion in capital investments in new electricity generation and grid infrastructure. These outcomes underscore the central role of sustainable cooling in reducing emissions, safeguarding energy systems, expanding access and lowering costs for end users and the power sector.

Despite projected growth in air conditioners, nearly three billion people may still lack access by mid-century. Addressing this challenge requires strategies that combine passive measures, efficient and off-grid solar-powered technologies, innovative business models and targeted financial mechanisms to ensure equitable and inclusive access.

Passive cooling strategies and complementary solutions

Passive cooling strategies—including climate-responsive design, improved building envelopes, cool surfaces, nature-based solutions and heat rejection techniques—are the most equitable and cost-effective options to protect vulnerable communities from extreme heat. They deliver benefits ranging from reduced heat-related mortality and improved air quality to reduced energy use, lower peak demand and strengthened grid stability during extreme heat events.

Passive cooling in buildings delivers immediate comfort and long-term energy savings, with payback periods ranging from around 2 years for external shading to around 14 years for green roofs. Cool surfaces provide quick returns, building envelope upgrades yield major energy savings, and evaporative or nature-based solutions can lower indoor temperatures by up to 7°C. Strategic combinations of multiple passive interventions can achieve total temperature reductions of 6–9°C, often removing the need for mechanical cooling in many tropical and temperate buildings. Integrating these measures into modern building energy codes is therefore essential to achieving long-term resilience and low-carbon development.

Low-energy space cooling technologies—such as high-efficiency fans, evaporative coolers and hybrid air-conditioning systems—complement passive cooling strategies, offering additional solutions to meet rising cooling demand. Energy-saving hybrid approaches can cut energy use by more than 30 per cent compared to conventional air conditioning, providing affordable and sustainable comfort solutions, particularly for populations with limited access to reliable electricity.

New frameworks for addressing sustainable cooling

Two frameworks introduced in this report provide structured approaches for policymakers and practitioners:

- The **Sustainable Cooling Hierarchy** sets out a four-step process to guide design and implementation and to avoid locking in inefficient cooling equipment that has high global warming potential. Applying this hierarchy can also reduce peak electricity demand and limit costly expansion of power generation and transmission. The four steps are: 1) minimize cooling loads (e.g. through passive building design); 2) use low-energy cooling (e.g. through fans in place of air conditioning); 3) maximize the energy efficiency of new and existing equipment (e.g. through variable-speed compressors; improved control and maintenance); and 4) implement a rapid phase-down of HFC refrigerants.
- The **Tiered Access to Sustainable Cooling Framework** sets out a progressive approach to equitable access, from Tier 0 (no access) to Tier 5 (full access to sustainable cooling), highlighting low-energy and hybrid solutions as key enablers across all tiers.

Conclusion and call to action

Sustainable cooling is fundamental to achieving global climate adaptation and mitigation goals. Governments, cities, industries and development partners must work collectively to accelerate the transition towards sustainable, efficient and inclusive cooling systems. Integrating passive and active measures within coherent national strategies, supported by coordinated finance, policy, and innovation, can protect lives and livelihoods, reduce emissions and build resilience in a rapidly warming world.

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01 Introduction

Cooling is both essential for adapting to a rapidly warming world and a major contributor to climate change.

Cooling protects people from rising temperatures, safeguards food and vaccines, and underpins productivity in homes, schools and workplaces. Yet the increase in peak electricity demand to power inefficient air conditioners is straining power grids beyond their limits, especially during prolonged heat waves. This leads to power outages, limits electricity access for the vulnerable and drives costly infrastructure expansion. Sustainable cooling is now a global priority: critical for protecting health and livelihoods for billions of people while safeguarding the climate and promoting equitable, inclusive and gender-responsive development.

1.1 Global Cooling Watch 2023 and the Global Cooling Pledge

The *Global Cooling Watch 2023* report warned that under a business-as-usual (BAU) path, the global installed cooling capacity could nearly triple by 2050 – doubling electricity use and pushing annual greenhouse gas (GHG) emissions from cooling to 6.1 billion tons of carbon dioxide equivalent (CO_2e) (United Nations Environment Programme [UNEP] 2023). To avoid this, the report recommended a mix of passive cooling, higher energy efficiency standards and a faster phase-down of potent GHG refrigerants. It projected that, together, these measures could reduce the annual emissions from cooling in 2050 by over 60 per cent from BAU levels, a cumulative reduction of 61 billion tons of CO_2e through 2050. This is equivalent to the lifetime emissions of roughly 700–800 large (500-megawatt) coal-fired power plants. When combined with rapid grid decarbonization, emissions from cooling could be reduced to nearly zero.

Photo: Richard Vanlerbergh/Unsplash

This analysis helped catalyse the Global Cooling Pledge, launched at the 2023 United Nations Climate Change Conference (COP28) in Dubai, United Arab Emirates. By October 2025, 72 countries and 80 non-state actors had joined. The Pledge is the focal point for raising collective ambition on sustainable cooling, aiming to cut cooling-related emissions at least 68 per cent globally by 2050 (relative to 2022) and to greatly improve cooling energy efficiency and access to cooling by 2030. The first Progress Report shows promising early actions, with governments embedding cooling targets in climate strategies, strengthening standards and piloting large-scale passive cooling and efficient appliance programmes (UNEP 2024a).

1.2 Theme of this year's report: extreme heat and access to cooling

Extreme heat is an escalating global threat. In 2024, the United Nations Secretary-General issued a Call to Action on Extreme Heat, warning that it is now the leading cause of weather-related deaths worldwide (UN Secretary-General 2024). The Call urges governments to adopt national heat action plans, strengthen early-warning systems and ensure equitable access to sustainable cooling solutions – framing this as both an adaptation and mitigation priority. It emphasizes that current efforts remain fragmented and underfunded, calling for coordinated and adequately financed strategies to close this gap.

Global Cooling Watch 2025 builds on the 2023 report in response to growing global concern over intensifying extreme heat—which will increase cooling demand even further—as well as persistent gaps in access to sustainable and affordable cooling, particularly for vulnerable populations. This shapes the report's updated modelling scenarios, emission trajectories, and the assessment of policies, technologies and access pathways. The report stresses that societies cannot simply "air condition their way out" of escalating heat risks. Instead, adaptation and mitigation must be addressed together, with systemic approaches that integrate passive and active cooling solutions at the national and subnational levels.

1.3 The structure of Global Cooling Watch 2025

The report is organized into three parts:

Part I: Framing the challenge

- **Chapter 2** provides a framing of extreme heat trends and the implications for future cooling demand. It emphasizes the need to build a resilience narrative that bridges adaptation to extreme heat with mitigation of cooling energy demand.
- **Chapter 3** introduces two core concepts: 1) the Sustainable Cooling Hierarchy and 2) the Tiered Access to Sustainable Cooling Framework. These concepts are used throughout the report to support the analysis of a pathway to sustainable cooling that provides cooling access in the poorest households.

Part II: Future outlook and current trends

- **Chapter 4** provides outputs from updated modelling of the likely growth in cooling equipment between now and 2050, together with analysis of the pathways to achieve near-zero GHG emissions from cooling globally.
- **Chapter 5** summarizes the findings from the 2025 Global Cooling Watch policy survey and provides a detailed review of building energy codes for passive cooling strategies. It includes relevant case studies and recommendations.

Part III: Solutions and opportunities

- **Chapter 6** integrates input from contributing authors and experts who provide a state-of-the-art review on cooling technologies, focusing on the Sustainable Cooling Hierarchy and addressing extreme heat issues.
- **Chapter 7** shows that passive cooling solutions in buildings are highly cost-effective, lowering indoor temperatures by up to 8 degrees Celsius (°C) and reducing cooling energy use by 15–55 per cent, while delivering wider economic and social value.

PART I:
FRAMING THE CHALLENGE

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02

Bridging Extreme Heat and Access to Cooling

In recent decades, the frequency, intensity and duration of extreme heat events driven by human-caused climate change have risen dramatically.

Heatwaves are a seasonal hazard – recurring crises that kill more people than any other climate-related event (World Health Organization [WHO] 2024). In urban areas, the urban heat island effect amplifies exposure, creating localised temperature spikes of 5–10°C above surrounding regions and driving up both discomfort and demand for cooling. For farmers, fishers, and vegetable sellers, extreme heat not only impacts human health but drives spoilage of the produce on which their livelihoods depend.

Vulnerability is greatest in low-income communities and among high-risk groups—including women—that have limited access to reliable cooling and resilient infrastructure, compounding systemic risks across sectors and regions.

Extreme heat events expose a growing divide: for those without reliable, affordable or sustainable cooling there is often no escape. Homes, schools, workplaces and hospitals become dangerously hot; outdoor labourers face productivity and health losses; farmers and fishers face major losses; and during prolonged humid heat events, even nighttime offers no relief. When power grids fail, often triggered by peaks in cooling demand, entire populations are at risk.

The escalation of extreme heat is shifting the narrative from a focus on short-term emergency response to the need for long-term heat mitigation – by building access to cooling and the cold chain as public protection. Cooling forms the basis of heat adaptation and is essential for protecting lives, yet it risks driving further emissions unless pursued through sustainable solutions. To build resilience, integrated strategies are needed that bridge adaptation and mitigation across built environments and cold chains. Addressing global disparities in access to cooling requires policies and actions that align heat adaptation, sustainable cooling and broader development goals through a resilience-focused narrative.

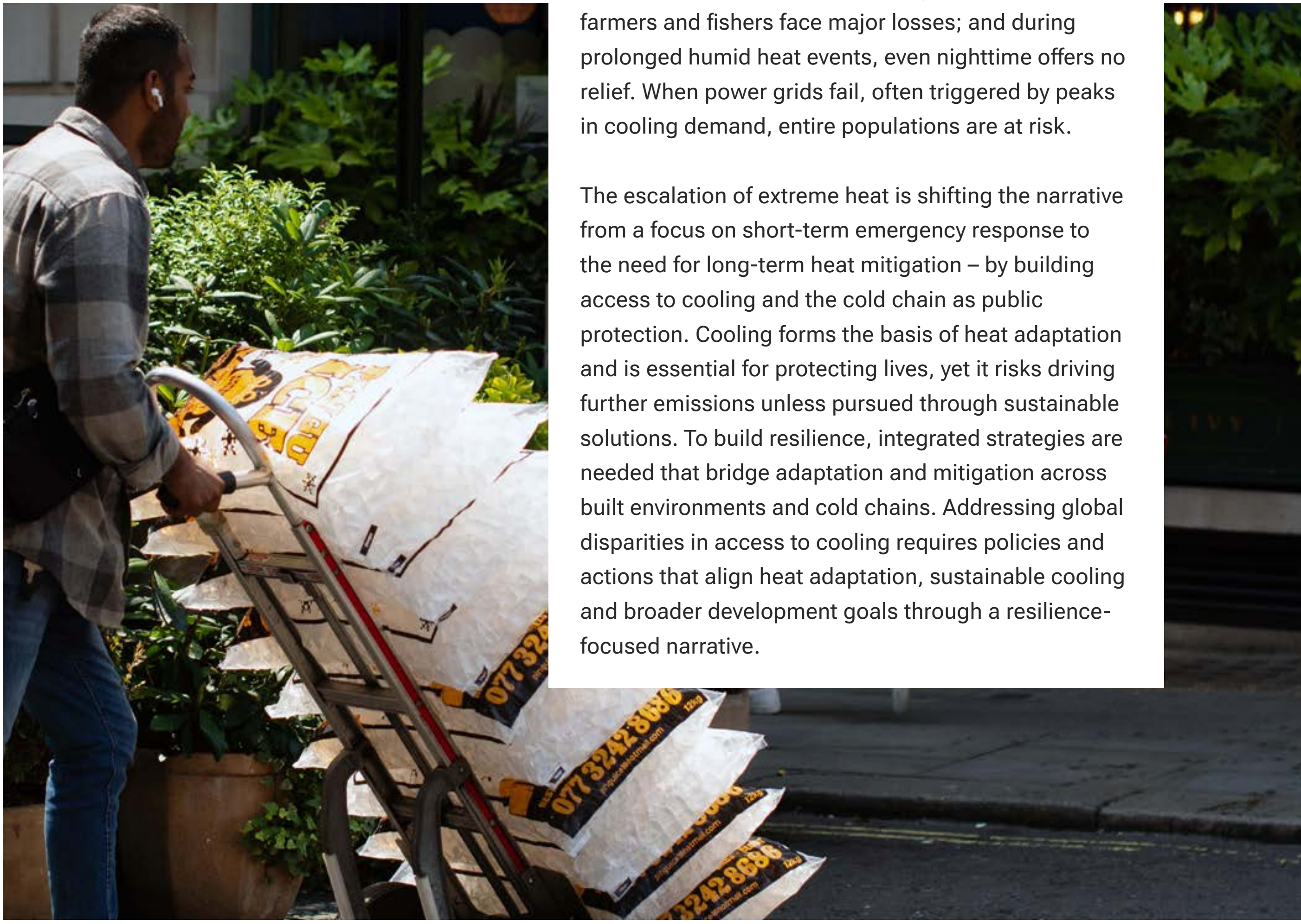


Photo: Alastair Johnstone/Climate Visuals

Government efforts such as India's National Disaster Management Authority, which aims to minimise heat-related mortality, are recognising that mitigating the impacts of extreme heat cannot be achieved through early-warning systems or emergency measures alone. Preventing avoidable mortality requires year-round investment in heat mitigation and cooling access – particularly passive and low-energy measures that protect all citizens, not only those who can afford air conditioning. Subnational governments such as Tamil Nadu state in India have declared heat as a disaster and are now prioritising greater efforts on passive cooling in schools, urban areas and affordable housing.

2.1 Growing extreme heat

The Intergovernmental Panel on Climate Change (IPCC) projects that the global share of the population exposed to deadly heat stress could rise from around 30 per cent today to between 48 per cent and 76 per cent by the end of the century, depending on future warming levels (IPCC 2023). At a warming level of around 2°C, heat extremes are projected to more frequently exceed critical health-tolerance thresholds, highlighting the urgency of adaptation and cooling strategies (IPCC 2021; IPCC 2023). Already, between May 2024 and May 2025, roughly four billion people — around half of the global population — experienced at least 30 additional days of extreme heat, and in 195 countries and territories, the number of extreme heat days doubled or more, because of climate change (Climate Central *et al.* 2025).

The impacts of extreme heat for humans are intensified when accompanied by humidity, as high levels of moisture in the air prevent sweat from evaporating, making it harder for the body to cool and increasing the risk of overheating and dehydration (Matthews *et al.* 2025). Humid heat has more than doubled in frequency since 1979, and it is increasingly severe and more intense than previously reported (Raymond, Matthews and Horton 2020). Collectively, temperature, relative humidity, solar radiation exposure and wind speed are critical in shaping heat stress that severely affects humans and infrastructure.

These heat risks are compounding and occur across interlocking dimensions of human safety and comfort, food security and nutrition, productivity, critical infrastructure, and health services and medical impact (Sustainable Energy for All [SEforALL] 2025). The scale of this challenge is already significant, with extreme heat causing the deaths of 356,000 people in 2019 alone (The Lancet 2021) and additional estimates quantifying heat-related deaths at 489,000 annually between 2000 and 2019 (Johnson 2024). Access to cooling becomes the critical pivot that determines whether extreme heat can be endured or not.


Photo: Tandem X Visuals/Unsplash

Extreme heat is typically defined as a sustained period during which daily temperatures—often maximum, minimum or diurnal average—exceed the 90–95th percentile of historical norms for that specific calendar day or period. The World Meteorological Organization defines a heatwave as a period of cumulative excess heat over several unusually hot days and nights, emphasizing that heatwaves are a localized and sustained form of extreme heat (Nairn and Mason 2025).

Humid heat is typically measured by wet-bulb temperature, which combines heat and humidity. Humid heat is increasing in both frequency and severity, particularly in highly populated tropical and coastal regions (Rogers *et al.* 2021).

As global temperatures climb to 1.5°C, and possibly further to 2°C, above pre-industrial levels, the greatest absolute increase in demand for cooling will occur in African countries. However, the steepest relative increase in cooling demand, highlighting a lack of preparedness, is expected in European countries, underscoring the worldwide toll of intensifying heat (Miranda *et al.* 2023). Conventionally colder regions, such as Europe and the United States of America (USA), are now facing rising heat and must integrate heating and cooling through solutions such as passive cooling measures, reversible heat pumps, hybrid heating-cooling systems and smart building designs. Clean, non-fossil fuel electricity, including solar power, can be paired with cooling technologies, shifting demand away from peak hours and easing pressure on the grid.

Impact of extreme heat on critical infrastructure resilience: electricity grids and the urban environment

Heatwaves and prolonged high temperatures are placing unprecedented strain on electricity grids globally, driving peak demand and accelerating equipment failure. Overloaded systems and degraded infrastructure increase the risk of blackouts, which are especially dangerous during heatwaves when critical infrastructure such as hospitals, water supply systems and public transport is affected. In 2025, a heatwave in Buenos Aires, Argentina cut power to over 600,000 customers amid extreme temperatures and grid stress (Associated Press 2025). Similarly, Southeastern Europe saw a multi-country blackout in 2024 during an extreme heat episode (ICS Investigation Expert Panel 2025).

Rapid urban growth often outpaces utility planning, resulting in inadequate forecasting of electricity needs and underinvestment in critical infrastructure (Li *et al.* 2024). This mismatch leads to frequent outages and system overloads. In China, heatwaves raised outage frequency by 4 per cent and duration by 8 per cent between 2019 and 2021 (Liang *et al.* 2025). Without major investment in grid resilience, rising heat will further threaten electricity reliability and essential services.

Globally around 666 million people still lack access to electricity (International Energy Agency [IEA] *et al.* 2025)—mainly in rural areas—facing a "double penalty" of high heat stress and no access to modern cooling. Women and girls are disproportionately affected. Expanding electricity and sustainable cooling access in off-grid areas is key to delivering a just, inclusive energy transition.

Photo: Harsh Aryan/Unsplash

2.2 Cooling access: the foundation of resilience

Growing extreme heat reflects a failure of climate mitigation efforts, resulting in a rising set of adaptation needs. Cooling is the front line of heat adaptation, but if delivered through inefficient technologies, it becomes a driver of emissions and grid collapse. The challenge is therefore two-sided: to expand access to cooling and cold chains for climate adaptation and resilience, while reducing the energy and carbon footprint of cooling for climate mitigation.

These parallel efforts constitute a resilience interdependency: neglecting one dimension compromises the effectiveness of the other. Without efforts to promote access to efficient, reliable, and affordable cooling, communities remain dangerously vulnerable to intensifying heat risks. Conversely, extreme heat, urbanisation (Box 2-1) and rising incomes are together driving an unprecedented surge in global cooling demand. Without fast adoption of strategies to achieve near-zero cooling emissions, this threatens to overload grid infrastructure and to accelerate rather than mitigate GHG emissions (Khosla *et al.* 2021a).

Box 2-1 Rising urban heat exacerbates cooling demand

The rapid expansion of urban areas over the past 50 years has led to localized increases in heat exposure that have different physical mechanisms compared to regional and global drivers of climate change. The conversion of natural, forested landscapes to a mosaic of concrete, glass, and asphalt, together with waste heat emissions from traffic and energy consumption from buildings, are major factors driving the urban heat island phenomenon. These locally driven heat islands often magnify the heat exposure from climate change-induced warming. Notably, urbanization has exacerbated changes in temperature extremes in cities, up to 5–10°C, in particular during nighttime extremes when cities are not able to cool down due to high temperatures (Doblas *et al.* 2021).

The IPCC has assessed with very high confidence that future urbanization will amplify the projected air temperature change in cities, regardless of the characteristics of the background climate. This is expected to result in a warming signal on minimum urban temperatures that could be as large as the global warming signal. The likely consequence would be to further intensify cooling demand in cities, where nearly 70 per cent of the world's population will reside by 2050 (United Nations 2019).

Modelling for this report projects that installed cooling capacity could more than triple by 2050—pushing cooling-related emissions to 7.2 billion tons of CO_2e—despite ongoing energy efficiency and refrigerant phase-down policies. The dominant drivers of increasing cooling demand are space cooling needs in residential and commercial sectors, and cold chain expansion for food systems and medical supplies. Combined, they already use around 20 per cent of global electricity.

Even with rapid growth in air conditioning, modelling in this report projects that nearly three billion people could still lack access to air conditioning and be exposed to dangerous heat by mid-century (see chapter 4), especially in low-income regions, highlighting major equity challenges (Davis *et al.* 2021). In parallel, economies face rising cooling demand from digital infrastructure – notably data centres, which require continuous, high-efficiency thermal regulation (see section 6.9).

2.3 Two sides of resilience: adapting to extreme heat and managing cooling energy demand

The dual reality for cooling—fast-increasing consumption for some, life-threatening absence for others—demands a new policy paradigm that frames cooling as a critical measure for heat resilience. During a heatwave, accessible and sustainable cooling is the difference between survivability and disaster; year-round, it determines whether economies can function, children can learn, food systems can function, and cities can remain habitable. Access to sustainable cooling—including passive cooling and refrigeration—must therefore be treated alongside water, energy and sanitation as part of essential infrastructure.

This report discusses how to increase cooling access and build heat resilience through a passive-first approach that is captured in the Sustainable Cooling Hierarchy (chapter 3) and bolstered by economic evidence (chapter 7). Passive and urban cooling strategies are the first and most equitable approach to providing thermal resilience for vulnerable populations. Their integration with both low-energy and conventional mechanical cooling systems is crucial not only for significant energy savings, but also for reducing peak demand to ensure the stability of electricity grids during extreme heatwaves. In urban areas, passive cooling strategies—such as reflective surfaces, better insulation, ventilation, green infrastructure (including urban greenery) and shaded streets—can cut emissions by up to 25 per cent, while low-energy fans and evaporative coolers offer an additional 20 per cent reduction.

Another approach is the use of hybrid systems—which combine low-energy fans and/or evaporative coolers with high-energy air-conditioning systems—that can greatly reduce annual electricity requirements and also improve comfort conditions. Additional low-energy or renewable-powered cooling solutions (such as high-efficiency fans, evaporative coolers and solar cold storage) provide a vital, affordable, and scalable tier of cooling, particularly for populations without access to reliable electricity.

Clean energy-powered cold storage infrastructure, including solar refrigeration and thermal energy storage, is essential to ensure temperature stability in sectors such as health care, agriculture and food distribution (Box 2-2) (Efficiency for Access 2025). In addition, the adoption of technologies that use refrigerants with low global warming potential (GWP) helps reduce direct emissions. The key to climate resilience is to update testing standards and policies to drive these superior technologies to market.

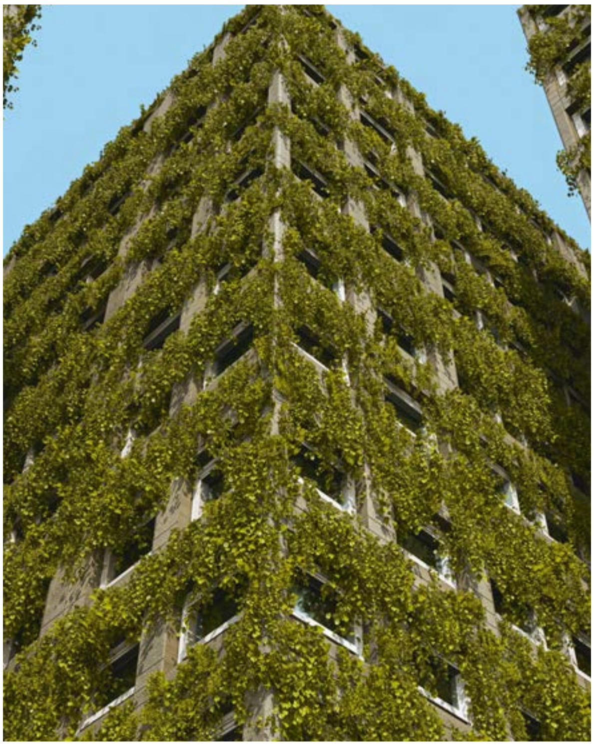


Photo: Mohamed Nohassi/Unsplash

Box 2-2 Case study: farmers in Bihar, India deploying sustainable cold chain systems


Photo: Rishi Mohan/Unsplash

Bihar, a major Indian horticulture state, loses 30–40 per cent of harvests annually due to weak cold chain infrastructure, poor handling, and climate impacts such as heatwaves and erratic rainfall. Smallholder farmers—most of the workforce—are hardest hit, lacking nearly 1,600 first-mile packhouses with pre-cooling and reliable logistics. To bridge this gap, Mithila Union, a 12,000-member cooperative (one-third women), will launch Bihar's first integrated net-zero emissions packhouse in 2026 with support from the UNEP Cool Coalition, the Alliance for an Energy Efficient Economy (AEEE) and the Bihar Cooperative Department. Using natural refrigerants, solar energy, and rainwater harvesting, the "packhouse-as-a-service" model will cut losses, stabilize incomes and expand market access while creating rural jobs and training opportunities. With replication under review and VEGFED's 50,000-member network offering scale, the project demonstrates how climate-smart cold chains can secure food, incomes and resilience under mounting climate pressures.

The use of cooling as an adaptation strategy is usually linked to heat, thermal comfort and energy consumption; however, evidence shows that adaptation to extreme heat by cooling directly supports all 17 of the UN Sustainable Development Goals (SDGs) (Khosla *et al.* 2021b). For example, the goals of zero hunger (SDG 1), food security (SDG 2) and good health and well-being (SDG 3) require heat-resilient cold chain facilities for food and medicine. Domestic space cooling for thermal comfort and heat adaptation is essential for good health and well-being (SDG 3), quality education and comfortable learning environments (SDG 4), productivity (SDG 8) and reduced inequalities (SDG 10). Further, cooling affects gender equity (SDG 5), helping to reduce women's vulnerability in heat-exposed jobs and households.

A systemic view is needed to fully operationalize the multiple linked benefits of tackling heat adaptation and cooling energy mitigation together. Often, adaptation strategies are limited to specific reactive interventions—such as using air conditioners for buildings—which can fragment responses and create uncoordinated surges in electricity demand, particularly during peak heat events. Instead, coordinated planning for a Sustainable Cooling Pathway (chapter 4) can deliver the most benefits and optimize cooling loads. This pathway will deliver a 64 per cent reduction in global cooling-related emissions by 2050 relative to BAU—falling from 7.2 billion tons to 2.6 billion tons of CO_2e—while providing access to cooling for three billion people.

Phasing out high-GWP refrigerant gases is also key to reducing emissions (see chapter 5). Cumulatively, this will bring US$17 trillion in electricity savings and avoid US$13–26 trillion in power sector investments through reduced peak load electricity demand. Coupled with rapid decarbonization of electricity grids, near-zero emissions from cooling (0.2 billion tons) could be achieved by mid-century.

Small steps are being taken around the globe. District cooling systems in Dubai and Singapore centralize cooling infrastructure and chilled water production and distribute it to multiple buildings, which reduces electricity use, air pollution and urban heat. In Rwanda, the deployment of commercially viable and suitably designed off-grid solar-powered, rural, milk cooling hubs can simultaneously enhance climate adaptation, food security and livelihoods. Post-harvest losses are reduced, with further benefits when these strategies are embedded in agricultural development and energy access policies (International Fund for Agricultural Development and SunDanzer 2021).

2.4 From hazard response to systemic extreme heat and cooling governance

Historically, governance approaches for heat and for cooling have developed separately. Heat action plans led by meteorological or disaster agencies—focus on early warning and emergency relief, while cooling policies—led by urban, energy or environment ministries—address urban design, buildings, appliance efficiency and refrigerants. As heat becomes a chronic disaster risk, these agendas must converge. The intrinsically local nature of heat and the critical role of subnational governments in delivering public safety, infrastructure and habitats means that this governance must be multi-level, and that we need to empower subnational governments to take action.

Existing heat governance frameworks and the Global Cooling Pledge

International frameworks, led by the United Nations and international organizations, increasingly recognize extreme heat as a cross-sectoral critical challenge, and are responding with dedicated strategies, resources and governance mechanisms. This includes initiatives and priorities across organizations such as the World Meteorological Organization, the World Health Organization, the United Nations Office for Disaster Risk Reduction, the International Labour Organization, the United Nations Children's Fund, the International Federation of Red Cross and Red Crescent Societies / Red Cross Climate Centre, the Food and Agriculture Organization of the United Nations, the United Nations Development Programme, and the United Nations Office for the Coordination of Humanitarian Affairs, among others (Global Heat Health Information Network [GHHIN] n.d.).

Countries including Australia, Bangladesh, Canada, Ecuador, France, India, the Republic of Korea, Senegal, the United Kingdom, and the USA, among others, have all adopted heat action plans (GHHIN *et al.* 2025). These plans are often co-developed with civil society and technical agencies. They identify local heat risks by mapping vulnerable populations, temperature hotspots, and local health data, enabling targeted interventions such as public cooling centres, early-warning systems and behavioural advisories. However, most heat action plans lack long-term strategies for structural adaptation and cooling demand management.

Integrating access to sustainable cooling into heat governance is essential. Singapore is a strong example of such coordinated national and local action for heat resilience. The country has taken a proactive, anticipatory approach, firstly through initiating a Heat Resilience Working Group within the Inter-Ministerial Committee on Climate Change to strengthen resilience to current and future environmental challenges through heat-related adaptation measures and implementation strategies. Subsequently, the inter-agency Mercury Taskforce was set up to coordinate 37 public agencies to develop and implement a national heatwave plan for coordinated response (Chin 2025). This recently expanded into a whole-of-government integrated strategy for heat resilience in partnership with businesses, academia and communities (Singapore, Ministry of Sustainability and the Environment 2025).

Cooling governance is also advancing globally. The Global Cooling Pledge now includes 72 countries committed to cutting cooling-related emissions 68 per cent globally by 2050 while increasing access to cooling for all, underpinned by the Sustainable Cooling Pathway. The Pledge emphasizes passive cooling, efficient appliances and faster phase-down of refrigerant gases, aligning with the Kigali Amendment to the Montreal Protocol (UNEP 2023a). A key challenge remains ensuring that the mitigation of cooling emissions aligns with heat adaptation needs, access to cooling and critical infrastructure resilience.

The Beat the Heat Implementation Drive — a collective effort of the COP30 Brazilian Presidency and the UNEP Cool Coalition — aims to address this challenge by driving national-to-local collaboration and bridging gaps in finance, policy and delivery for extreme heat resilience and sustainable cooling. Underpinned by the subnational Cooling Pledge, Beat the Heat includes commitments to advance urban heat planning that incorporate cooling, expand passive cooling and nature-based spaces, and pursue public procurement of efficient low-GWP cooling technologies. Based on the findings of this report, it is clear that achieving heat resilience and expanded access requires multi-level governance that integrates adaptation and mitigation and prioritizes passive-first policies.

Tackling heat resilience, cooling demand and their compounding risks within broader developmental policy

A growing range of policy instruments tackle heat resilience and cooling access, including Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC), National Adaptation Plans (NAPs), National Cooling Action Plans (NCAPs), and ozone and refrigerant management strategies (via the Kigali Amendment to the Montreal Protocol and Kigali Implementation Plans). These offer entry points to integrate extreme heat and cooling access efforts into broader developmental policy frameworks.

However, financing remains fragmented, and cross-sectoral policy coherence is still limited. Strengthening institutional mandates, building capacity and mobilizing climate finance will be critical to scale up integrated solutions for extreme heat and cooling access. In India, for example, the National Disaster Management Authority in coordination with the Finance Commission have created National and State Disaster Mitigation Funds, which include guidelines and support for local heat action plans.

Heat and cooling are cross-cutting issues linked to other policy priorities. Intensifying heat can often compound risks for other policy concerns. Rising ambient temperatures, surging cooling demand and worsening air pollution — particularly elevated levels of particulate matter ($PM_{2.5}$) and ozone — create dual exposure hazards. Poor air quality limits natural ventilation, especially in urban environments, pushing wealthier households towards energy-intensive air conditioning, often in thermally inefficient buildings that lack insulation or shading. This leads to high peak electricity demand, increased GHG emissions, rapid proliferation of high-GWP refrigerants and worsening urban heat island effects.

These burdens fall hardest on low-income and marginalized communities, especially in high-density urban zones where access to clean energy, water and health-care services is already constrained (WHO 2025a; WHO 2025b). Cities such as Delhi and Kolkata in India, and Dhaka in Bangladesh, face heightened heat-related morbidity and mortality, lower labour productivity and stressed water systems due to heightened evaporative losses and infrastructure stress (Debnath *et al.* 2023). Applying the Sustainable Cooling Hierarchy (chapter 3) offers a path to tackle these interwoven vulnerabilities.

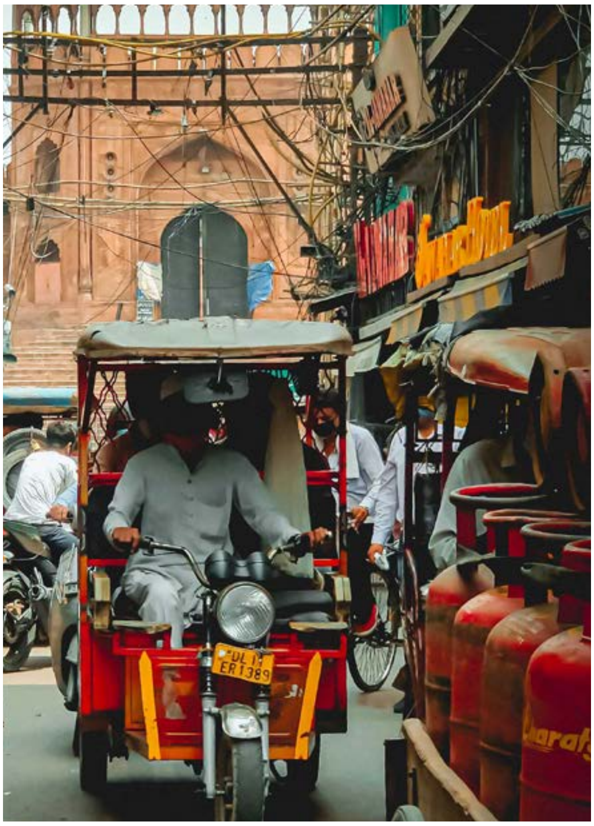


Photo: Anurag Chandra/Unsplash

2.5 Core principles for bridging extreme heat and cooling

a) **Integrate mitigation and adaptation** in planning and governance so that cutting cooling emissions also enhances protection for vulnerable populations from heat.

b) **Recognize extreme heat as a disaster** that requires systemic cooling solutions combining emergency preparedness for heat with holistic measures to drive access to cooling – both for thermal comfort as well as for transport and storage of food and medicines.

c) **Design national and urban heat plans** and policy instruments that tackle heat resilience and cooling access synergistically.

d) **Treat heat protection and cooling** as a public good, not a consumer privilege, through inclusive policies, finance and design standards – with specific leadership from local governments to integrate into critical public infrastructure including housing, schools, labour conditions and kindergartens.

e) **Prioritize passive and nature-based solutions** to cut cooling loads, mitigate the urban heat island effect and reduce grid stress. Combine passive with low-energy or hybrid, high-efficiency and low-GWP cooling systems, as per the Sustainable Cooling Hierarchy.

f) **Enable equitable access** via the Tiered Access to Sustainable Cooling Framework, which maximizes the use of affordable cooling solutions that require no and/or low use of energy at lower tiers and energy-saving designs at higher tiers for grid stability.

Photo: Victor/Unsplash

03 The Sustainable Cooling Hierarchy and Tiered Access

To meet the expected growth in cooling demand sustainably, new cooling equipment must be designed, selected, operated, maintained and funded to minimize energy use and environmental impacts.

In this chapter, two important and separate concepts that support these objectives are described:

- The Sustainable Cooling Hierarchy is a technical framework for cooling system design and use that minimizes the need for the most energy-intensive cooling technologies and ensures that when these are employed, they are optimized.
- The Tiered Access to Sustainable Cooling Framework describes different levels of access to sustainable cooling.

3.1 The Sustainable Cooling Hierarchy

The rapid growth in cooling equipment presents a key opportunity to avoid locking in inefficient cooling equipment that uses high-GWP refrigerants, and to minimize energy consumption and environmental impact. To support these goals, a four-step Sustainable Cooling Hierarchy can guide the design, installation and operation of cooling equipment, as summarized in Table 3-1.

Photo: Swaraj/Unsplash

Table 3-1 The Sustainable Cooling Hierarchy

	Action	Description
Step 1	Passive Cooling	**Adopt passive strategies that reduce cooling load from both comfort cooling and refrigeration systems,** to lower the upfront capital investment needed in cooling equipment and to reduce both direct refrigerant emissions and indirect energy-related greenhouse gas emissions. Passive cooling strategies include urban design, passive building design and various other techniques that can minimize cooling loads (e.g. use of doors on retail refrigerated display cabinets).
Step 2	Low-Energy Cooling	**After the cooling load has been minimized, prioritize low-energy cooling systems over high-energy options.** For comfort cooling, a system that incorporates fans and evaporative cooling in place of, or alongside, air conditioning can greatly reduce the energy used and the cost of providing comfortable conditions.
Step 3	Best Energy Efficiency	**Ensure that all new cooling equipment is designed and selected to achieve the maximum practical energy efficiency.** For example, variable-speed compressor systems are much more efficient than fixed-speed systems. **Operate all existing cooling equipment with optimized control settings and with regular monitoring and maintenance**, to ensure that energy efficiency and performance are maintained throughout the operating life.
Step 4	Rapid HFC Phase-Down	**Select the refrigerant with the lowest practical global warming potential (GWP) that does not compromise the system efficiency**, to continue the momentum and to achieve sustainable cooling.

The Sustainable Cooling Hierarchy will:

a) **Set passive cooling solutions** as the foundation for sustainable cooling.

b) **Prioritize low-energy cooling solutions** such as the use of fans and evaporative coolers where appropriate. Box 3-1 illustrates the significant benefits of hybrid comfort cooling systems that combine the use of low-energy fans with high-energy air conditioning.

c) **Ensure that all cooling solutions are designed**, operated and maintained in the most efficient way.

d) **Encourage rapid uptake of low-GWP refrigerants** and good lifecycle refrigerant management to minimize refrigerant GHG emissions.

Modelling presented in chapter 4 uses the four steps in the Sustainable Cooling Hierarchy to characterize the potential for emission savings (see Figure 4-8). The results indicate that investing in sustainable cooling solutions yields significant savings in energy infrastructure and cumulative costs, reducing the need for costly electricity infrastructure. Policies should steer markets away from low-efficiency, high-GWP cooling solutions and towards more passive, efficient and climate-friendly solutions aligned with the Hierarchy.

Box 3-1 Hybrid cooling case study: use of fans in combination with air conditioning

Measurements of the use of newly installed ceiling fans in an office in Singapore showed that the elevated air movement produced by fans can reduce air-conditioning energy requirements by allowing temperature setpoints to be raised without compromising thermal comfort.

For a two-week period, the office air-conditioning system was used without fans at a temperature setpoint of 24°C. During the following three weeks, the air-conditioning setpoint was raised to 26.5°C and ceiling fans were used, with occupants allowed to select the optimum fan speed setting. The exercise was repeated during two further three-week periods. Occupants completed thermal comfort questionnaires twice every day.

With the higher temperature setpoint plus fans, there was a measured energy saving of 32 per cent. The thermal satisfaction survey showed a small preference for the higher temperature setpoint, with only 3 per cent of occupants dissatisfied with the comfort conditions; this compared to 7 per cent of occupants dissatisfied during the operation of air conditioning alone at the lower temperature setpoint.

This case study illustrates the large potential for hybrid comfort cooling systems that combine fans with air-conditioning systems, a design strategy encouraged in Step 2 of the Sustainable Cooling Hierarchy.

Source: Kent et al. 2023

3.2 Tiered Access to Sustainable Cooling Framework

This section describes the Tiered Access to Sustainable Cooling Framework, which supports policy measures that provide improved access to comfort cooling and refrigeration in households while reducing emissions.

This new framework builds on earlier work defining a more-nuanced tiered methodology for electricity access, as introduced in a 2015 World Bank / Sustainable Energy for All report (Energy Sector Management Assistance Program [ESMAP] and SEforALL 2015). Previously, a binary definition of electricity access was used to simply identify the percentage of a country's population with or without access. However, this approach failed to reflect real-world conditions. Many households may technically have electricity access but can only use limited amounts of power or experience frequent outages. Others rely solely on minimal off-grid supply.

Access to cooling can similarly be represented with a tiered access framework, highlighting that the most sustainable pathway will maximize the use of cooling solutions that are based on the Sustainable Cooling Hierarchy. The framework uses tiers that range from Tier 0 (no access to cooling technologies) to Tier 5 (comprehensive use of sustainable passive and/or active cooling solutions). This report focuses on residential comfort cooling and residential cold chains (i.e. refrigerators and freezers). A similar approach still needs to be developed for other parts of the cooling market—such as non-residential comfort cooling, the food cold chain, etc.—with consideration for health, safety and productivity impacts.

Tiered access to sustainable cooling: residential comfort cooling

The Sustainable Cooling Hierarchy indicates that efforts should be made to minimize the comfort cooling load and to provide some or all of this cooling without high-energy air conditioning, in order to achieve widespread impact, especially in poor and vulnerable communities. This approach is applicable across all tiers of access to cooling, including higher tiers where more cooling options are available to higher-income households. The characteristics in the access tiers are split into three groups: passive cooling measures that reduce cooling load (i.e. urban planning, building design); low-energy cooling (fans and evaporative coolers); and hybrid cooling (air conditioning in conjunction with fans and evaporative cooling).

The tiers of access for each characteristic are shown in Table 3-2. The basis of the tiers is:

- Tier 0 represents the extreme case of no access to cooling.
- Tiers 1 to 4 represent improving levels of access, with the lowest-cost measures (e.g. fans, including solar-powered models, and window shades) included in Tier 1, while more expensive measures (e.g. advanced passive cooling measures, hybrid air conditioning) are available only at higher tiers.
- Tier 5 represents "best in class" – for example, an urban residence with best urban planning measures (e.g. excellent tree cover), together with effective building design that integrates the best passive cooling measures with (if needed) hybrid air conditioning that also uses fans and evaporative coolers.

Table 3-2 **Tiers of access to residential comfort cooling**

		Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Passive cooling	Urban planning	No tree cover, no access to green spaces, no community cooling centres, etc.	Very low level of natural tree shading	Low level of shading	Mid level of shading, some green corridors, some water features	Widespread use of good urban planning related to green cover, water features and community cooling facilities.	"Best-in-class." Most streets have tree cover. Easy access to public parks. Access to community centres with active cooling.
	Building design	No protection against ambient temperature and solar gain	Basic protection against ambient temperature (e.g. external window shades)	Low-level thermal protection (e.g. window shading, roof insulation). No advanced passive cooling features.	Mid-level thermal protection (e.g. shading, shutters on windows, some use of reflective coatings). No advanced passive cooling features.	High-level thermal protection (e.g. extensive shading, shutters, reflective coatings). Limited use of advanced passive cooling features.	Best-in-class thermal protection. Full use of advanced passive cooling features.
Low-energy non-refrigerant	Fans	None	1 basic fan per household	More than 1 fan	Fans in most rooms	Fans in most rooms (high efficiency)	Highly efficient hybrid use
	Evaporative coolers	None	None	Limited use (1 basic unit)	Comprehensive use (where appropriate)	Comprehensive use (where appropriate)	Highly efficient hybrid use
Refrigerant based	Air conditioning	None	None	None	Limited use (only if required)	Partial use (only if required). Good efficiency. Low GWP refrigerant.	Highly efficient hybrid use (only if required). Low GWP refrigerant.

The boundaries between the tiers are independent. For example, a house or apartment could have a Tier 4 air-conditioning unit but be at only Tier 1 in terms of building design measures.

The "best in class" will vary by climate conditions and in relation to other factors such as building type and location. For example:

- In hot-humid climates, best in class could mean hybrid use of air conditioning with fans, whereas in hot-dry climates it could mean hybrid use of air conditioning with both evaporative cooling and fans.
- In warm climates, best in class could mean complete avoidance of air conditioning through use of advanced passive design features and fans / evaporative coolers.
- In climates with significant seasonal and daily variations in temperature, best-in-class control systems would use a "fans-first" principle, i.e.

to maximize the use of low-energy fans and evaporative coolers at lower ambient temperatures, avoiding the need for air conditioning.

Tiered access to sustainable cooling: residential cold chain

A similar tiered approach can be adopted for other categories of cooling, such as the residential cold chain, as shown in Table 3-3. The first priority is keeping perishable food chilled, especially meat and dairy products. At Tier 1, this includes traditional, non-mechanical methods used for centuries. Refrigerators, which consume less power than room air-conditioning units, can be used at lower tiers of electricity access, but reliable electricity supply is crucial to prevent food spoilage during outages.

Residential frozen food storage requires a higher electricity tier and depends on an "upstream cold chain" – where perishable products are chilled or frozen in factories, transported in refrigerated vehicles and sold from refrigerated display cases in shops and supermarkets. For best-in-class residential cold chains, a reliable upstream cold chain is essential.

Table 3-3 **Tiers of access to residential cold chain**

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Access to refrigerator	No access to a refrigerator or any other means of protecting food against external ambient temperature	No access to a refrigerator. Some basic cooling techniques (e.g. clay pots / charcoal coolers with evaporative cooling).	Some access to a refrigerator, shared between households. Use of good non-mechanical techniques (e.g. ambient parlour or cellar).	1 basic refrigerator in the household, but unreliable electricity	1 good, reliable refrigerator - adequately reliable electricity. Good efficiency. Low GWP refrigerant.	1 or more, best-in-class refrigerators and fully reliable electricity. Very good efficiency. Low GWP refrigerant.
Access to freezer	No access	No access	Limited access via ice box in refrigerator	Limited access via ice box in refrigerator	1 freezer or fridge-freezer. Good efficiency. Low GWP refrigerant.	1 or more, best-in-class freezers or fridge-freezers and fully reliable electricity. Very good efficiency. Low GWP refrigerant.
Access to chilled or frozen food	No access. All food bought at ambient temperature (e.g. fresh, dried, canned).	Very limited access to chilled food, for high-risk items (e.g. meat, dairy)	Reasonable access to chilled food for high-risk items. No access to chilled food for low-risk items.	Good access to chilled food for high-risk items. Reasonable access to chilled food for low-risk items.	Full access to chilled food for high-risk items. Good access to chilled food for low-risk items.	Full and easy access to chilled and frozen food of all kinds

Low-energy cooling for off-grid households

In 2023, an estimated 700 million households were without access to reliable grid electricity (see section 4.1) (IEA *et al.* 2025). However, low-power solar energy systems, sometimes incorporating battery storage, are increasingly available (see section 6.10). These systems are usually too small to support air conditioning but can provide sufficient power for fans, small refrigerators and walk-in cold rooms. This represents an important opportunity to use the passive cooling and low-energy features of the sustainable cooling hierarchy to improve access to cooling in low-income households.

PART II:
FUTURE OUTLOOK AND CURRENT TRENDS

Photo: David Clode/Unsplash

04 The Pathway to Near-Zero Emissions from Cooling

This chapter provides forecasts of GHG emissions from cooling equipment between 2022 and 2050.

The forecasts are based on outputs from the Global Cooling Emissions Model, a bottom-up tool estimating energy use, refrigerant consumption, and direct and indirect GHG emissions from the global stock of cooling equipment. Originally used in the *Global Cooling Watch 2023*, the model has been updated to provide the latest forecasts and new insights into the pathway towards near-zero emission cooling.

Future scenarios range from "Without Measures" (which assumes no improvement to current practices) to a "Sustainable Cooling Pathway" that follows the Sustainable Cooling Hierarchy (see chapter 3). The modelling covers equipment in the four main markets for stationary cooling—residential space cooling, non-residential space cooling, residential cold chain and non-residential cold chain / process refrigeration—as well as two transport cooling sectors: mobile air conditioning and refrigerated transport.

Key updates in this report include assessment of how extreme heat events will affect the rate of cooling equipment growth, evaluation of low-energy cooling alternatives (e.g. fans and evaporative coolers), improved passive cooling analysis and modelling of hybrid combinations of different cooling solutions using the Sustainable Cooling Hierarchy.

Photo: Mitchell Luo/Unsplash

Photo: Ryoji Iwata/Unsplash

4.1 Modelling the potential growth in cooling demand

The rapid growth in the global stock of cooling equipment expected between now and 2050 is driven by factors including:

- population growth, especially in urban areas
- growth in gross domestic product (GDP)
- increased access to reliable electricity supplies
- changes to temperature and humidity conditions, including more frequent and intense extreme heat events and urban heat islands
- the impact of policies to provide improved access to cooling in the poorest households.

Modelling algorithms have been developed to estimate how changes to these drivers are likely to stimulate the growth of different types of cooling equipment. These are applied at a country level to estimate annual growth in cooling equipment stock between 2022 and 2050. Based on these estimates, global stock data are estimated for 14 geographic regions as well as the global total.

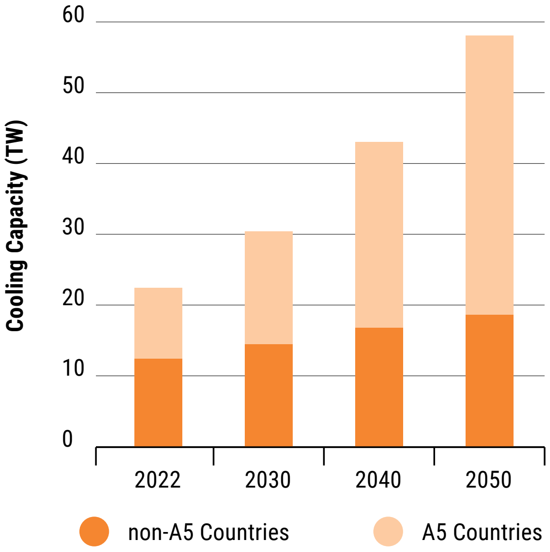
Two growth scenarios have been developed: i) a Business-as-Usual (BAU) Growth scenario that takes into account increases in population and per capita GDP; and ii) an Increased Growth scenario that also accounts for expected increases in extreme temperatures and improved access to cooling in low-income households.

Business-as-Usual Growth scenario

This scenario is based on projections for changes in population and GDP using the United Nations mid-growth forecast for population growth (United Nations 2025) and the SSP2 "middle of the road" socioeconomic pathway (Riahi *et al*. 2017) for GDP growth. These inputs are used to estimate the global stock of refrigeration and air-conditioning equipment.

Figure 4-1 shows the BAU Growth scenario where global installed cooling capacity is projected to rise from 22 terawatts (TW) in 2022 to 58 TW in 2050 – a growth factor of 2.6. Growth is expected to be significantly higher in Montreal Protocol Article 5 (developing) countries, with an average growth factor of 4.0, compared to 1.5 in non-Article 5 (developed) countries.

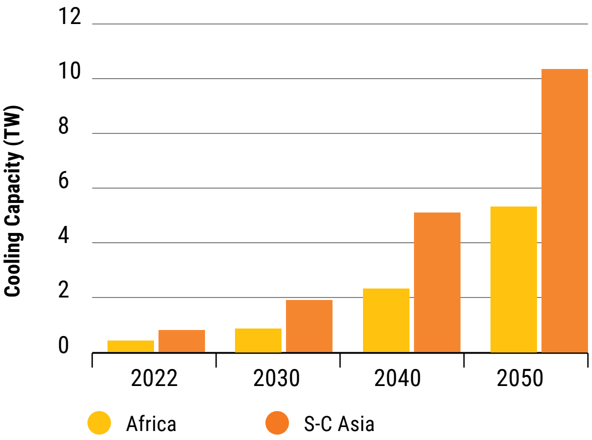
Figure 4-1 Installed cooling capacity under the BAU Growth scenario, global



Source: Global Cooling Emissions Model

Cooling equipment growth varies by region, with countries in Africa and South-Central Asia forecast to have the fastest growth – nearly 13-fold by 2050 (Figure 4-2). These same regions also face major challenges in electricity access and grid reliability. Rapid growth in high-energy cooling could strain power systems and drive up infrastructure costs. Prioritizing passive and low-energy cooling measures, alongside highly efficient appliances, offers a more affordable and sustainable solution.

Figure 4-2 Installed cooling capacity under the BAU Growth scenario, Africa and South-Central Asia



Note: The South-Central Asia region covers Afghanistan, Bangladesh, Bhutan, India, Iran, Iraq, the Kyrgyzstan, Maldives, Nepal, Pakistan, Sri Lanka and Turkmenistan.

Source: Global Cooling Emissions Model

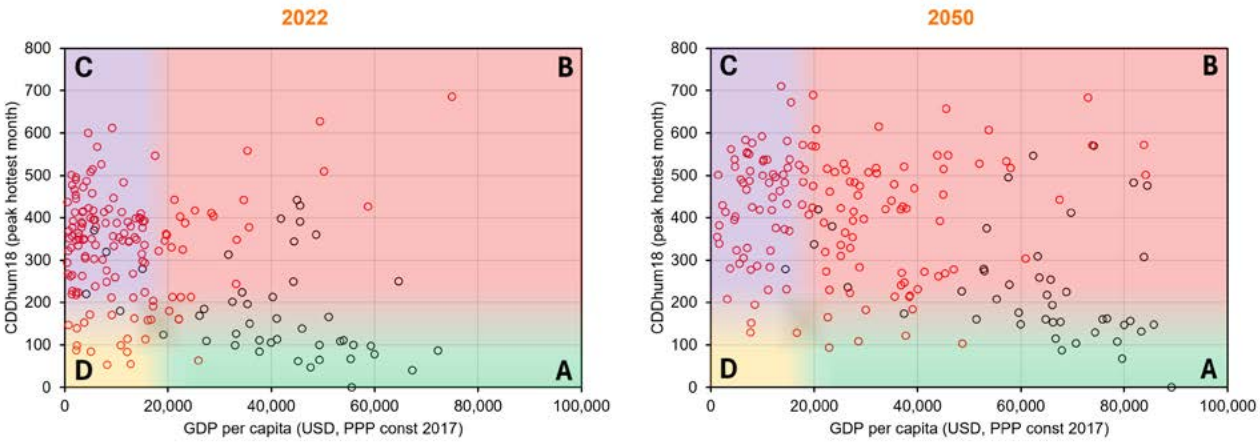
Categorization of countries by GDP per capita and cooling degree days (CDDs)

Cooling degree days (CDDs) are a metric used to assess the need for comfort cooling. The increases in average temperatures and the more regular occurrence of extreme heat events are leading to increases in CDDs in the hottest months. This makes the future need for cooling more critical. The Annex details the impact of extreme heat and outlines how growth in CDDs is forecasted. The impact of extreme heat events on the growth in demand for comfort cooling depends on the economic circumstances of each country. Countries are categorized as:

- **Category A:** Higher-income countries with a mild summer climate (below 160 CDDs in the hottest month). Residential air conditioning is not commonly used, because the number of days with uncomfortably high temperature and humidity is historically low, and air conditioning has been considered unnecessary. However, if a country in this category has longer spells of high temperature, there could be rapid growth in air-conditioning installations, as a large proportion of households would be able to afford an air-conditioning unit.
- **Category B:** Higher-income countries that already have a hotter summer climate (above 160 CDDs in the hottest month). Residential air conditioning is already widespread. Further temperature increases will have little impact on the growth in the number of households using air conditioning but will lead to an increase in the average installed cooling capacity and in the annual operating hours of air-conditioning equipment.
- **Category C:** Lower-income countries located in the tropics and subtropics (with a GDP below US$17,500 per capita and CDDs above 160 in the hottest month). These are countries where climate conditions are already hot enough for air conditioning to be highly desirable. However, most households are unable to afford purchasing and operating an air-conditioning unit. Based on forecasted increases in GDP, the BAU Growth scenario already projects high growth in cooling equipment stock in developing countries, albeit from a very low starting point. Affordability will likely remain a constraint to the growth in cooling equipment purchases in the poorest households.
- **Category D:** Lower-income countries with a mild climate. These are countries that have little to no demand for air conditioners due to the low cooling loads and lack of purchasing power.

These four categories of countries are illustrated in Figure 4-3, which shows the GDP per capita versus CDDs in the hottest month, for every country, for 2022 and 2050. All countries are forecast to have growth in both GDP per capita and CDDs between 2022 and 2050. The figure illustrates fuzzy boundaries between these categories, as the transition happens over a range of GDP and CDDs. An important feature shown in Figure 4-3 is that a large number of countries will move from Category A and Category C into Category B, which significantly drives the demand for active cooling in 2050. In addition, the figure shows that in 2050, a large number of countries will still remain in Category C and are likely to lack access to cooling. This country and population shift is summarized in Table 4-1.

Figure 4-3 Country GDP per capita versus peak monthly cooling degree days, 2022 and 2050



Note: Each dot represents an individual country. Article 5 Parties are in red, and non-Article 5 Parties are in black. The four coloured chart areas represent the Categories A to D described in this section. CDDhum18 is the cooling degree days (CDDs) corrected for humidity with a reference temperature of 18°C.

Source: Global Cooling Emissions Model

Table 4-1 Distribution of countries and population by climate-income category, 2022 and 2050

		Category A	Category B	Category C	Category D	Total
Number of countries	2022	23	50	109	11	193
	2050	12	118	61	2	193
Population (billion)	2022	0.51	2.73	4.48	0.28	8.00
	2050	0.20	6.54	2.90	0.01	9.65

Two further complications arising from the spatial granularity of the national-level analysis have been considered when using the data in Figure 4-3 to model the possible impact of extreme heat on the growth in cooling stock:

1) The CDD data are population-weighted averages for each country. In many countries, climate conditions vary widely across regions, due largely to differences in altitude or latitude. For example, the modelling predicts that in 2050 the United Kingdom remains in Category A, with peak monthly CDDs of under 100. However, in London, a combination of the urban heat island effect and the southern latitude means that households in the city are likely to fall into Category B.

2) The GDP data are averages for the whole population of each country. The spread of income across the population means that the poorest households of a country in Category B could have an income well below the country average and are less likely to have air conditioning.

Modelling the impact of extreme heat on cooling equipment stock

The Global Cooling Emissions Model has been expanded to assess how extreme heat influences the growth of air conditioning for comfort cooling. Driven by rising CDDs during periods of extreme heat and growing GDP per capita, the model projects a significant growth in residential air-conditioning demand by 2050 (Table 4-2). The analysis shows that extreme heat is driving the growth in global cooling demand, with Category C countries—facing high heat exposure, rapid population growth and limited purchasing power—at greatest risk. Without intervention, growth in active cooling could strain energy systems, especially in regions such as Africa and South-Central Asia that have limited and unreliable electricity infrastructure. The impact of extreme heat is projected to increase installed cooling capacity to 64 TW in 2050, a 10 per cent increase over the BAU Growth scenario.

Table 4-2 Modelled changes to global residential air-conditioning ownership, 2022 to 2050

Category (Number in 2022)	Change in category between 2022 and 2050	Proportion of households with air conditioning	Installed residential air conditioner cooling capacity
Category A **23 countries**	**14 countries move to Category B by 2050**	2022: 10% 2050: 40%	2022: 0.1 TW 2050: 0.6 TW
Category B **50 countries**	**Increases to 118 countries in 2050**	2022: 60% 2050: 93%	2022: 8 TW 2050: 16 TW
Category C **109 countries**	**51 countries move to Category B by 2050**	2022: 10% 2050: 60%	2022: 0.8 TW 2050: 14 TW
Category D **11 countries**	**3 countries move to Category A, 3 to Category B and 3 to Category C**	Minimal need for air conditioning	Minimal

Photo: Ryoji Iwata/Unsplash

Impact of policies to provide improved access to cooling

Affordability creates a significant barrier to the provision of cooling in many households in warm or hot low- and middle-income countries. There is a close relationship between household income and ownership of refrigerators and residential air-conditioning units.

Figure 4-4 shows modelled estimates of residential air-conditioning cooling capacity per capita, together with estimates of the average number of monthly CDDs in the hottest month, for four regions. The figure shows the change of these parameters between 2022 and 2050.

A high peak-month CDD value indicates the need for comfort cooling. The "West Asia A5 Group 2" region—which includes Gulf Cooperation Council countries—has the highest air-conditioning ownership globally. This is due to the combination of a very hot climate (creating very high comfort cooling loads) and high GDP per capita. North America has much fewer peak-month CDDs, but there is sufficient wealth for nearly 90 per cent of households to have some air conditioning (United States Energy Information Administration 2020).

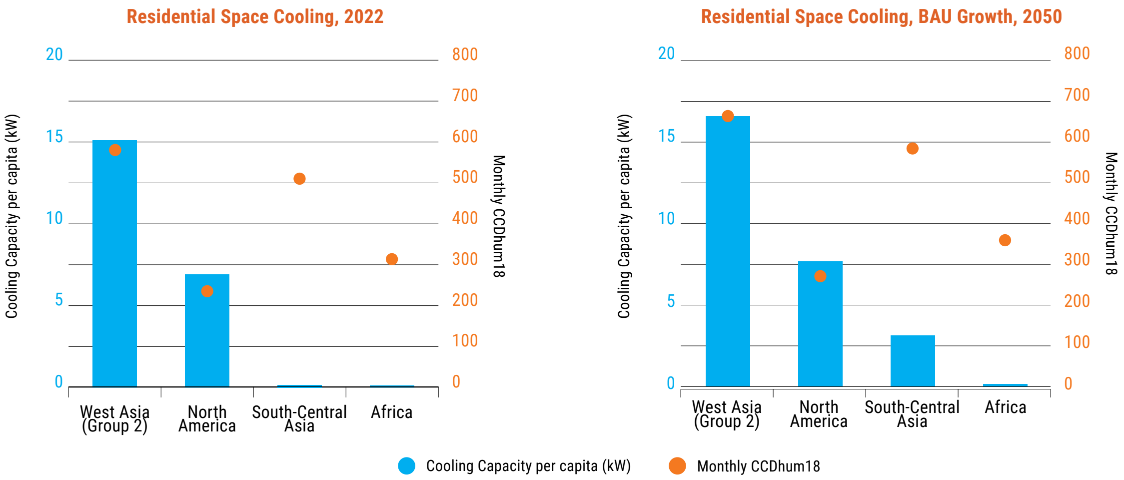
South-Central Asia and Africa have much higher CDDs than North America, but in 2022 they owned only around 1 to 2 per cent of the amount of residential air-conditioning owned by North American households. Under the BAU Growth scenario, air-conditioning ownership in South-Central Asia and Africa grows considerably by 2050 (see Figure 4-2), but without strong policy measures many low-income households still lack access to adequate cooling.

A key barrier is affordability, compounded by limited or no access to electricity. In 2023, almost 92 per cent of the world's population had electricity access (IEA *et al.* 2025), up from 87 per cent in 2010, but this still left nearly 700 million people without it. Rural areas are disproportionately affected, accounting for 84 per cent of those without access. Achieving SDG 7—universal access to affordable, reliable and modern energy services by 2030—remains a major challenge, especially in Sub-Saharan Africa (IEA *et al.* 2025), which accounts for 85 per cent of the global population lacking access to electricity and where electrification is lagging behind population growth.

Many households have some access to electricity but have limited power supply, which is insufficient to operate air conditioning. In many hot countries, electricity demand peaks during the hottest weather due to cooling loads – precisely when power cuts are most likely. Therefore, expanding access to air conditioning must go hand-in-hand with increasing the capacity and reliability of electricity infrastructure.

Comfort cooling: Under the BAU Growth scenario, demand for high-energy air conditioning could grow significantly, driven by rising population and per capita GDP. Nevertheless, an estimated three billion people

Figure 4-4 Residential air-conditioning cooling capacity (kW per capita) and climate (CDDs in hottest month) by region, 2022 and 2050



Note: CDDhum18 is the cooling degree days (CDDs) corrected for humidity with a reference temperature of 18°C.

Source: Global Cooling Emissions Model

(around 800 million households) will still not be able to afford sufficient residential comfort cooling in 2050, even though they live in hot climates. This includes the majority of people in lower-income countries (i.e. two billion people in Category C) and the least well-off in higher-income countries in Category B (around one billion people).

If additional measures are taken to close this access gap—by, for example, providing each underserved household with a 5-kilowatt air-conditioning unit—this would add 4 TW of global installed cooling capacity in 2050, an increase of 7 per cent above BAU growth. Similarly, there is likely to be outstanding demand for cooling in non-residential buildings (e.g. schools, hospitals), which could add a further 0.3 TW of installed capacity.

Residential cold chain: Despite generally rising living standards, around 350 million households could still lack access to a domestic refrigerator in 2050. Closing this gap would add 0.1 TW of installed cooling capacity to the residential cold chain, and 0.2 TW to the non-residential cold chain, in 2050.

Increased Growth scenario

A new Increased Growth scenario has been modelled, taking into account the likely increase in extreme heat events and the need to provide access to some form of cooling to the lowest-income households. Under this scenario, the total global installed cooling capacity in 2050 rises to 68 TW, a growth factor of 3.1 compared with 2022 and a 17 per cent increase above the BAU Growth level. This increase from the BAU Growth estimate includes 6 TW attributed to extreme heat and 4 TW to improved access.

Note that this scenario assumes that the extra cooling required will be provided exclusively by active refrigeration and air-conditioning equipment. This scenario can be considered a worst case among the options presented in this report. There are opportunities to reduce this load considerably through use of passive cooling and low-energy cooling technologies such as fans, evaporative air coolers and hybrid air conditioners. This is discussed in the next subsection, with Figure 4-6 illustrating both the Increased Growth scenario and the opportunities for load reduction.

4.2 Reduction of air-conditioning and refrigeration loads

The BAU Growth and Increased Growth scenarios provide worst-case projections of the possible growth in high-energy cooling equipment for comfort cooling and refrigeration applications between 2022 and 2050, with no effort made to mitigate cooling loads. As discussed in chapter 3, the Sustainable Cooling Hierarchy illustrates that:

- In mild climates, adequate comfort cooling can be achieved while avoiding high-energy air conditioning through a number of measures including improved urban and building design to minimize the thermal load and use of fans and evaporative air coolers.
- In hotter climates, while air conditioning may be needed in many buildings, the most sustainable comfort cooling solutions will be hybrid systems that also incorporate these low-energy measures.
- In all climates, there is potential to reduce refrigeration loads.

In this section, the impact of load reduction and the use of low-energy cooling solutions is assessed, to identify the potential to reduce energy consumption and GHG emissions. This can be achieved through the implementation of climate-appropriate measures in the Sustainable Cooling Hierarchy (section 3.1).

Load reduction through passive cooling

Passive cooling refers to methods of reducing comfort cooling and refrigeration loads including:

- **Urban design:** The urban heat island effect (see Box 2-1) can increase ambient temperature in cities by several degrees compared to the countryside, increasing the comfort cooling load and reducing the efficiency of air-conditioning equipment. Good urban design can reduce the heat island effect, hence reducing the heat load on buildings and the demand for air conditioning.
- **Building design:** In both urban and rural settings, it is possible to adopt building design measures that reduce the cooling load. The effectiveness of passive building design measures is greatest during new construction, although the pace of new building is relatively slow as buildings often

last over 50 years. Significant opportunities also exist to apply passive measures through retrofits and during refurbishments of existing buildings. Chapter 6 provides details of the technical potential to reduce heat load through passive building design measures, while chapter 7 describes case studies showing the cost effectiveness of such measures.

- **Refrigeration:** There is also excellent potential to reduce the cooling load in many refrigerated cooling applications, for example by ensuring that all refrigerated retail display cases are fitted with doors, or by pre-cooling hot cooked products prior to chilling and freezing.

Load reduction through low-energy comfort cooling solutions

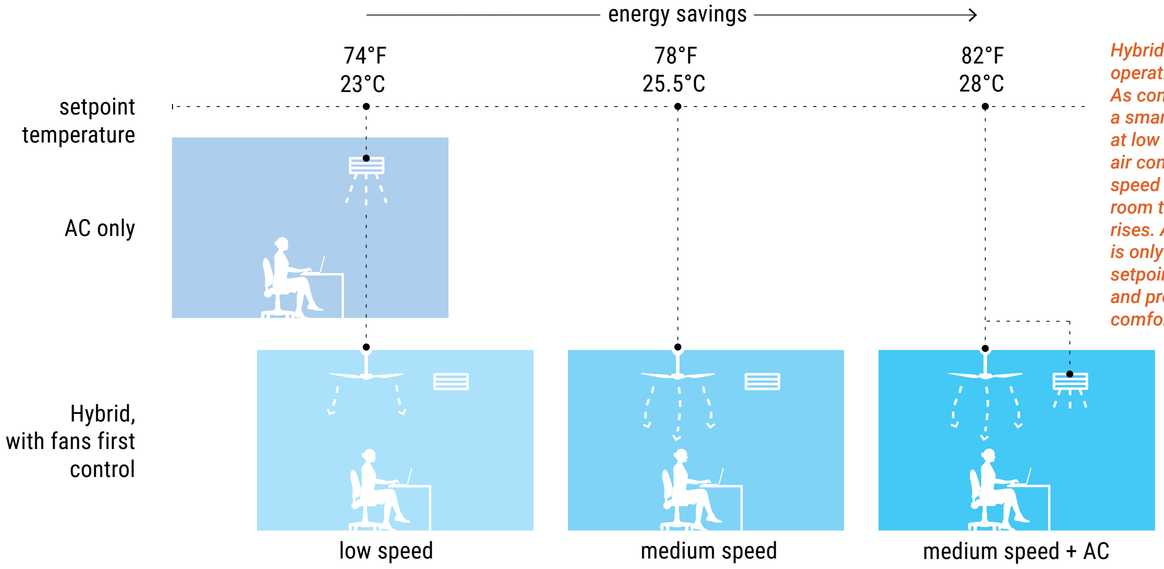
Using active air conditioning for comfort cooling can be very effective, but it is the most energy- and GHG-intensive option and is not affordable in resource-constrained households. Many designs ignore opportunities to create comfortable conditions without air conditioning or with air conditioning operating at a higher temperature setpoint. The use of fans and evaporative coolers can greatly improve indoor comfort conditions and is the only viable option for off-grid populations (section 6.10).

Fans: Air movement is an important factor that improves comfort levels. Hybrid designs that combine an air-conditioning unit with fans can provide comfortable conditions at a higher temperature setpoint, as illustrated in Figure 4-5 (DeKay and Brager 2023). In the hybrid design, the temperature setpoint is shown as 5°C higher than in the air conditioning-only design – this can save 25 to 35 per cent of the energy usage. The key aspect of the hybrid design is the cooling effect of increased air movement felt by occupants, which provides comfort at the higher temperature setpoint. A case study on the use of fans in an air-conditioned office building in Singapore (see Box 3-1) resulted in energy savings of 32 per cent and improved levels of comfort.

A small room air-conditioning unit typically consumes more than 1,500 watts (W) of power. Older fans with conventional alternating current motors use only around 40 W, whereas the latest designs of fans using brushless direct current motors have greater speed control and typically use just 10–15 W. Fans have proven effective in both dry and humid conditions (Miller 2021; Kent *et al.* 2023).

Evaporative air coolers: These devices use water evaporation to provide cooling. A typical residential evaporative air cooler uses around 200 W of electric power. In low-humidity conditions, an evaporative air cooler can reduce air temperature by up to 10–15°C while consuming 80–90 per cent less power than an air-conditioning unit.

Figure 4-5 **Different comfort cooling design options for an air-conditioned room**



Hybrid "fans first" operating strategy: As conditions warm, a smart fan turns on at low speed without air conditioning; fan speed increases as room temperature rises. Air conditioning is only used at a higher setpoint, saving energy and providing greater comfort control.

Source: DeKay and Brager 2023

Modelling the impact of load reduction measures

The cooling load reduction measures described above have the potential to significantly reduce the growth in cooling loads forecasted in the BAU Growth and Increased Growth scenarios. Modelling the impact of these measures is complex and involves several variables:

- The effectiveness of individual passive building design and urban design measures is dependent on climate, local building practices and the rate of building replacement and refurbishment.
- The effectiveness of fans and evaporative coolers is dependent on climate, in particular on humidity and seasonal/diurnal temperature variations.
- The rate of uptake of the non-air-conditioning options for comfort cooling and of refrigeration load reductions is dependent on the level of ambition towards the promotion of sustainable cooling technologies – which will depend on government actions (e.g. building regulations, guidance documents etc.) and on how industry stakeholders embrace these technologies.

Another important consideration is how to quantify the impact of sustainable cooling technologies on the growth in the active cooling equipment stock and on the energy being consumed. A good example is the increased uptake of fans. If optimized fan systems are adopted, the modelling must take into account the following impacts:

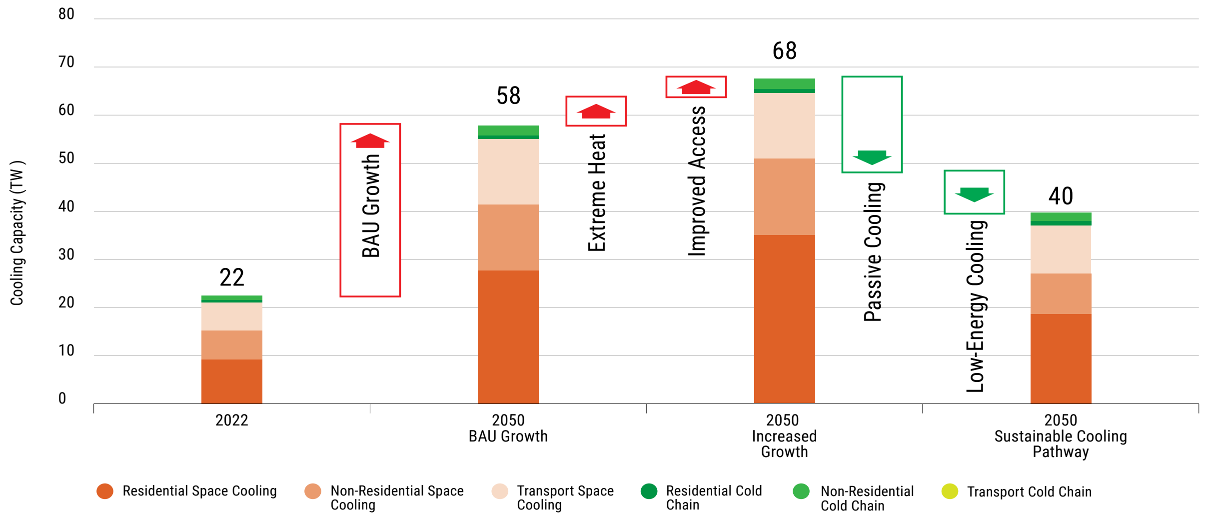
- For buildings in mild climates, the use of fans will avoid the installation of some air conditioning.
- For buildings in hot climates in locations with low incomes or inadequate electricity supply, the use of fans provides improvement in comfort conditions, avoiding the installation of some air conditioning.
- For all buildings that need air conditioning, the use of fans enables a higher temperature setpoint. This reduces the building cooling load and hence the size of air-conditioning units required.
- For buildings with hybrid air conditioning and optimized fans, the reduced cooling load requires fewer air-conditioning operating hours.
- For buildings with hybrid air conditioning and optimized fans, the increased temperature setpoint means a higher refrigerant evaporating temperature and hence a more efficient air-conditioning unit.

In the Global Cooling Emissions Model, all these impacts are considered to estimate the potential for reduced cooling loads and for reduced electricity consumption.

Figure 4-6 shows estimates of the 2022 cooling equipment stock as well as estimates under the BAU Growth and Increased Growth scenarios in 2050. The Increased Growth scenario projects 68 TW of installed capacity in 2050. Under the Sustainable Cooling Pathway:

- Passive cooling measures can reduce the cooling equipment stock by 29 per cent.
- Effective use of fans, evaporative coolers and hybrid cooling could further reduce this stock by 18 per cent.
- This gives potential for the 2050 cooling equipment stock to grow to only 40 TW.

Figure 4-6 **Global cooling equipment stock scenarios, 2022 and 2050**



Source: Global Cooling Emissions Model

4.3 Outputs from the Global Cooling Emissions Model

The modelling provides annual estimates between 2022 and 2050 of:

- the stock of cooling equipment in all stationary and transport cooling applications
- the quantity of energy used by cooling systems and the related indirect GHG emissions
- the quantity of refrigerants emitted from cooling systems and the related direct GHG emissions.

Modelling outputs are available at a global level and for 14 geographic regions that reflect the Kigali Amendment groupings[1]. Details of these regional groups and the modelling methodology were provided in the *Global Cooling Watch 2023* report.

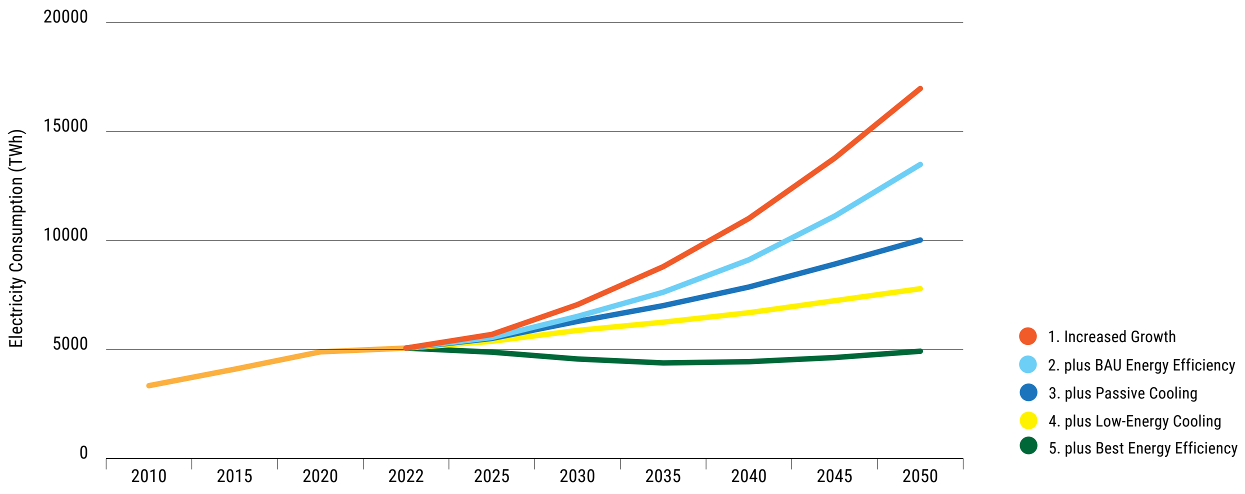
Electricity saving opportunities

The modelling of electricity savings is based on the analysis of five pathways to 2050 (see also Figure 4-7):

Pathway 1:	Assuming the Increased Growth scenario and no electricity saving or load reduction.
Pathway 2:	As (1) plus BAU energy efficiency measures that assume a slow improvement in cooling equipment energy efficiency.
Pathway 3:	As (2) plus the impact of passive cooling.
Pathway 4:	As (3) plus the impact of low energy cooling (fans, evaporative coolers and hybrid air conditioning).
Pathway 5:	As (4) plus rapid uptake of the best energy efficiency measures.

In 2022, an estimated 5,000 terawatt-hours (TWh) of electricity was consumed by cooling equipment in all market sectors. By 2050, this could rise to 18,000 TWh under the worst-case Pathway 1. Adopting all the measures in Pathway 5 allows for significant growth in cooling by 2050 while keeping electricity consumption to around the same level as in 2022.

Figure 4-7 Modelled pathways for global electricity consumption for cooling, 2010 to 2050



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[1] The Kigali Amendment HFC phase-down targets are defined for four different groups of countries: Article 5 Group 1 (the majority of developing countries), Article 5 Group 2 (10 developing countries with very high ambient temperatures), non-Article 5 earlier start (the majority of developed countries) and non-Article 5 later start (5 countries from the former Soviet Union).

Achieving Pathway 5 could generate major financial savings compared to Pathway 2:

- Electricity savings of 8,500 TWh in 2050, equivalent to end-user savings of US$1.3 trillion in 2050 (2020 US$; at US$0.15 per kilowatt-hour [kWh]).
- Cumulative electricity reductions of 110,000 TWh from 2022 to 2050, saving US$17 trillion.
- Reduced peak electricity demand of 5–10 TW in 2050, which could avoid the construction of up to 10,000 large power stations (1,000 megawatts each). At US$2 million per megawatt to build a new electric power station plus a further 30 per cent for extra transmission and distribution costs, this could save US$13–26 trillion by 2050 (2020 US$). This is an important co-benefit of sustainable cooling, especially as electricity demand rises for electric vehicles and for heating decarbonization.

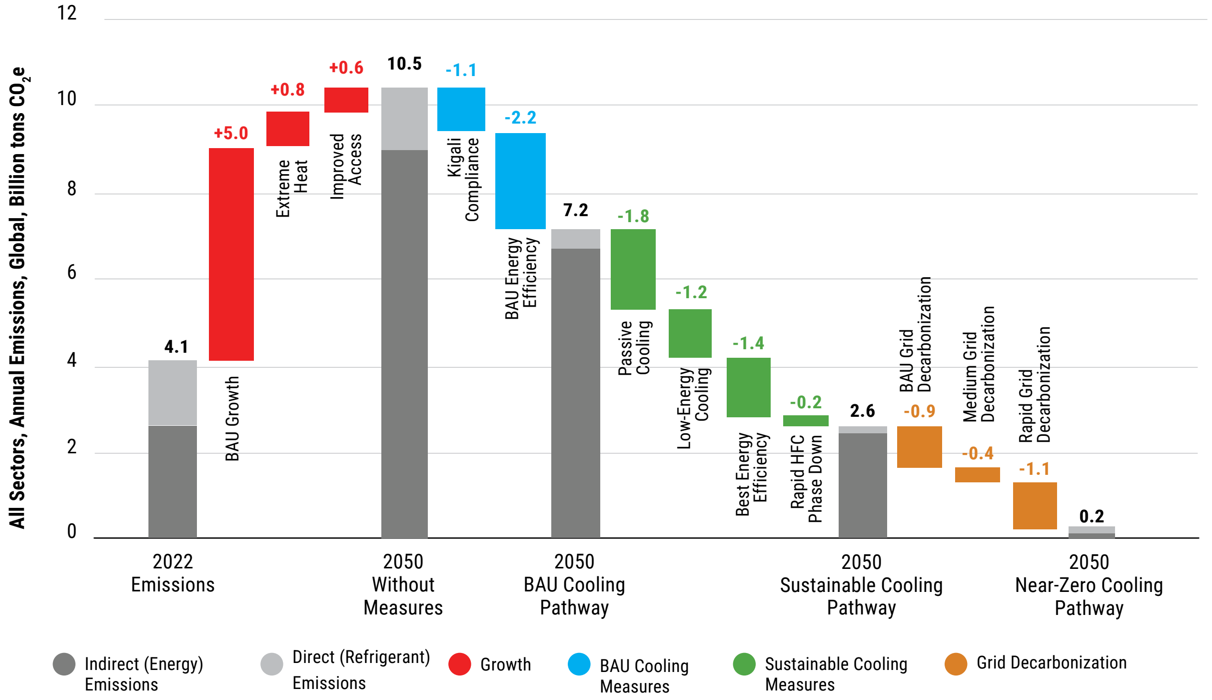
Quantification of greenhouse gas emission reduction opportunities

GHG emissions from all global cooling equipment are summarized in Figure 4-8. This illustrates that:

- Emissions in 2022 were 4.1 billion tons of CO_2e.
- In a "Without Measures Pathway", 2050 emissions grow to 10.5 billion tons of CO_2e. This is a counterfactual scenario that assumes the Increased Growth scenario and no improvement to energy efficiency after 2022
- A "BAU Cooling Pathway" includes HFC reductions in compliance with the Kigali Amendment and BAU improvements to energy efficiency, resulting in 2050 emissions of 7.2 billion tons of CO_2e.
- A "Sustainable Cooling Pathway" also includes the benefits of the four steps in the Sustainable Cooling Hierarchy (passive cooling, low-energy cooling, best energy efficiency and rapid HFC phase-down), resulting in 2050 emissions of 2.6 billion tons of CO_2e.
- A "Near-Zero Cooling Pathway" also includes the rapid decarbonization of electricity generation, resulting in 2050 emissions of 0.2 billion tons of CO_2e.

The contribution from direct emissions also shifts over time: from 36 per cent in 2022 to 14 per cent in the Without Measures Pathway, 6 per cent in the BAU Cooling Pathway and 5 per cent in the Sustainable Cooling Pathway. However, under the Near-Zero Cooling Pathway, with indirect emissions greatly reduced, direct emissions make up 59 per cent of remaining emissions. This underscores the critical need to accelerate the phase-down of HFC refrigerants and ensure proper lifecycle refrigerant management.

Figure 4-8 Modelled pathway to near-zero GHG emissions from cooling in 2050



Intermediate targets for the Global Cooling Pledge

The Global Cooling Pledge includes the following quantitative commitment (UNEP 2023a):

> *Commit to work together with the aim of reducing cooling-related emissions across all sectors by at least 68% globally relative to 2022 levels by 2050, consistent with limiting global average temperature rise to 1.5°C and in line with reaching global net-zero emissions targets with significant progress and expansion of access to sustainable cooling by 2030. This aim will be advanced through individual countries' domestic actions as consistent with their domestic plans and priorities, and international collaboration.*

The 68 per cent target was based on the Global Cooling Emissions Model and is consistent with the pathway shown in Figure 4-8, assuming a Sustainable Cooling Pathway plus Medium Grid Decarbonization. Pledge signatories would need to consider intermediate targets based on the estimates of the latest modelling results from the Global Cooling Emissions Model. Table 4-3 shows intermediate targets based on these estimates. It illustrates that an impending significant reduction target of 18 per cent by 2030 is important in order to remain on the pathway towards this commitment.

Table 4-3 Potential Global Cooling Pledge targets for reducing global GHG emissions from cooling, 2030 to 2050

Year	Potential Global Cooling Pledge target reduction from 2022
2030	18%
2035	39%
2040	55%
2045	63%
2050	68%

Photo: Evgeniy Beloshytskiy/Unsplash

Photo: Joshua Kettle/Unsplash

05

Global Cooling Policy and Legislative Landscape

Countries and jurisdictions are adopting diverse policy and legislative tools to promote sustainable cooling and move towards near-zero emissions from cooling.

Key technology-focused measures include building energy codes that encourage passive design and efficiency, minimum energy performance standards (MEPS) for appliances, and regulations to accelerate the transition to low-GWP refrigerants. These are paired with targets to reduce cooling-related emissions and energy use. Complementary economic and informational instruments—such as tariff reforms, financial incentives and awareness programmes—support these efforts, along with initiatives to improve equitable access to cooling.

Momentum is growing. The 2025 Global Cooling Watch policy survey[2] found that 172 countries have prioritized sustainable cooling in national policies. Of these, 54 countries have developed comprehensive regulatory frameworks that address all three pillars needed to achieve near-zero GHG emissions from cooling: integrating passive cooling measures (through building energy codes), improving energy efficiency (through MEPS), and rapidly phasing down high-GWP refrigerants; a further 78 countries cover two of these pillars, and 40 countries cover only one. 20 countries have yet to begin.

Figure 5-1 shows a global map of cooling-related policy coverage, reflecting the three main pillars. The figure highlights the widespread ratification of the Kigali Amendment to the Montreal Protocol (orange dots) and the integration of passive cooling measures in building energy codes (green dots).

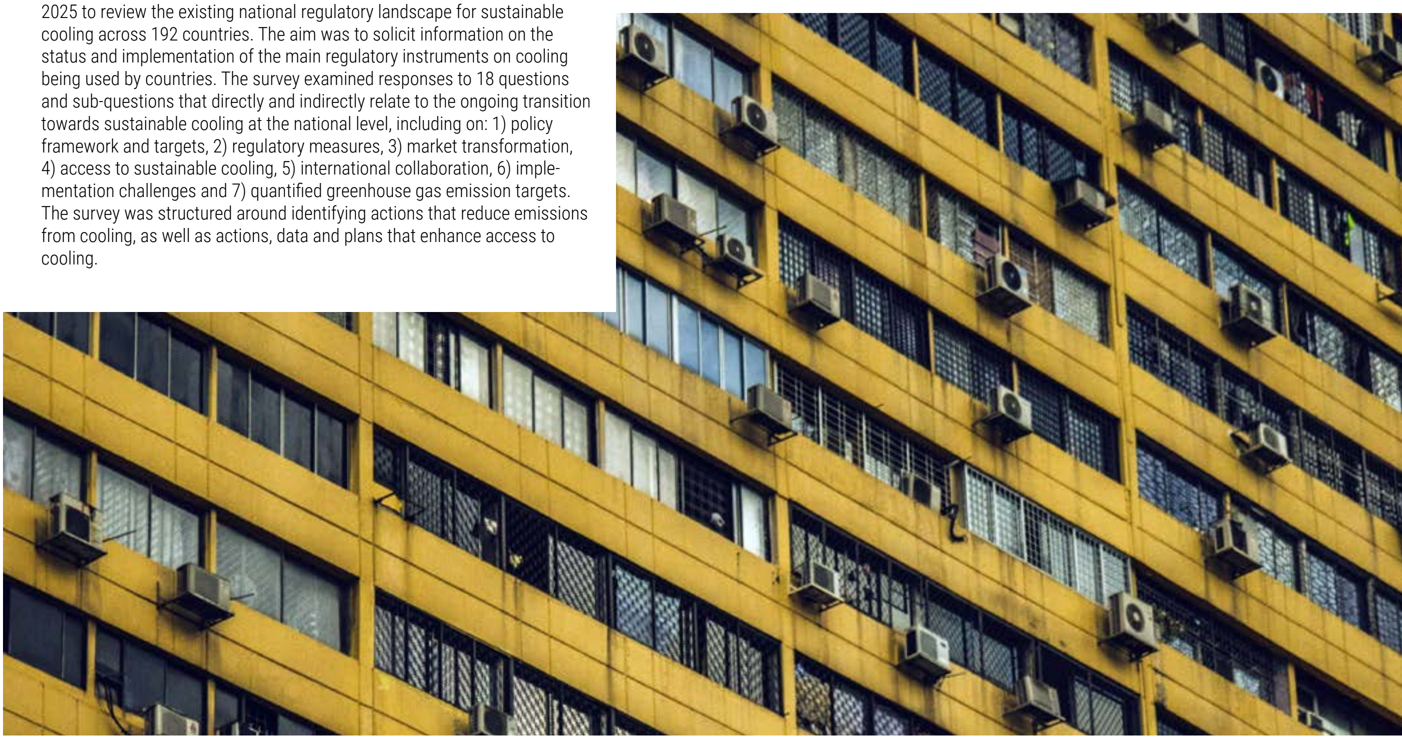


Photo: Remon Geo/Unsplash

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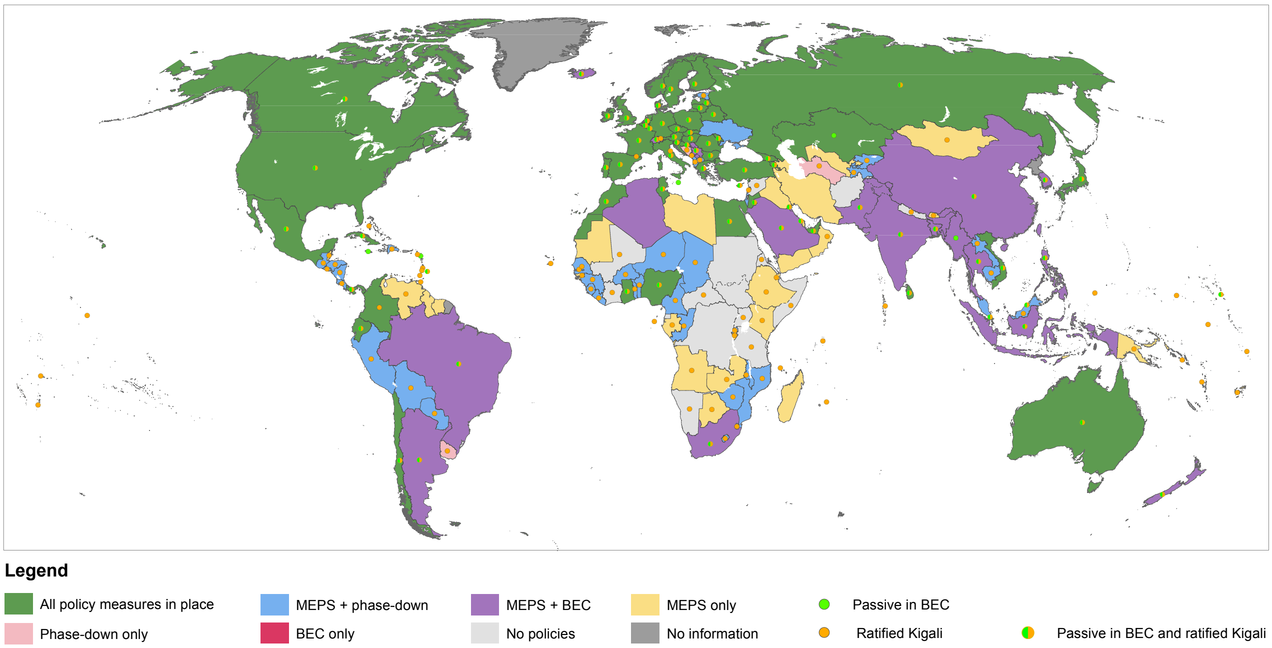
[2] The data collection survey, designed by UNEP Cool Coalition and reviewed by global cooling experts (CREED Working Group), was conducted in mid-2025 to review the existing national regulatory landscape for sustainable cooling across 192 countries. The aim was to solicit information on the status and implementation of the main regulatory instruments on cooling being used by countries. The survey examined responses to 18 questions and sub-questions that directly and indirectly relate to the ongoing transition towards sustainable cooling at the national level, including on: 1) policy framework and targets, 2) regulatory measures, 3) market transformation, 4) access to sustainable cooling, 5) international collaboration, 6) implementation challenges and 7) quantified greenhouse gas emission targets. The survey was structured around identifying actions that reduce emissions from cooling, as well as actions, data and plans that enhance access to cooling.

Figure 5-1 **Adoption of cooling-related policies by country, 2025**



MEPS = minimum energy performance standards BEC = building energy code

Source: 2025 Global Cooling Watch policy survey; IEA 2024

5.1 National cooling strategies

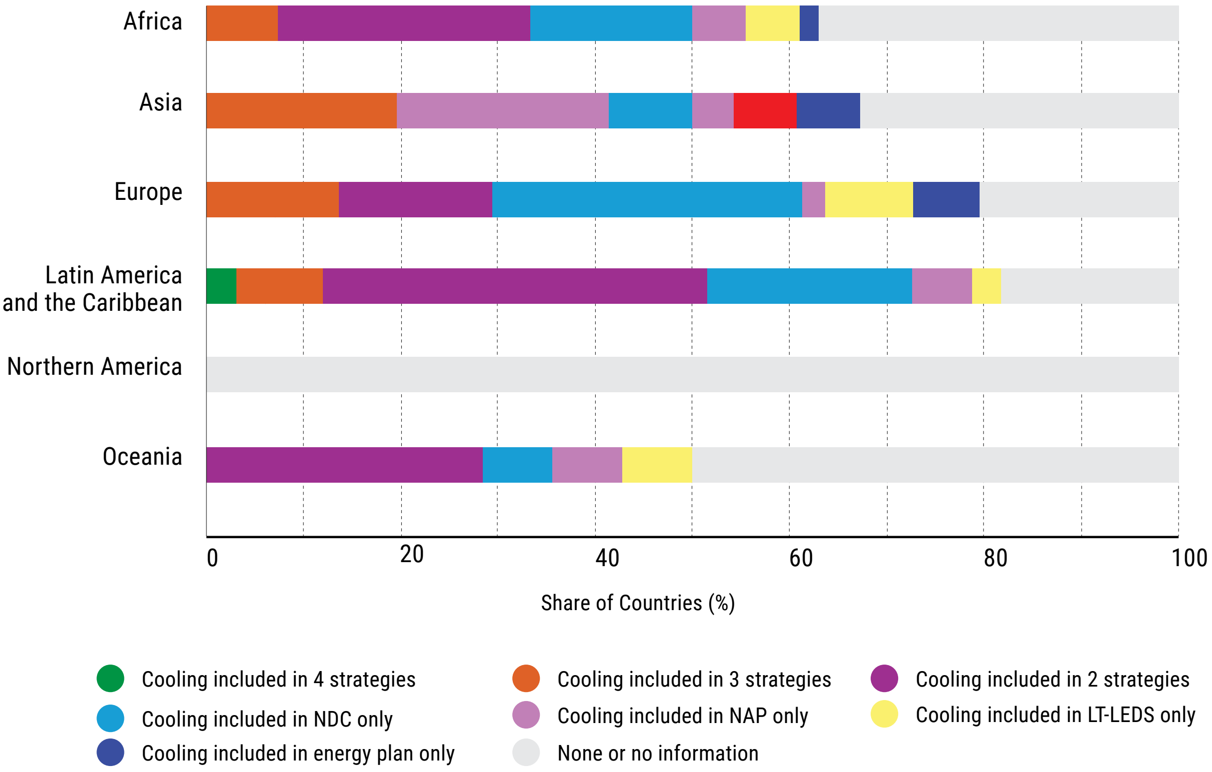
Sustainable cooling is increasingly embedded in national strategies and international commitments, providing an overarching framework that links technology deployment with long-term climate and development goals. These include Nationally Determined Contributions (NDCs) towards reducing GHG emissions under the Paris Agreement, National Cooling Action Plans (NCAPs), National Adaptation Plans (NAPs), Long-Term Low Emission Development Strategies (LT-LEDS), heat action plans, energy plans and other climate strategies. While some of these instruments are legally binding and anchored in legislation, others are voluntary or support measures to guide implementation.

As of mid-2025, 134 countries had cooling-related targets in national strategies (NDCs, NAPs, LT-LEDS and/or energy plans). Figure 5-2 illustrates the progress that countries have made, grouped by region, in mainstreaming cooling into their NDCs and other national strategies and roadmaps. Another active area of national cooling action activity is the development and implementation of cooling plans such as NCAPs, heat action plans, or other cooling action plans, which are currently being developed or implemented by 59 countries. (See Box 5-1 for a recent heat mitigation study in the United Kingdom).

The NDCs Cooling Guide, prepared by the UNEP Cool Coalition, provides methodologies for integrating cooling into NDCs, addressing design, energy efficiency, adaptation to extreme heat and equitable access to cooling. The guide provides a practical blueprint, including a framework for measurement, reporting and verification (MRV), to raise ambition and ensure effective implementation of cooling measures in NDCs (UNEP 2025a).

Some countries have established specific targets for reducing cooling-related GHG emissions. These include targets to reduce indirect energy-related emissions from cooling as well as direct emissions from the use of hydrofluorocarbon (HFC) refrigerants. As of mid-2025, only 29 countries had specific targets for reducing cooling-related greenhouse gas emissions, with the regional distribution shown in Figure 5-3.

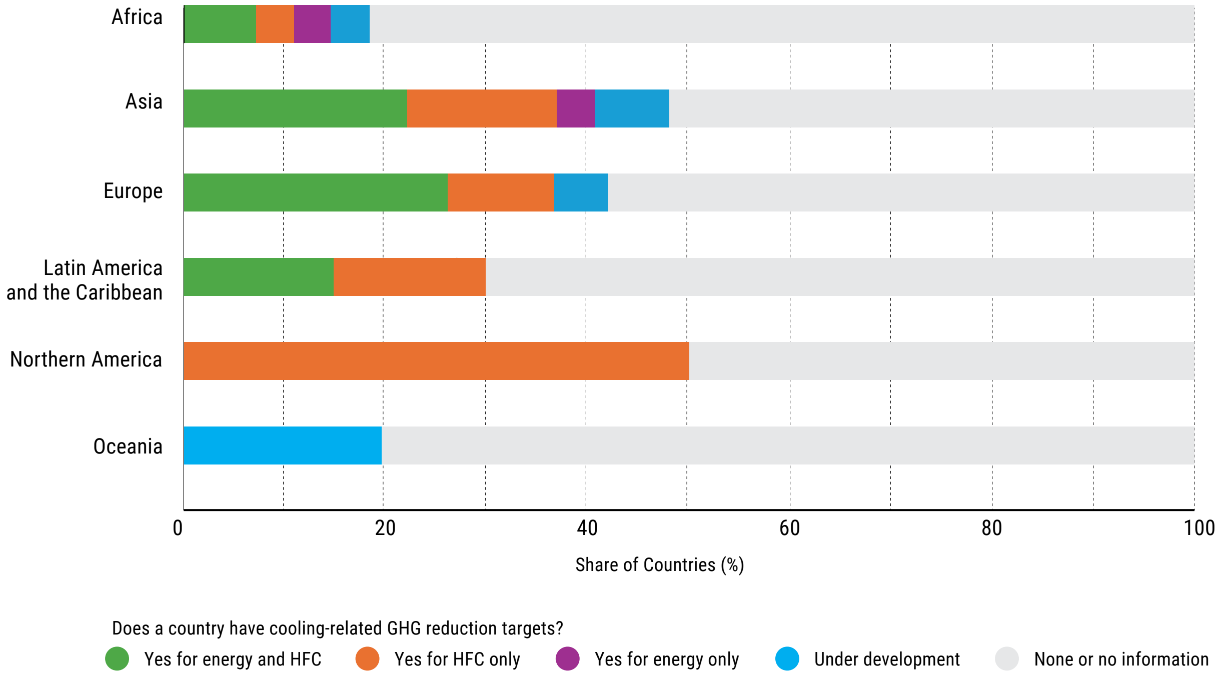
Figure 5-2 **Regional distribution of cooling in national strategies, 2025**



Note: Northern America includes USA and Canada

Source: 2025 Global Cooling Watch policy survey

Figure 5-3 **Regional distribution of countries with cooling-related GHG reduction targets, 2025**



Note: Northern America includes USA and Canada

Source: 2025 Global Cooling Watch policy survey

Box 5-1
Case study: adapting homes to increasing heat in Greater Manchester, United Kingdom

The Greater Manchester region in the United Kingdom faces rising climate risks—including flooding, heatwaves and drought—driven by shifting rainfall patterns, with wetter winters and drier summers. A case study explored how to adapt the most vulnerable homes in the region to increasing heat, focusing on identifying at-risk buildings and occupants and assessing cost-effective adaptation strategies.

Risk assessment combined building performance modelling with a Heat Vulnerability Index, which considered heat sensitivity, occupant sensitivity (age, health) and adaptive capacity (income, housing tenure, access to windows and green space). Flats, mid-terrace and semi-detached houses were most prone to overheating, especially in dense urban areas like central Manchester and Salford. Highly sensitive occupants are distributed across Greater Manchester.

Adaptation strategies were tested on five home archetypes under 2030 and 2050 climate scenarios. External window and wall shading were found most effective, while internal shading was the most cost-efficient individual measure. The most cost-effective overall strategy combined internal shading with behavioural changes. Socio-technical barriers that hinder adoption include low awareness, cost, landlord resistance and aesthetic concerns.

Key recommendations include prioritizing retrofits for vulnerable homes, promoting low-cost measures (e.g. internal shading), using vulnerability maps for funding and emergency planning, integrating green infrastructure in planning and involving health-care providers and communities in heat resilience efforts.

The study was led by Ricardo, University College London, and the University of Manchester, and sponsored by the Greater Manchester Combined Authority (GMCA) and the UK Department of Energy Security and Net Zero (DESNZ) under the CS-N0W programme.

Source: UK Department for Energy Security and Net Zero 2025

Photo: William McCue/Unsplash

5.2 Building energy codes for passive cooling

As global demand for cooling rises, shifting from energy-intensive mechanical cooling to passive, design-led solutions is not merely an option but is critical for protecting people, conserving resources and reducing GHG emissions.

Passive cooling strategies are the first line of defence against increasing heat conditions (UNEP 2023b). By reducing a building's need for active cooling, these measures tackle the problem at its source. However, widespread adoption cannot rely on voluntary action alone; it requires a robust regulatory framework to transform markets and establish new construction norms.

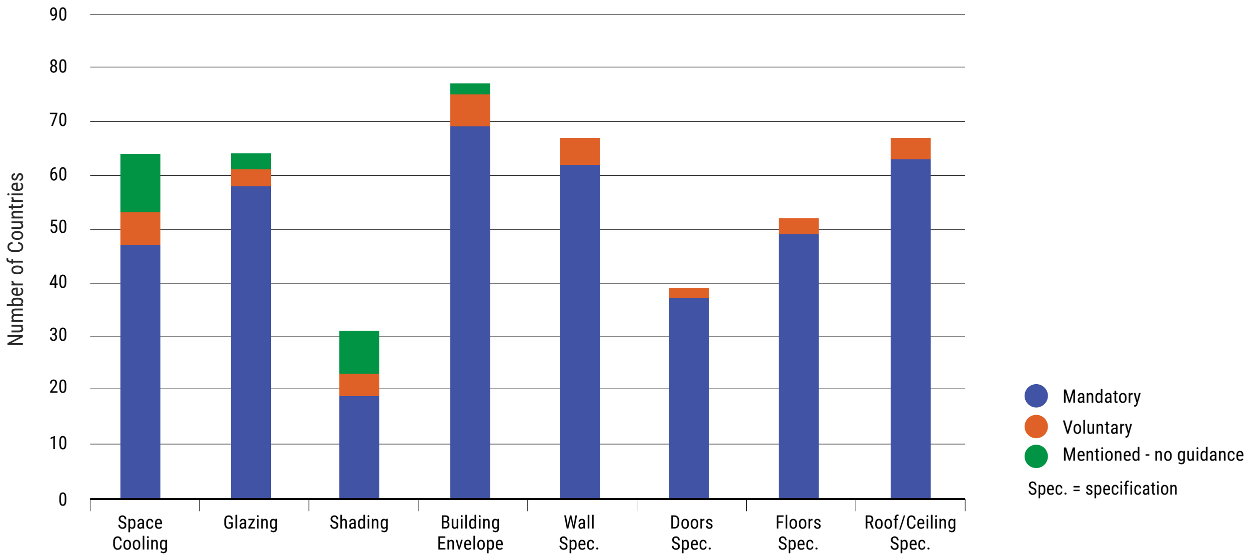
In this context, building energy codes are the most effective tool for embedding passive cooling into the built environment. These codes set mandatory minimum standards for the energy performance of new buildings and major renovations. When designed effectively, they move passive cooling from a niche feature of high-end "green" buildings to a non-negotiable baseline for all construction. This regulatory certainty sends a clear market signal, prompting architects, engineers and developers to prioritize thermal performance from the outset. The impact is widespread and lasting. A building designed with a high-performance envelope, optimal orientation and effective shading will have a much lower cooling load for its entire lifespan. This lowers demand for mechanical cooling systems, reduces energy use, eases pressure on electricity grids, decreases refrigerant charge and cuts GHG emissions.

Tracking building energy codes with passive cooling strategies

The implementation of building energy codes, particularly those incorporating passive cooling strategies, varies widely across the globe. While some progress is evident in a few hot-climate regions, such as in the Association of Southeast Asian Nations (ASEAN) region, adoption remains limited, particularly in low- and middle-income countries. Closing these gaps is crucial to fully realizing the benefits of passive cooling.

A global analysis of residential building energy codes (Figure 5-4) shows varying adoption of passive design features. Of the countries that mandate passive cooling actions, 69 mandate envelope insulation, and 58 set glazing heat transmission standards. However, only 19 countries mandate window or façade shading, a critical strategy for blocking solar radiation. Reflective surfaces are even less commonly required, typically included in guidelines rather than as mandatory elements.

Figure 5-4 Number of countries with residential building codes with requirements for passive cooling-related elements, 2025

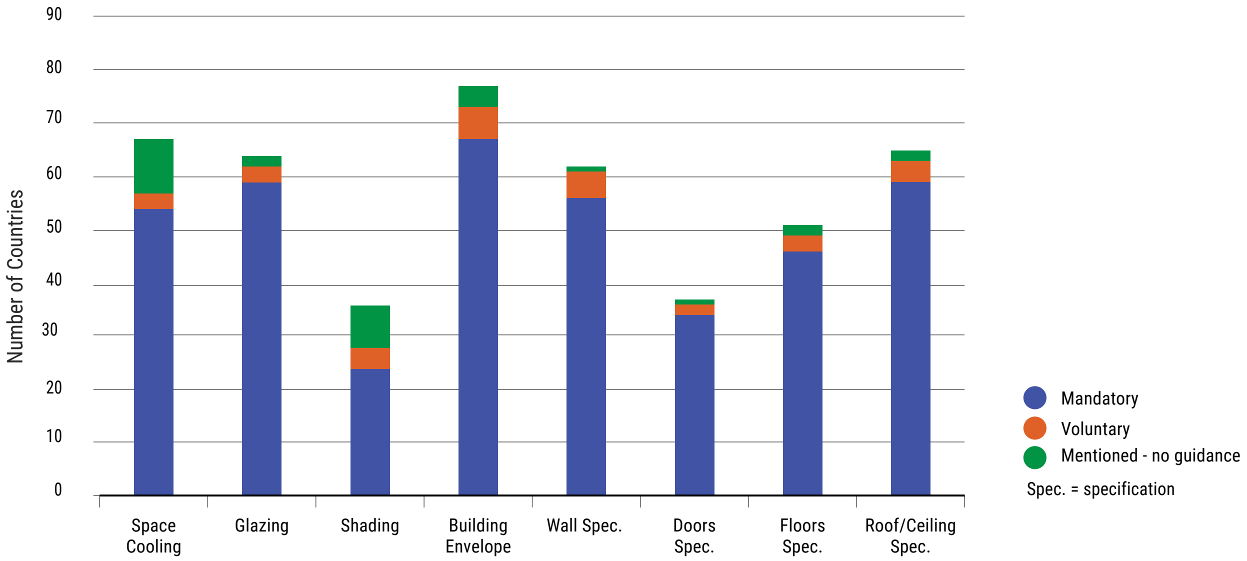


Source: IEA 2025a

A similar trend is observed in non-residential building energy codes (Figure 5-5), although with slightly different rates of implementation. A total of 67 countries have mandatory requirements for building envelope insulation, with 59 requiring both roof insulation and glazing heat transmission standards. The requirement for shading of windows or façades remains the least adopted measure, mandated by only 23 countries.

The adoption of building energy codes is not uniform across regions (Table 5-1). According to the International Energy Agency (2024), more than half of the 51 billion square metres (m^2) added per year of new floor space is built without any applicable energy code, mainly in emerging and developing economies. High-income countries have widely adopted building energy codes, whereas adoption is much lower in developing regions (around 20 per cent in Africa and 29 per cent in Asia-Pacific).

Figure 5-5 **Number of countries with non-residential building codes with requirements for passive cooling-related elements, 2025**



Source: IEA 2025a

Table 5-1 **Global residential building energy codes by region**

Region	Building energy code status		Space cooling		Building envelope**		Glazing		Shading	
	M*	V*	M*	V*	M*	V*	M*	V*	M*	V*
Africa	9	1	5	1	6	1	4	0	3	0
Latin America	11	5	6	2	9	2	6	1	4	1
Asia Pacific	14	6	10	2	13	1	10	0	8	1
Middle East	6	1	2	0	3	1	3	1	0	2
Europe	38	0	21	1	32	1	29	1	4	0
North America	2	0	1	1	2	0	2	0	0	0
Eurasia	7	0	1	0	4	0	4	0	0	0
Total	87	13	46	7	69	6	58	3	19	4

* M = Mandatory, V = Voluntary; **Codes with envelope requirements cover many heating-dominated countries, but these still provide cooling efficiency benefits.

Source: IEA 2025a and research conducted for Global Cooling Watch 2025

Globally 55 per cent of building energy codes include minimum requirements for active space cooling. In contrast, requirements for passive cooling elements vary widely (Box 5-2). Building envelopes (primarily insulation) are included in nearly 80 per cent of codes, glazing in 67 per cent and shading in just 22 per cent. While insulation is more common in cold-climate countries, it remains essential in hot-climate countries—especially in roofs and walls—to limit heat gain and improve thermal performance.

Box 5-2 Case studies: passive cooling strategies in building energy codes

Pakistan – Energy Conservation Building Code (ECBC) 2023: Pakistan's updated ECBC introduced mandatory energy efficiency measures, emphasizing low-cost passive strategies. These include optimized building orientation, enhance insulation, double glazing and external shading. A 2025 World Bank analysis found that improvements to the building envelope alone can yield energy savings for cooling and heating between 18 per cent and 37 per cent, while proper orientation can reduce energy needs by up to 4.5 per cent (World Bank 2025).

Kenya – National Building Code 2024: As part of its Global Cooling Pledge, Kenya launched its revised National Building Code in July 2024, which came into effect in March 2025 (Government of Kenya 2024). It mandates passive cooling strategies such as shading, natural ventilation, insulation, evaporative cooling and reflective coating. The 2024 update positions Kenya as a regional leader in codifying passive design and model for other low- and middle-income countries to follow for integrating climate-aligned design into national regulations.

California, USA – Title 24: California's Title 24, among the world's most advanced building energy codes, was updated in January 2023 (State of California 2023). It includes mandates for new buildings to install "cool roofs" that reflect solar radiation and reduce the heat island effect. The code evolves every three years to address emerging climate risks like extreme heat.

Photo: Ahmed/Unsplash

Features of a modern passive cooling building energy code

Modern building energy codes must evolve beyond traditional approaches to embrace comprehensive strategies that integrate passive cooling elements with efficient active systems. Research demonstrates that strategic passive cooling measures can achieve average temperature reductions of 2.2°C, cooling load reductions of 31 per cent and energy savings of 29 per cent (Hu *et al.* 2023). When combined with high-performance active systems, these benefits are substantially amplified, making integrated cooling design essential for sustainable building performance.

Essential passive cooling elements

Building envelope performance: The building envelope is the first line of defence against unwanted heat gain. Modern cooling codes must establish rigorous thermal performance standards that reduce cooling load. Key requirements include maximum thermal resistance values (R-values) for walls, roofs, and floors that account for cooling loads, with exterior insulation preferred to reduce heat gain compared to interior placement. Preventing thermal bridging limits localized heat transfer, while continuous insulation requirements help maintain uninterrupted thermal barriers (Alassad *et al.* 2025).

Advanced fenestration standards: Windows are major sources of solar heat gain and must be addressed through robust fenestration performance standards that refer to both thermal and optical properties. These should include solar heat gain coefficient (SHGC) limits appropriate for each climate zone, window-to-wall ratio restrictions that balance daylighting and thermal performance, and glazing specifications for multi-pane systems, low-emissivity coatings. Research shows that reducing window-to-wall ratios from 40 per cent to 20 per cent can cut cooling loads by 2–12 per cent in commercial buildings (Fereidani *et al.* 2021).

Mandatory shading systems: External shading, including nature-based solutions, is one of the most effective passive cooling strategies, reducing solar heat gain by up to 80 per cent. Modern codes should mandate comprehensive shading requirements including minimum overhang projection factors based on window orientation, vertical fin specifications for east- and west-facing glazing, and automated control systems in larger buildings. Horizontal shading is most effective for sun-facing openings, while vertical elements are essential for east and west orientations due to challenging solar angles (Hu *et al.* 2023).

Cool roof and surface requirements: Roof surfaces receive intense solar radiation and are primary sources of unwanted heat gain. Cool roofs with solar reflectance of 0.85 and infrared emittance of 0.9 can reduce peak heat loads by up to 71 per cent compared to conventional surfaces. Modern codes should establish minimum Solar Reflectance Index values, thermal emittance standards for heat rejection capability and durability requirements ensuring performance retention over time. In hot climates, cool roofs can reduce cooling demand by 53 per cent while shifting heat gain from day to night periods (Fereidani *et al.* 2021).

Natural ventilation integration: Natural ventilation strategies can reduce cooling energy consumption by 22 per cent when properly implemented, and up to 64 per cent when combined with evaporative cooling techniques. Modern codes should establish performance-based requirements for natural ventilation potential (including provisions for cross-ventilation pathways), stack-effect optimization for vertical air movement and night-flush capability for enhanced nighttime cooling. The effectiveness varies greatly by climate, with hot-dry conditions showing particular benefit from night ventilation strategies that can extend thermal comfort hours by 23 per cent (Hu *et al.* 2023).

Passive cooling building materials: These include materials with high thermal mass—specific concretes, stone, painting and rammed earth—that absorb and slowly release heat to stabilize indoor temperatures. They also include materials that reflect sunlight, such as light-coloured roof coatings and specialized paints. Phase change materials (PCMs), which absorb or release heat at specific temperatures as they change state, and light-coloured or insulating windows, are also key components that reduce heat gain and improve energy efficiency (de Azevedo Correia *et al.* 2024).

Climate-responsive implementation

Modern building energy codes must reflect climate-specific passive cooling strategies. Hot-dry climates benefit from thermal mass, night ventilation and evaporative cooling, whereas hot-humid climates require dehumidification, air movement and solar protection. Mixed climates need balanced approaches. Codes must include adaptive design, energy modelling mandates, commissioning requirements and ongoing performance monitoring to ensure real-world efficiency.

Comprehensive cooling standards are vital for reducing energy use, protecting health, and building climate resilience in a warming world.

5.3 Policies to support low-energy solutions: fans and evaporative coolers

As extreme heat intensifies, low-energy cooling solutions like fans[3] and evaporative coolers are essential – particularly in underserved regions where air conditioning remains unaffordable. These low-energy solutions offer affordable, scalable relief and scalable and support long-term climate resilience and energy equity, yet their potential remains underused.

With the right policies—such as energy star labelling, financing mechanisms including public procurement, and integration into local heat action plans—these solutions can deliver substantial adaptation benefits while easing the burden on electricity grids and reducing emissions (given their refrigerant-free nature). Prioritizing and scaling low-energy active cooling is one of the most practical and equitable pathways to ensure sustainable cooling for all – and to expand off-grid access to modern cooling technologies.

Because fans offer the entry-level solution to access cooling, policy momentum is growing to help them scale. In India, where the total energy use of fans is 5.6 times greater than that of room air conditioners (Yan *et al.* 2025), mandatory energy labels introduced in 2023 have driven the adoption of brushless direct current fans, which use 50 per cent less energy compared to conventional alternating current fans. Pakistan revised its fan labelling programme in 2023 to include a mandatory five-star rating system. South Asian cities like Ahmedabad and Karachi now include fans in municipal heat action plans, showing their life-saving impact.

Evaporative coolers are effective in dry climates but less effective in humid environments. Indirect evaporative cooling systems and hybrid configurations are expanding their suitability to tropical climates, albeit at higher cost and complexity. A key challenge with evaporative cooling systems is that they require water, raising concerns in many regions globally; in some cases, these systems may even pose health risks (e.g. legionella bacteria) if the water quality or the overall system is not maintained properly.

Where these technologies fall short—especially in humid, dense urban areas—there is growing recognition that the next step in climate adaptation must include access to air conditioning. This will require providing dramatically more energy-efficient units while ensuring affordability for the most vulnerable. If the growth in cooling demand is met with inefficient systems, it could overload power grids and lock in decades of avoidable emissions.

5.4 Minimum energy performance standards for cooling equipment

The status of energy efficiency regulations and their integration with refrigerant GWP limits varies by equipment type across countries (Table 5-2). Globally, the adoption of MEPS for cooling appliances is widespread, establishing a strong foundation for efficiency improvement. In several categories—including domestic refrigeration, room air conditioning and self-contained commercial refrigeration—a majority of countries report that their regulations are regularly updated to keep pace with technological progress. In contrast, central air conditioning[4] shows very limited evidence of regular updates.

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[3] Fans for cooling people include ceiling fans, desk/table fans, pedestal fans, tower fans, box fans, wall-mounted fans, exhaust fans, bladeless fans, misting fans and wearable fans. The larger the diameter and the higher the rotational speed, the more air is moved (Raftery *et al.* 2019).

[4] Central air-conditioning systems are typically above 17 kilowatts and used in non-residential buildings.

Table 5-2 **Summary of survey results on minimum energy performance standards for cooling equipment**

Equipment	Countries with MEPS/ efficiency regulations*	Countries that regularly update policies	Countries integrating GWP limits with efficiency
Domestic refrigeration	135	87	54
Room air conditioning	149	88	47
Central air conditioning	128	5	29
Self-contained commercial refrigeration	113	69	7

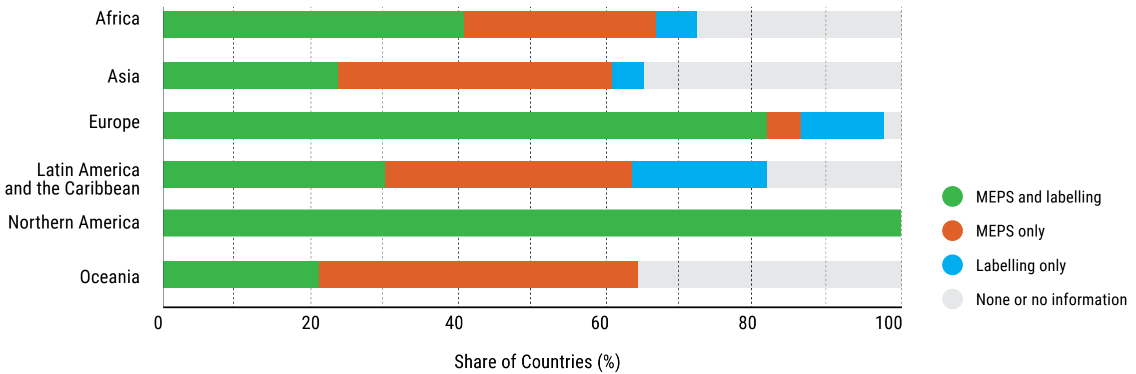
*The MEPS/regulations summarized in the table may be either national, regional, mandatory or voluntary.

Source: 2025 Global Cooling Watch policy survey

Across all product groups, a key gap lies in the integration of energy and climate policies. The data reveal a significant opportunity for advancement, as currently less than one-third of energy efficiency regulations are coupled with limits on refrigerant GWP. To accelerate the transition to sustainable cooling, a more concerted effort is needed to craft holistic policies that address both the energy consumption of equipment and the direct climate impact of the refrigerants.

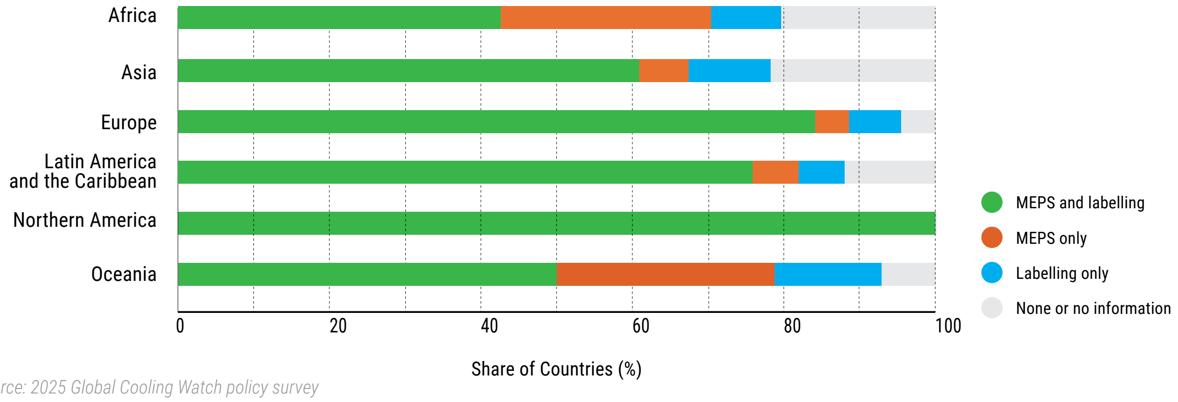
Regional coverage of regulations for refrigeration and air conditioners is shown in Figures 5-6 and 5-7, respectively. Analysis from the International Energy Agency revealed that, as of 2024, MEPS cover around 89 per cent of the energy consumption from global air conditioning and 90 per cent of the energy consumption from global residential refrigeration. In Africa, however, these figures are only around 51 per cent for air conditioning and 61 per cent for residential refrigeration (IEA 2024).

Figure 5-6 **Regional distribution of domestic refrigeration regulations, 2025**



Source: 2025 Global Cooling Watch policy survey

Figure 5-7 **Regional distribution of room air conditioner regulations, 2025**



Source: 2025 Global Cooling Watch policy survey

A review of MEPS across ten economies for room air conditioners and domestic refrigerators (CLASP n.d.) identified notable differences in stringency. For room air conditioners[5], the most stringent MEPS is around 65 per cent higher than the least stringent, with forthcoming updates expected to reduce this to 34 per cent. Domestic refrigerators show less variation: the difference between the most and least stringent MEPS is around 12 per cent, with forthcoming regulations expected to increase this to 15 per cent; reflecting a more mature product market with incremental gains. In contrast, room air-conditioning standards vary more due to technological diversity and uneven market progress.

United for Efficiency (U4E) has developed comprehensive Model Regulation Guidelines (U4E n.d.), including for refrigerators and air conditioners, which cover efficiency metrics and refrigerant GWP restrictions to support energy-efficient and climate-friendly appliances. U4E has also played a pivotal role in supporting MEPS harmonization to facilitate trade, compliance and market transformation (U4E 2023; U4E 2024).

5.5 Refrigerant management

As of 15 October 2025, 167 Parties to the Montreal Protocol had ratified the Kigali Amendment, committing to a phase-down of high-GWP hydrofluorocarbon (HFC) refrigerants. Among these, 73 Article 5 countries had approved Kigali Implementation Plans, while 38 were in the process of developing them.

Currently 62 countries are following a refrigerant phase-down schedule that is stricter than the Kigali schedule (e.g. the European Union's F-gas Regulation (European Commission n.d.)), 50 are following the Kigali schedule, 43 are developing their refrigerant phase-down plans, and 38 have yet to initiate such plans. Survey responses regarding current progress with the HFC phase-down revealed that 3 countries are ahead of their stated policies, 3 are lagging and 14 are broadly on track with their commitments.

These findings highlight both strong momentum and uneven progress. While many countries are advancing decisively, others are still at early stages of planning or face delays. Greater ambition is urgently needed to ensure an effective and timely transition to sustainable low-GWP refrigerants and to avoid the build-up of large refrigerant banks and the long service tail needed. Accelerating the Kigali Amendment could cut emissions another 72 per cent by 2050, a crucial step to keeping the 1.5°C climate target within reach (Purohit *et al.* 2022).

Lifecycle refrigerant management involves minimizing atmospheric emissions across the full life cycle of refrigerants - from design and production through end-of-life recovery, recycling, reclamation and destruction (Climate and Clean Air Coalition [CCAC] n.d.). A critical challenge is the common practice of venting refrigerants from end-of-life equipment. This approach is often more practical, as it is faster and less costly for service technicians and recyclers than proper recovery, especially in countries lacking adequate reclamation or destruction infrastructure.

Sustainable financing schemes are urgently needed to enable effective lifecycle refrigerant management, without which countries risk falling short of their Kigali commitments and locking in avoidable emissions from legacy equipment. Enabling a circular economy in refrigerant management is imperative to reduce greenhouse gas emissions (CCAC 2024). A Technology and Economic Assessment Panel (TEAP) analysis showed that the global refrigerant bank contained 24 gigatons of CO_2e in 2024 and is projected to reach 61 gigatons by 2050 (UNEP 2024b).

In 2025, only 56 countries have in place mandatory refrigerant and service requirements, 12 have requirements for servicing only, and 56 are developing such requirements. On the other hand, refrigerant recovery and recycling is a more established practice, with 74 countries having such requirements; meanwhile, 12 have requirements for end-of-life only, 8 have requirements for servicing only, and 71 are developing their requirements. Given the low legislative global penetration of comprehensive lifecycle refrigerant management, there is an urgent need for wider adoption of such frameworks to unlock its full potential.

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[5] Based on cooling-only air-conditioning units with a capacity of 7 kilowatts.

5.6 The Global Cooling Pledge as a catalyst for policy

Launched at COP28 in 2023, the Global Cooling Pledge is a transformative framework for international climate action that has reshaped how countries approach sustainable cooling policies. The Pledge commits more than 70 signatory countries to: reduce cooling-related emissions at least 68 per cent globally by 2050 (relative to 2022 levels); boost the global energy efficiency of new air conditioners 50 per cent by 2030; and greatly expand access to sustainable passive and low-GWP cooling solutions (UNEP 2023a). These targets respond to the paradox of rising cooling demand in a warming world. The potential benefits include savings of 78 billion tons of CO_2e by 2050, trillions of dollars in energy and infrastructure cost reductions, and life-saving access to cooling for vulnerable populations (UNEP 2023b).

The impact of the Pledge on global policy has been profound, with 72 signatory countries in 2024 including cooling considerations in their NDCs. This systematic integration of cooling strategies into national climate commitments has elevated cooling from a peripheral concern to a central pillar of climate policy, driving coordinated action across passive cooling solutions, super-efficient technologies, and climate-friendly refrigerants, while prioritizing equitable access for vulnerable populations most affected by extreme heat (COP28 UAE n.d.). At the subnational level, including cities, the pledge is fostering urban heat resilience through green and blue infrastructure[6], public procurement of efficient technologies and localized cooling action plans (UNEP n.d.).

In essence, the Global Cooling Pledge is catalysing a cohesive, multi-tiered policy transformation – uniting mitigation, adaptation, resilience, health and equity in the global pursuit of sustainable cooling.

5.7 Market transformation to climate-friendly technologies

Market transformation is central to achieving sustainable cooling, ensuring that efficient, climate-friendly technologies move from niche adoption to mainstream markets. The International Energy Agency has noted that efficient cooling products are often available at no additional cost for mature markets, with long-standing efficiency policies helping to expand affordable options, even though higher efficiency is not always visible or accessible to consumers (IEA 2024). Best-in-class cooling appliances can reduce lifetime costs by up to 40 per cent, making these units much cheaper when both upfront and energy costs are considered.

The shift towards sustainable cooling technologies requires a range of policy instruments, including tax incentives for high-efficiency equipment, consumer rebate programmes and green public procurement standards that prioritize low-GWP and high-performance technologies. Embedding cooling considerations into broader frameworks, such as carbon pricing, energy efficiency obligations, and public or blended investment programmes, can further reduce financial and institutional barriers, enabling large-scale deployment of sustainable solutions (UNEP and World Bank 2024). Consumer awareness and capacity-building play an important role in market transformation, and equipment manufacturers must collaborate with policymakers, financiers and civil society to make sustainable cooling widely available and affordable.

Current state of play

Market transformation is not a minor adjustment – it is a structural shift in technologies, incentives and regulation. The current business-as-usual approach of the cooling market is environmentally unsustainable and financially inefficient in the long term. Addressing this requires a targeted, policy-driven approach to overcome systemic barriers and unlock significant economic and climate benefits.

The 2025 policy survey showed that 36 countries have at least one market transformation programme supporting sustainable cooling, while 48 countries have implemented two or more – some with as

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[6] Green and blue infrastructure refers to natural and semi-natural features, including land (green) and water (blue) elements, that provide environmental, economic and social benefits.

many as seven programmes. In contrast, 39 countries reported having no such initiatives, and no information was available for 70 countries, highlighting significant gaps in global efforts to scale sustainable cooling.

The transition to sustainable cooling is hindered by a range of barriers that a policy framework must address, as confirmed in the survey responses:

- **High upfront costs** of energy-efficient and low-GWP cooling technologies were the most cited challenge (57 per cent), especially in countries with limited access to finance. The split incentive dilemma—building owners invest but tenants benefit—remains widespread. Still 84 countries have implemented one or more programmes to overcome it.
- **Weak or unenforced efficiency standards,** such as MEPS, allow outdated equipment to remain on the market. Half of respondents cited this as a key issue, along with lack of clear, long-term policy signals for investors.
- **Limited awareness** among consumers and policymakers slows adoption. In regions facing extreme heat, social stigma and logistical issues (e.g. lack of transport to public cooling centres) can also hinder the adoption of life-saving measures.
- **Other barriers** included lack of technical capacity (67 per cent), market/consumer awareness barriers (57 per cent) and lack of access to sustainable cooling technologies (50 per cent).

A recent review (Carbon Trust 2023) of 55 major cooling companies assessed their climate commitments, including participating in the Science Based Targets initiative (SBTi) and the Race to Zero[7] campaign and the alignment of a company's products with the passive cooling, energy efficiency and refrigerant transition priorities highlighted above (Climate High-Level Champions n.d.; SBTi n.d.). The analysis revealed that 31 companies have validated SBTi targets, with most setting ambitious 2030 goals for Scope 1 and 2 emissions[8] that exceed net zero pathways, and 28 of these also including Scope 395 targets. Of the surveyed companies, 16 participate in the Race to Zero campaign, 10 of which also have validated SBTi targets. Even among the companies without these formal commitments, many have established non-binding climate goals and include decarbonization technologies in their product portfolios.

Pioneering cooling suppliers leading the transition to net-zero emissions share three key features. First, they establish clear, verified targets for their climate goals, often validated by third parties such as the SBTi. Second, they actively collaborate and communicate, sharing experiences with partners both inside and outside the industry to accelerate progress. Finally, they leverage green finance, such as green bonds, and reprioritize their capital investment frameworks to fund the substantial transformation required to manufacture sustainable cooling solutions at scale.

Effective policy interventions for market transformation

Market transformation towards sustainable cooling requires a cohesive and integrated suite of policy interventions. Sustainable cooling is defined by two complementary pillars: reducing indirect emissions through passive cooling and equipment (fans, evaporative cooling or hybrid air conditioners) and energy efficiency; and eliminating direct emissions through use of low-GWP refrigerants. A piecemeal approach is insufficient; countries must implement a strategic package of policies that work in synergy to overcome technical, financial and behavioural barriers.

This framework is built on three core areas of intervention (York *et al.* 2017):

1) **Regulatory and standards-based measures (market push)** – set mandatory requirements that direct industry and eliminate the least sustainable cooling options from the market.
    - **Urban design and building energy codes:** Incorporating passive cooling elements in urban design and building energy

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[7] Race to Zero is the world's largest coalition of non-state actors taking immediate action to halve global emissions by 2030. Participants are committed to the same overarching goal: reducing emissions across all scopes swiftly and fairly in line with the Paris Agreement, with transparent action plans and robust near-term targets.

[8] Scope 1 emissions are direct emissions from sources a company owns or controls, such as on-site fuel combustion and company vehicles. Scope 2 emissions are indirect emissions from the generation of purchased electricity, steam, heat or cooling that the company consume

[9] Scope 3 emissions are all indirect greenhouse gas emissions that occur in a company's value chain, both upstream and downstream, from sources the company does not own or control.

codes ensures equitable cooling for all. By embedding climate-responsive design and minimum performance standards into regulations, governments phase out inefficient, polluting options and guide investments towards buildings and systems that minimize cooling demand from the outset. This raises the baseline for efficiency and removes unsustainable options.

- **MEPS and labelling:** MEPS are the cornerstone of efficiency policies, banning products that fall below a set efficiency level. MEPS must be regularly and ambitiously updated to drive innovation – preferably towards the most stringent global MEPS. Complementary, clear, comparative labelling empowers consumers to choose the most efficient products, translating energy savings into tangible economic benefits. International harmonization of standards and testing protocols should be pursued to create larger, more competitive markets.

- **Refrigerant regulations and phase-down:** Following the Kigali Amendment, governments must enforce timelines to phase down high-GWP refrigerants through import quotas, bans on specific refrigerants in new equipment and robust monitoring to prevent illegal trade. These regulations give manufacturers the certainty to shift to climate-friendly alternatives.

2) **Market-based and financial mechanisms (market pull)** – create demand for superior products and overcome high upfront costs to speed adoption of sustainable technologies.

   - **Green public procurement:** As major purchasers of cooling equipment for schools, hospitals, and public buildings, government agencies can shape the market by requiring products that exceed current MEPS and use low-GWP refrigerants. This creates a substantial, guaranteed market for advanced technologies, thereby de-risking private sector investment in innovation.

   - **Fiscal incentives:** Consumer rebates, tax credits and "trade-in" programmes that offer subsidies for replacing old, inefficient units can directly stimulate demand and make sustainable options more affordable. For example, China's consumer goods trade-in programme provides subsidies to incentivize consumers to upgrade to high-efficiency air conditioners, leading to significant energy savings (UNEP and World Bank 2024).

   - **Innovative financing and business models:** Solutions like on-bill financing address landlord-tenant split incentives, allowing efficiency upgrades to be repaid through utility savings. Emerging business models such as "cooling-as-a-service", where customers pay for cooled air rather than owning the equipment, promote efficiency and longer service life. Finally, the Multilateral Fund recently approved a US$40 million revolving fund to support energy-efficient refrigeration, air-conditioning and heat pump financing (UNEP and World Bank 2024).

3) **Foundational and supporting frameworks (enabling environment)** – ensure that the above policies are effective through a robust ecosystem that fosters knowledge, skills and long-term sustainability.

   - **Capacity-building and professional training:** National programmes are needed to train and certify technicians in the proper installation, maintenance and safe handling of new-generation refrigerants. This ensures that efficiency gains are realized and that safety standards are met throughout the equipment's life cycle.

   - **Consumer awareness and engagement:** Public information campaigns are crucial to educate consumers about the economic and environmental benefits of sustainable cooling. An informed public is more likely to demand efficient products, participate in incentive programmes and support ambitious government regulations.

   - **End-of-use management and circular economy:** A comprehensive strategy must include policies for the responsible recovery of cooling equipment. This involves collection schemes and technical infrastructure for the recovering, recycling, and reclaiming, and safe destruction, of used refrigerants—as well as promoting the re-installation of other valuable components—to foster a circular economy for the cooling sector.

PART III: SOLUTIONS AND OPPORTUNITIES

Photo: Nick Sorockin/Unsplash

06 Sustainable Cooling Solutions for Access and Extreme Heat

Both passive and efficient active cooling solutions are needed to safeguard vulnerable populations, preserve vaccines and food, and ensure thermal comfort – while minimizing energy demand and emissions.

Prioritizing sustainable cooling aligns urgent adaptation needs with long-term climate mitigation goals.

6.1 Cooling technologies for different tiers of access

An effective comfort cooling hierarchy ought to prioritize adaptation, equity and sustainability. It begins with passive cooling—both urban and building-specific solutions—followed by non-refrigerant appliances like fans and evaporative coolers. When these are insufficient, hybrid refrigerant-based air conditioning can be used.

Income level and access to electricity are key barriers to cooling access. Despite being the most equitable and energy-efficient solutions, lower-level options in the hierarchy—such as urban cooling and passively designed buildings—remain underfunded, while investment is concentrated in energy-intensive air conditioning (UNEP and World Bank 2024). This underscores a funding imbalance: vulnerable populations have less access to funding for passive cooling, while higher-income populations benefit from active cooling technologies.

Combining measures across the cooling hierarchy levels can provide over 20°C of cooling without refrigerant-based air conditioning (Konsam *et al.* 2025). Biological and behavioural thermal adaptations further expand access to low-energy comfort:

- *Biological adaptation* refers to changes in the body's responses to thermal environmental factors that reduce strain over time. It includes genetic adaptation—long-term evolutionary changes—and acclimation/acclimatization, short-term thermoregulatory adjustments by the body in response to thermal stressors.

Photo: Ahmad Jafar/Unsplash

- *Behavioural adjustment* refers to changes that affect the body's thermal balance, including personal adjustments (altering clothing, activity, posture, food or location), environmental adjustments (modifying windows, fans or heating) and cultural adjustments (adapting schedules, dress codes or practices like siestas).

Gender also affects thermal comfort (Hashiguchi *et al*. 2010; Haselsteiner 2021; Parkinson *et al*. 2021; Zhou *et al*. 2024). Using adaptive thermal comfort models and prioritizing air movement can reduce energy use, carbon emissions and peak electricity demand (Brager and de Dear 1998; Nicol and Humphreys 2002; Lipczynska *et al*. 2018; Barathi *et al*. 2023; Lei *et al*. 2024).

6.2 Urban cooling

Urban cooling is the first line of defence for vulnerable communities, forming the foundation of climate-resilient urban design. In the proposed Tiered Access to Sustainable Cooling Framework (section 3.2), Tier 0 represents neighbourhoods with no cooling infrastructure – no green cover, shaded public areas or cooling centres. As tiers progress from 1 to 5, urban planning systematically increases tree and green cover, integrates reflective surfaces to reduce the urban heat island effect (United States Environmental Protection Agency [EPA] n.d.; Kolokotsa *et al*. 2022; Alzahrani *et al*. 2025), and ultimately ensures equitable access to community centres with active cooling during heat waves (UNEP 2021).

Urban cooling technologies are essential for creating equitable, resilient cities in the face of climate change. Nature-based solutions—such as tree canopies, urban forests, green roofs and parks—provide passive cooling through shade and evapotranspiration, with added benefits like improved air quality, biodiversity and mental wellbeing (Lungman *et al*. 2023). These can be enhanced with complementary technologies, including cool roofs and reflective pavements, which significantly lower ambient and surface temperatures (Santamouris and Kolokotsa 2016).

Photo: Christian Julliard / Climate visuals

Water bodies, or blue infrastructures such as lakes, rivers, ponds, canals and reservoirs, also help cities cool by moderating land surface temperatures through evaporation, heat convection and solar radiation absorption (Yao *et al*. 2023; Jandaghian *et al*. 2024). The cooling potential of urban water bodies depends on their size, shape and geometry. Larger surfaces usually allow for better heat absorption and evaporative cooling (Jandaghian and Colombo 2024).

Combined, water bodies and trees in urban spaces can create powerful cooling effects, lowering the temperature of the air and surrounding surfaces and improving thermal comfort in densely populated urban areas. However, their effectiveness varies by climate. In hot-humid regions, high humidity limits evaporation and can increase heat stress of residents (Yao *et al*. 2023). In contrast, in dry climates, water bodies are more effective due to greater evaporation potential. Therefore, design and placement must consider local climate, temperature, humidity and wind conditions to maximize cooling benefits.

Equitable access requires strategic deployment in the hottest, most vulnerable neighbourhoods, guided by community input to ensure that solutions reflect local needs (Urban Institute 2022; IEA 2025b). Targeted policies, dedicated funding (Box 6-1) and prioritization of historically marginalized populations can transform urban cooling from a mitigation tool into a driver of climate justice.

Box 6-1 Nature-based finance for urban cooling solutions

Cities launching nature-based cooling solutions could attract international investors by aligning projects with nature-based finance taxonomies. The International Finance Corporation's (IFC) *Biodiversity Finance Reference Guide* (IFC 2023) provides a structured approach to help investors and financiers identify biodiversity-eligible activities, building on the Green Bond and Green Loan Principles. It includes an indicative list of investment projects, activities and components that help protect, maintain or enhance biodiversity and ecosystem services, as well as sustainable resource management. The Guide is complemented by a compendium of case studies, *Nature-Based Solutions in Cities: Solutions and Examples for Municipalities and the Private Sector,* highlighting co-benefits such as cooling, flood prevention and climate resilience.

Photo: Sophie N/Unsplash

6.3 Passive cooling technologies

More than 1.2 billion people, primarily in low- and middle-income countries, face severe heat risks due to limited or unaffordable access to air conditioning (IEA 2023a). Passive cooling strategies, ranging from architectural design to nature-based solutions, offer low-cost, electricity-free protection, making them vital for vulnerable communities. These measures offer equitable, scalable and cost-effective cooling without the need for costly infrastructure.

Preventing heat gain

Preventing heat from entering buildings is the foundation of passive cooling and can reduce indoor temperatures by 2–8°C and cut annual cooling demand by 25–70 kWh per m^2. In hot-dry regions, strategies like thermal mass and night ventilation can cut energy use by up to 60 per cent, while reflective roof coatings can lower surface temperatures by 15–20°C (Aga Khan Agency for Habitat India and International Institute of Information Technology Hyderabad 2023). These measures reduce cooling loads, extend comfort hours and improve resilience for energy-poor households during heat waves.

Case studies found that:

- A well-insulated envelope with optimal shading and natural ventilation resulted in only occasional use of smart ceiling fans and no use of air conditioners (Barathi *et al*. 2023).
- A naturally ventilated office building constructed with high thermal mass materials (stone and double brick) resulted in a 40 per cent reduction in thermal discomfort during the summer (Kumar *et al*. 2018).
- External shading with horizontal fins and overhangs reduced annual cooling energy demand up to 15.5 per cent (Mohammed *et al*. 2022).

- Ventilated roofs with high-reflectance surfaces reduced annual heat transfer by 33–36 per cent compared to standard reinforced cement concrete roofs and offered greater nighttime heat release and enhanced comfort without active cooling (Chetia *et al*. 2024).
- Moderate thermal mass in walls, floors and partitions resulted in 19–21 per cent more hours within the comfort range (<26°C) during summer in classrooms; temperature swings were reduced by 20–30 per cent (Su *et al*. 2023).

Rejecting heat to natural sinks

Where heat gains are unavoidable, passive systems can reject heat to natural sinks—air (natural/night ventilation), water (evaporative cooling), sky (radiative cooling) or earth (ground-based cooling)—often with minimal energy use and no refrigerants. Well-designed natural ventilation can reduce air-conditioning use by up to 55 per cent (Rawal *et al*. 2023), while innovations such as radiative roof coatings improve efficiency even under direct sun (California Energy Commission 2025). Demonstrations in India (Natural Resources Defense Council 2024) and Syria (Keeler and Vaidya 2016) show indoor temperature reductions of 5–8°C through a mix of wind towers, evaporative curtains, mist fans, layered roofs, shaded courtyards, underground earth-cooling pipes and solar chimneys.

Geothermal systems leverage the Earth's stable underground temperatures to regulate indoor conditions. Circulating heat-exchange fluids through subterranean pipes allows these systems to extract excess indoor heat and dissipate it underground, providing consistent cooling with high energy efficiency (Coninx *et al*. 2024). Although initial investment and installation costs are higher, geothermal systems deliver reliable pre-cooling across different climates with minimal operational energy.

Nature-based and traditional solutions

Nature-based solutions, such as green roofs and courtyard designs, complement passive architectural strategies by using vegetation and landforms to cool the surrounding environment. Green roofs and walls reduce surface and indoor temperatures through evapotranspiration, improve microclimates and mitigate the urban heat island effect. Green roofs alone can deliver up to 3°C temperature reductions and energy savings of 15–35 kWh per m^2 annually. Notable examples include green roofs and vertical greenery on Singapore's public housing (Wong *et al*. 2021) and the "Green Corridors" programme in Medellín, Colombia (Thomsen 2024).

Traditional courtyard designs, especially prevalent in the Middle East and South Asia, provide shaded, ventilated spaces that cool adjacent rooms. In traditional houses in Mali, the high thermal mass of local materials such as earth stores and releases heat over the day–night cycle, while low window-to-wall ratios reduce direct solar gains. Similarly, shaded verandas in traditional buildings in India and Southeast Asia improve ventilation and protect interiors from direct sunlight.

These solutions not only enhance thermal comfort and reduce pressure on electricity grids during extreme heat events, but also offer a passive, scalable approach—particularly in low-income settings—to mitigate heat stress, stabilize power systems and strengthen climate resilience.

Integrating passive cooling strategies with refrigerant-free mechanical cooling

Refrigerant-free cooling systems such as fans and evaporative coolers can bridge the gap between passive comfort and energy-intensive cooling. Prioritising ceiling fans can expand the adaptive comfort range, cutting or eliminating air-conditioning use and achieving up to 98 per cent cooling energy savings over a constant 24°C setpoint.

In a building at the National University of Singapore, a combination of natural ventilation, ceiling fans and personalized cooling—implemented with 27°C setpoints—maintained comfort and air quality while reducing energy use by up to 52 per cent (Lei *et al*. 2024). In another study (Kent *et al*. 2023), hybrid cooling achieved a 32 per cent measured energy savings in heating, ventilation, and air conditioning (HVAC) by increasing the temperature setpoint from 24°C to 26.5°C, with fans used to compensate for the higher setpoints (see Box 3-1). In Bangalore, India, the Infosys Crescent building uses a Radiflux radiant cooling system with 16°C chilled water in aluminium ceiling panels, paired with a dedicated outdoor air system, delivering high indoor air quality and a superior cooling capacity (Infosys Limited 2023).

Integrating passive cooling strategies with efficient refrigerant-based mechanical cooling

Combining passive cooling with efficient refrigerant-based systems, district cooling and free cooling can help close the cooling access gap while easing pressure on overburdened electricity grids. By lowering cooling loads and improving natural ventilation, passive strategies enhance efficiency and lifespan and reduce operational stress (Hu *et al*. 2023). These synergies are critical in food and health sectors where reliable refrigeration is essential but often constrained by power interruptions.

Even in regions with widespread access to air conditioning, passive cooling strategies provide cost-effective energy savings, enhance occupant comfort, mitigate peak electricity demand and strengthen system resilience. This integration also boosts grid flexibility, which is critical during heat waves when surges in cooling demand risk grid instability and blackouts. By reducing both peak and total cooling loads, passive strategies enable significant peak shaving during the hottest hours, easing grid congestion and reducing the need for new generation capacity.

In India, the urgency of integration is clear. During May 2024, Delhi's electricity demand surged beyond 8,300 megawatts due to extreme heat and heavy air-conditioning use, pushing the grid to its limits and triggering blackouts in some areas (Press Trust of India 2024). Such events demonstrate the risks of overreliance on energy-intensive cooling, particularly for vulnerable communities in informal settlements.

6.4 Low-energy active cooling: fans and evaporative coolers

Low-energy active cooling solutions such as fans and evaporative coolers offer a vital and scalable approach to providing much-needed comfort, especially in regions with limited or unreliable electricity and where air conditioning remains financially out of reach (SEforALL 2025). Practical tools are available to help practitioners assess and maximize the benefits of these solutions (Raftery *et al*. 2023).

Electric fans, ranging from ceiling to pedestal and table models, operate on convective cooling principles by enhancing air movement and promoting evaporation of sweat from the body. With typical energy consumption of between 10 W and 70 W, fans can reduce perceived temperatures by 2–4°C. Although fans do not lower the ambient air temperature, they offer an affordable and much-needed respite during hot days.

The rise of brushless direct current motors in fans has dramatically improved energy efficiency (super-efficient fans), with top-rated models in India consuming less than 30 W at full speed (Lodha and RMI India Foundation 2023). High-volume low-speed fans operate quietly and, when combined with advances in blade aerodynamics and strategic placement, can promote uniform cooling and improved perceived temperature across different indoor zones. Bulk procurement programmes are being implemented to help shift markets towards super-efficient fan products.

Evaporative air coolers (or swamp coolers) use water evaporation to cool circulating air. They range from simple fan-and-pad setups to more complex systems with water-feeding mechanisms. A typical unit uses around 200 W of electric power, or 80–90 per cent less power than an air-conditioning unit. In hot-dry conditions (under 50 per cent relative humidity), they can reduce air temperature by up to 10–15°C making them an energy-efficient alternative for cooling in low-humidity conditions.

Innovations in evaporative cooling include indirect systems, where room air is cooled via a heat exchanger without added humidity, and hybrid systems that combine evaporative cooling with vapour compression-based air conditioners or desiccant materials. Multi-stage systems combine both direct and indirect methods to optimize cooling efficiency, water use and climate adaptability. Some systems feature staged processes—starting with indirect cooling, followed by direct evaporation—for better control of humidity levels and energy use. Advanced multi-stage designs feature variable controls that respond to outdoor conditions, improving performance in diverse environmental settings.

Fans and evaporative coolers are highly affordable (often under US$100), consume only a fraction of the electricity of a typical air conditioner (making them suitable for weak or off-grid use), and are easy to operate and maintain, enabling scalability. However, their effectiveness declines under extreme heat and humidity, underscoring the need for solutions that effectively reduce both air temperature and moisture.

6.5 High-energy active comfort cooling technologies

Air conditioning has become more efficient, with inverter-based systems using over 30 per cent less energy compared to conventional models (ESMAP 2020) and further emission cuts possible with low-GWP refrigerants (UNEP 2023b). However, most systems perform poorly in extreme heat and humidity, just when demand peaks. Solutions designed for high ambient conditions are increasingly vital as heatwaves intensify. The Global Cooling Prize (Rocky Mountain Institute [RMI] 2021) showcased prototypes with five-fold climate impact reductions using advanced vapour compression, hybrid evaporative systems and dehumidification materials – showing far greater efficiency potential than today's market average.

Humidity control is an emerging priority. Efficient thermal management is achieved through the segregation of latent (humidity-related) and sensible (temperature-related) heat transfer. By effectively segregating these two types of heat transfer, energy consumption can be substantially decreased, highlighting the significant energy-saving potential of this approach.

Latent cooling is gaining importance as wet-bulb temperatures rise and passive cooling strategies, which mainly address sensible loads, become widespread. Yet current testing standards largely ignore dehumidification, leaving consumers without visibility into performance during humid heat. Field trials in Palava City, India showed that super-efficient prototypes[10] reduced energy use by 60 per cent, halved peak demand and maintained comfort access across both temperature and humidity (Clean Cooling Collaborative n.d.; RMI 2025).

Emerging innovations, including solid-state cooling and advanced desiccant materials, offer additional pathways to efficiency but remain pre-commercial. Bridging the gap between proven technology ceilings and market uptake will require updating performance standards, prioritizing latent cooling and accelerating access to efficient systems. This transition is both a climate necessity and one of the most practical steps to safeguard communities and reduce grid and economic pressures (International Energy Conservation Centre 2025).

6.6 Mobile air conditioning and vehicle thermal management: opportunities and challenges

Electric vehicle (EV) thermal management systems have expanded beyond traditional mobile air conditioning to encompass critical battery thermal regulation essential for performance, safety and range optimization (Buidin and Mariasiu 2021). Passenger compartment heating can no longer use engine waste heat (reversible air conditioning), making heat pump systems the most efficient option. Modern EV systems require complex architectures with multiple heat transfer loops to simultaneously manage cabin comfort and maintain batteries within narrow optimal temperature ranges.

The accelerated phase-down of high-GWP refrigerants is driving rapid adoption of low-GWP alternatives to replace the most widely used refrigerant, HFC-134a. These alternatives include (U.S. EPA 2023; Ko and Jeong 2024; UNEP 2024b):

- **HFO-1234yf:** A near drop-in replacement with similar thermodynamic properties but mild flammability, requiring enhanced leak detection systems.

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[10] Super-efficient air conditioners use high-efficiency components and are designed and optimized for real-world conditions, resulting in dramatically lower energy use while providing better comfort and reduced bills for consumers. When operating in warm and humid climates, these products can deliver effective and efficient dehumidification without significantly overcooling the space, as typically observed with today's products. A super-efficient air conditioner, when tested and normalized for performance and refrigerant GWP relative to the Global Cooling Prize baseline unit, will achieve five times lower climate impact performance.

- **CO_2 (R-744):** A natural refrigerant with exceptional low-temperature heating performance for heat-pump applications – a growing need for EVs. However, high operating pressures demand robust safety controls, and its cooling efficiency degrades at elevated temperatures unless augmented by advanced cycle enhancements.
- **Propane (HC-290)**: A high-efficiency natural refrigerant, yet its flammability and transport and handling restrictions currently limit its widespread adoption in automotive environments.
- **Refrigerant blends:** Engineered mixtures that balance performance, safety and environmental impact. Some of these blends face regulatory complexity challenges because many hydrofluoroolefins (HFOs), including HFO-1234yf, fall under some classification as per- and polyfluoroalkyl substances (PFAS), their environmental persistence and emerging toxicological concerns are prompting regulators to contemplate further phase-outs (SAE International 2024).

Battery thermal management is advancing rapidly with technologies such as microchannel heat exchangers, heat pipes, immersion cooling, phase change materials and nanofluids (Nasiri and Hadim 2025). Vehicle manufacturers are also adopting intelligent mobile air conditioning control systems that optimize energy use across systems, reducing power consumption and emissions during air conditioner operation.

The global shift to EVs brings infrastructure and energy challenges: electrification could increase electricity demand by 10–15 per cent, or more if battery and system efficiencies lag adoption rates (IEA 2023b). Public charging points doubled between 2022 and 2025 with the rise in EV sales (IEA 2025c). This growth was largely dominated by fast-charging stations that generate significant thermal loads, requiring their own cooling solutions – especially when operating under extreme heat.

6.7 Alternative refrigerants for sustainable cooling

The use of refrigerants and other heat transfer fluids is set to grow rapidly to meet rising cooling needs in a warming world, particularly in low- and middle-income countries, and to support heat pumps as key decarbonization tools in high-income countries. Between 2025 and 2050, an estimated three billion new air conditioners will be sold worldwide (Villeneuve 2024). Following the Kigali Amendment, there has been a global shift from high-GWP HFC blends such as R-410A, or in some cases directly from HCFC-22 to lower-GWP options like HFC-32, R-454B, R-463A, R-452B and HC-290 in self-contained systems (UNEP 2023c).

In domestic refrigerators, the global transition from HFC-134a to isobutane, R-600a, has been aided by revision of safety standards that allowed safe deployment of larger amounts of flammable refrigerants such as hydrocarbons (UNEP 2025b). Millions of self-contained refrigeration cabinets containing hydrocarbon refrigerants are deployed in Europe and the Americas (ATMOsphere 2025). In large commercial and retail food refrigeration, CO_2 (R-744) continues to gain ground (UNEP 2025b), with innovations improving efficiency in high-ambient climates (Fricke *et al*. 2019; Gholizadeh *et al*. 2025).

Much of the installed base still uses high-GWP refrigerants such as R-404A, R-507A, R-410A, and HFC-134a, although retrofits to lower-GWP HFC/HFO blends are increasing (UNEP 2025b). Lifecycle climate performance analyses indicate that operational efficiency dominates total emissions, making the choice of refrigerants with a high Seasonal Energy Efficiency Ratio (SEER) critical for impact reduction (Höges *et al*. 2025; Vering *et al*. 2025).

No single refrigerant is ideal. Fluorinated gases raise PFAS-related concerns, while flammability constrains hydrocarbons in non-factory-sealed air conditioners. A safe transition to low-GWP refrigerants—especially in residential and light-commercial sectors—requires balancing efficiency with safety and environmental impact. The preparedness of service technicians is critical. Without large-scale training and certification in safe handling, leak detection, and recovery, the climate benefits of low-GWP refrigerants could be lost. National training and certification programmes should cover installation, servicing, end-of-life management of low-GWP refrigerant systems, and emergency response protocols, ensuring a skilled workforce for safe, effective refrigerant transition.

6.8 Lifecycle refrigerant management: the extreme heat challenge

Lifecycle refrigerant management aims to cut refrigerant-related emissions by addressing the entire refrigerant life cycle from design to destruction. High-ambient temperature regions face unique challenges, particularly in establishing reverse supply chains for refrigerant recovery and safe end-of-life handling (UNEP 2024b).

Refillable recovery cylinders, designed to store pressurized and liquefied refrigerants, are regulated under national and international standards and may require modification for high-ambient temperature applications. To maintain safe fill ratios[11] and prevent overpressure, either test pressures must increase or fill levels must decrease to stay within safety limits. Efficient recovery of refrigerant in such regions also requires machines that can access both liquid and vapour valves.

Safe handling and storage of new, recovered, recycled or reclaimed refrigerant in cylinders is critical. Under extreme heat, cylinders must be kept out of direct sunlight but in a well-ventilated area, to lessen the high-pressure release of refrigerant caused by excessive heat exposure.

Recycling and reclamation are more complex in hot climates, especially for refrigerant blends. Additional cooling may be needed to condense and remove non-condensable gases effectively. Addressing these operational constraints is critical to ensure the effectiveness of lifecycle refrigerant management as well as its safety and environmental performance in extreme heat scenarios.

Establishing national and regional refrigerant recovery and reuse infrastructure, particularly in high-ambient temperature regions and developing economies, will reduce emissions, enhance safety and conserve valuable resources. It also supports compliance with international commitments, fosters local technical capacity and promotes a more circular, sustainable cooling economy.

6.9 Data centre cooling

For decades, data centre cooling relied on Computer Room Air Handlers (CRAH) and Computer Room Air Conditioners (CRAC), which circulate cooled air through server rooms. While mature and reliable (IEA 2023c), these air-based systems struggle with today's rising rack power densities, especially from artificial intelligence (AI) and high-performance computing (IEA 2025d).

Advanced liquid and hybrid cooling are being adopted to meet the growing cooling demands. Direct-to-chip (D2C) cooling delivers coolant directly to computer processing units, while immersion cooling submerges servers in dielectric fluids for highly efficient heat

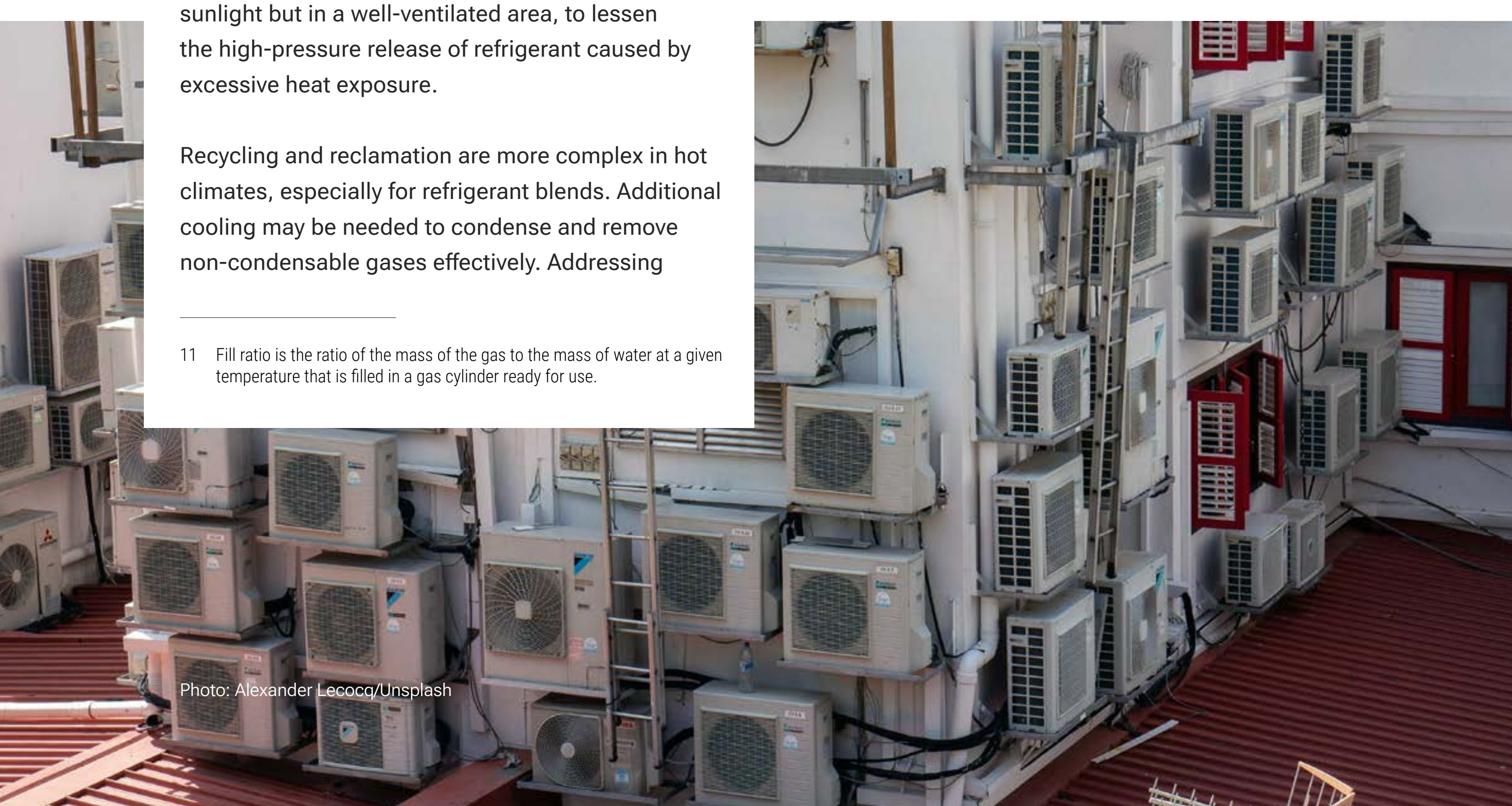

Photo: Alexander Lecocq/Unsplash

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[11] Fill ratio is the ratio of the mass of the gas to the mass of water at a given temperature that is filled in a gas cylinder ready for use.

transfer. These solutions support far higher rack densities than air cooling and cut cooling energy use by 20–50 per cent. Liquid cooling can handle thermal loads three to five times greater per volume, while AI-driven control systems further optimize chillers, fans and pumps in real time. Waste heat reuse is also gaining traction: over half of major European facilities now feed recovered heat into district heating networks. It is important to note that this technological shift may drive the demand for HFO refrigerants.

Resource use is another concern. Many legacy systems consume significant water, with Europe's colocation data centres averaging 0.31 litres per kWh of information technology energy consumed (Water Usage Effectiveness) (European Data Centre Association 2025) amid tightening regulation. Efficiency gains have lowered average Power Usage Effectiveness to 1.39 in colocation centres versus 1.85 in enterprise sites. Europe leads globally in renewable energy sourcing (94 per cent) and efficiency metrics but faces mounting grid and water constraints as cooling loads are expected to more than double by 2030. State-of-the-art efficient hyperscale data centres have Power Usage Effectiveness less than 1.07 (IEA 2025d).

Data centres accounted for around 1.5 per cent of global electricity use (415 TWh) in 2024, with consumption concentrated in the USA (45 per cent), China (25 per cent) and Europe (15 per cent) (IEA 2025d). By 2030, global demand is projected to more than double to 945 TWh, driven largely by AI and expanding digital services (IEA 2025d). While improvements in power usage effectiveness will temper cooling-related growth, cooling remains a critical challenge for sustainable digital infrastructure. Box 6-2 shows a sample road map for data centres in the United Kingdom.

Box 6-2 Road map for data centres in the United Kingdom

The Transport Industrial Commercial Refrigeration (TICR) project assessed UK data centre energy use and decarbonization options to 2050. In 2023, data centres consumed at least 1.1 per cent of national electricity and emitted 0.25 per cent of greenhouse gases, although actual figures are likely higher given that the United Kingdom hosts over 500 data centres, far more than the 193 in official datasets. Under a BAU scenario, cooling energy demand would rise 5.4-fold, from 3.63 to 19.58 TWh, and emissions by 437 per cent, from 0.16 to 0.85 million tons of CO_2e, by 2050.

The TICR found significant efficiency potential. Optimizing operations to best-practice Power Usage Effectiveness levels could cut cooling demand by 16 per cent, while widespread liquid cooling adoption could lower it by 42 per cent versus BAU. This would proportionally reduce indirect emissions, further supported by grid decarbonization and wider waste heat reuse, easing pressure on renewable capacity. In 2023, direct emissions from refrigerants represented 18 per cent of total sector emissions. Transitioning to ultra-low GWP alternatives and expanding liquid cooling could slash these by 93 per cent, reaching just 0.01 million tons of CO_2e by 2050 under TICR projections.

Photo: Ian Battaglia/Unsplash

6.10 Off-grid solutions to improve access to cooling

Expanding off-grid electrification and efficient cooling technologies offers a unique opportunity to advance the SDGs and the just and inclusive energy transitions called for by the Paris Agreement (ESMAP 2024). Innovations in off-grid electrification and cooling appliances are making space cooling and refrigeration more accessible (Box 6-3). However, scaling solutions requires integrated efforts – technological advancement, business models (Box 6-4), financing, skills and supportive policies. Investment in research and development funding and market incentives can accelerate deployment and improve health, livelihoods and food systems in a warming climate.

Box 6-3 Case studies: off-grid cooling technologies to improve access

Low-carbon cold room
A solar-powered cold room in Kenya reduced emissions 63 per cent and costs by 20 per cent compared to a conventional polyurethane-insulated cold room, while saving nearly four times more emissions over a 20-year lifespan than conventional models (Efficiency for Access 2025).

Energy-efficient space cooling
Harness Energy developed 20 W solar-compatible fans using brushless direct current motors. The rechargeable model includes built-in batteries and a USB port for mobile charging, making it ideal for urban households facing frequent power outages. The standard model is affordable (US$30), runs for over 10 hours daily, and improves sleep quality and reduces high heat risk (Efficiency for Access n.d.-a).

Solar cold chain solutions

- Adili Solar Hubs provides fully integrated, solar-powered cold chain solutions for fishers that supply refugee camps (Efficiency for Access n.d.-b.).
- Amped Innovation has developed an affordable solar refrigerator/freezer for micro-enterprises (Efficiency for Access n.d.-c).
- Savanna Circuit Technologies offers mobile solar chillers for milk and fish transport (Efficiency for Access n.d.-d).

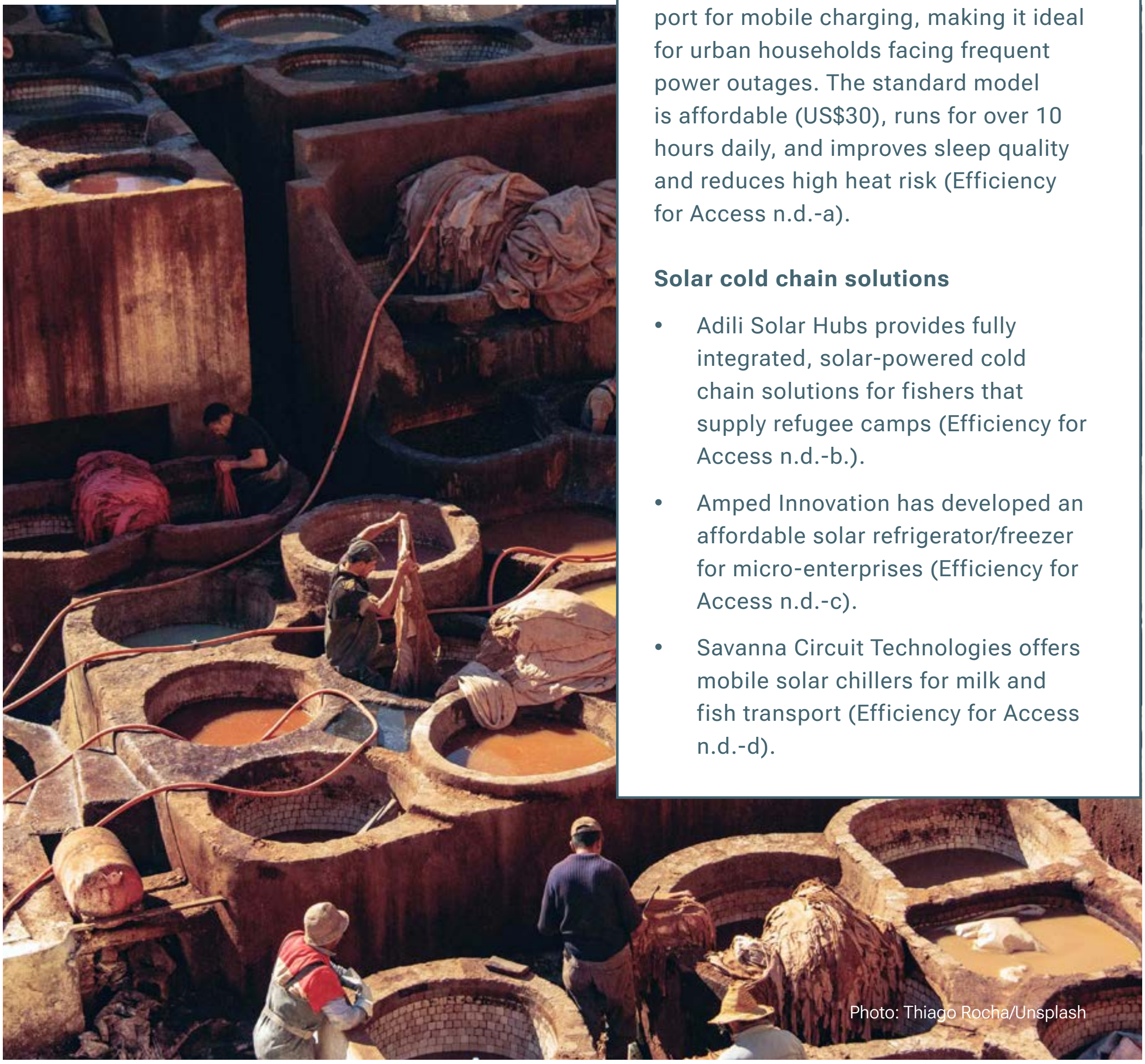


Photo: Thiago Rocha/Unsplash

Box 6-4 TechEmerge and the Sustainable Cooling Initiative

To address the need for energy-efficient, affordable, climate-smart cooling, the International Finance Corporation launched the TechEmerge Sustainable Cooling Innovation (TE-SCI) programme in 2019 in partnership with the UK Department for Energy Security and Net Zero.

The programme connected global innovators with leading companies in emerging markets to pilot sustainable cooling technologies and business models, helping to de-risk investment and accelerate adoption. It focused on key themes in Africa, Asia, and Latin America: cooling in cities, cold chains, temperature-controlled logistics, space cooling and Cooling-as-a-Service (CaaS). Many of the piloted solutions included off-grid applications and efficient appliances for use by businesses and consumers.

By its conclusion in September 2024, the programme had engaged over 500 organizations, received 380+ applications and supported 100 pilots across 10 countries (including in Bangladesh, Colombia, Ecuador, India, Kenya, Mexico, Nigeria, Rwanda, Türkiye and Viet Nam). These pilots field-tested 82 applications from 40 high-potential cooling innovators from across the globe. They were partnered with 51 major companies serving as adopters in sectors needing sustainable cooling.

TechEmerge has evolved into the IFC's Sustainable Cooling Initiative, a "five by five" strategy aimed at scaling cooling solutions across crucial sectors, aligned with the Global Cooling Pledge and aimed at increasing investment in sustainable cooling.

For more information:
https://www.ifc.org/en/what-we-do/programs-projects/sustainable-cooling.

Human safety and comfort

Off-grid populations often lack infrastructure and basic appliances, increasing their vulnerability to extreme heat. Low-cost passive cooling (e.g. cool roofs, insulation, clay roofing) can reduce indoor air temperatures by 2–10°C (SEforALL n.d.; Das *et al.* 2023). Solar-powered direct current fans can cut energy consumption by up to 50 per cent compared to conventional fans but remain under-distributed in rural sub-Saharan Africa (Efficiency for Access 2024). Evaporative coolers work well in hot-dry climates, with hybrid fan-evaporator designs offering better performance where water is available. Solar-compatible air conditioning with thermal storage and low-GWP refrigerants are increasingly viable in rural clinics, schools, although affordability remains a challenge (Al-Yasiri *et al.* 2022).

Agriculture and food cold chains

Most rural communities depend on agriculture, yet around 1.05 billion tons of food, or 19 per cent of global production, is lost each year (UNEP 2024c). Cold storage can reduce food waste, improve food security and boost farmers' incomes – especially for women in agriculture. Despite this, cold chain infrastructure is scarce in many off-grid rural areas.

Cooling must begin post-harvest and continue through the supply chain. While many cooling technologies exist, only a few are mature enough for commercial off-grid use – and fewer are adopted. Passive evaporative coolers like charcoal rooms or brick-based Zero-Energy Cool Chambers (ZECCs) (MIT D-Lab. n.d.), pot-in-pot clay ("zeer") coolers, cooling with snow or cold water, and underground storage work well in specific climates.

Walk-in solar-powered cold rooms, assembled locally or containerized, can store up to five tons of food (Defraeye *et al.* 2025), and are supported by flexible business models (e.g. pay-as-you-store, lease-to-own, upfront purchase). Cooling-as-a-Service (CaaS) serves small-scale producers. Gender gaps in access to energy, finance and land ownership can limit women's ability to benefit from these models and must be addressed.

Smaller off-grid solar refrigerators (30–600 litres) are more widely available but often not affordable for individual households and not suitable for large-volume agricultural produce. Sales remain low in sub-Saharan Africa, and fewer are adopted. Passive evaporative coolers like charcoal rooms or brick-based Zero-Energy and fewer are adopted. Passive evaporative coolers like charcoal rooms or brick-based Zero-Energy – below 1 per cent in off-grid rural areas (Efficiency for Access 2023). Ice-making using solar power provides a flexible cooling option, usable for hydrocooling and hybrid evaporative systems, which reduce air temperatures by 5–15°C and help preserve fresh produce by reducing moisture loss.

Health-care cold chains

Reliable cooling is essential for storing vaccines, medicines, and blood products safely – especially for maternal and newborn care. Yet around one billion people in low- and lower-middle-income countries rely on health centres without dependable electricity (WHO 2023). Energy-efficient medical appliances powered by solar photovoltaics or batteries can improve access to cooling for health-care needs (SEforALL and CLASP 2025).

Solar direct-drive refrigerators—prequalified by the World Health Organization—run directly on solar panels without requiring batteries, making them reliable and low-maintenance options (WHO 2017). These technologies are enabling sustainable, last-mile health-care services in off-grid areas.

Photo: Celine Lityo/Unsplash

07 Passive Cooling Solutions for Thermal Comfort: Unlocking Economic and Social Value

This chapter shifts focus from the technical potential of passive cooling measures in buildings to their economic opportunity – providing an evidence base for policymakers, informing investors and describing opportunities for building developers.

The analysis shows that passive cooling strategies are not an added expense but a forward-looking investment that enhances thermal comfort and reduces energy use. Depending on the strategy and local climate, it can lower indoor temperatures by 1–7°C on average. Economic benefits—from direct energy savings for building users (households and businesses) to avoided electricity infrastructure costs for utilities and governments—show that prioritizing passive design offers a cost-effective path to a resilient and sustainably cooled future.

7.1 Valuing passive cooling

With installed global cooling equipment expected to triple by 2050, passive cooling solutions offer major energy-saving potential (see Figures 4-5 and 4-6). Robust economic assessment strengthens the argument for integrating these measures into policy decisions and investment priorities. Beyond simple energy cost savings, passive cooling delivers measurable co-benefits related to health, productivity, property values and climate resilience. Quantifying these co-benefits alongside traditional financial metrics helps capture the full economic value of passive cooling and supports more informed investment decisions and policy development.

Cost-effectiveness of key passive cooling strategies in buildings: a global evidence review

Global evidence strongly supports the economic case for passive design. Studies show that passive design can cut a building's energy consumption for cooling by up to 60 per cent (Table 7-1) or more, depending on the strategies used and the local climate (Song *et al*. 2021). These strategies demonstrate considerable energy and cost savings

Photo: Chuttersnap/Unsplash

Table 7-1 Energy and temperature improvements from passive cooling strategies

	Average energy savings (%)	Average indoor temperature reduction (°C)
Roof pond	58	2.8
Evaporative cooling	56	7.4
Trombe wall	44	5.2
Radiant cooling	32	3.4
Solar chimney	21	6.9
Solar control glazing	20	3.0
Wind-driven ventilation	20	6.4
Phase change materials	19	4.0
Vegetation	16	6.0
Shading	15	1.1
Nighttime cooling	11	5.1

Source: Bhamare et al. 2019; Al-Absi et al. 2020; Fereidani et al. 2021; Hu et al. 2023

while requiring much lower operational expenditure than mechanical alternatives.

Key strategies for buildings include:

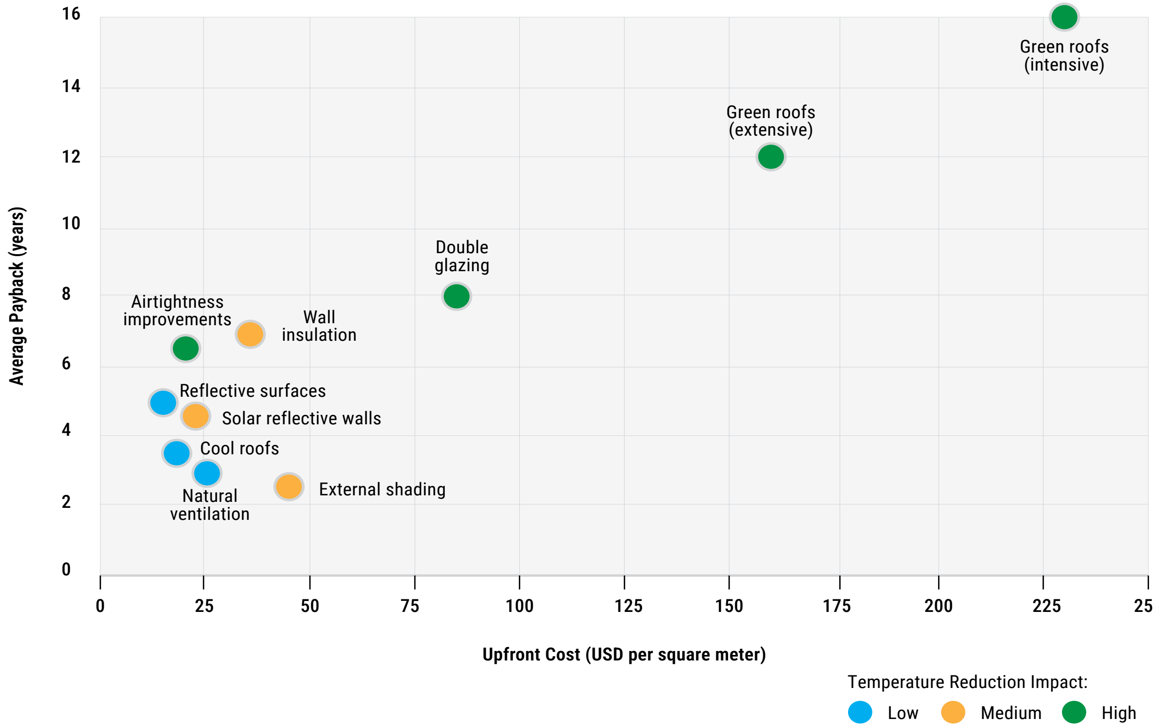
- **Urban design:** Measures such as building orientation, size and how buildings shade the surrounding environment all impact solar radiation levels on surfaces, along with potential for wind flow. Nature-based solutions, such as vegetation and street trees within site and landscaping plans, also have an impact.
- **High-performance building envelopes:** Measures such as insulation and high-performance windows typically have a modest upfront cost premium for new buildings (although more for existing building retrofits) but generate significant long-term energy savings, making them a core component of mandatory building energy codes worldwide.
- **Cool surfaces:** Cool roofs and façades are among the most cost-effective measures, often having little to no incremental cost during new construction or re-roofing, with rapid payback periods from energy savings (Bianchi *et al*. 2007).
- **Shading and natural ventilation:** Architectural elements such as overhangs and optimized window placement are fundamental to good design and can drastically reduce cooling loads at a minimal cost, especially when integrated early in the design process.

The financial appeal of passive cooling lies in its low incremental costs during construction or retrofit, as well as payback periods typically ranging from around two to eight years (Figure 7-1). Unlike active cooling systems that impose ongoing energy and maintenance burdens, passive strategies deliver continuous benefits through reduced utility costs and enhanced building durability. This economic advantage grows with rising energy prices and more frequent extreme heat events, offering both financial protection and thermal resilience for building occupants (BUILD UP 2024).

The review of cost-effectiveness across building types and climates highlights a strong investment case. External shading achieves the shortest payback periods at around two years, and cool surfaces between two and five years. Comprehensive building envelope improvements, such as wall insulation, yield the greatest energy savings (around 25 per cent) (see "high-performance building envelopes" below) despite longer payback periods of around seven years.

Natural ventilation strategies provide exceptional value by often eliminating the need for mechanical cooling, reducing use by roughly 25 per cent with payback periods under four years. These performance metrics, drawn from across multiple climatic zones and building types, show the critical importance of passive cooling as a cornerstone of sustainable, affordable and scalable climate-resilient building design (Climate Matters 2020; Santamouris *et al.* 2022; Iwuanyanwu *et al*. 2023).

Figure 7-1 **Initial investment cost versus payback period of passive cooling strategies**



Source: Research and analysis conducted for Global Cooling Watch 2025

High-performance building envelopes

High-performance building envelopes represent a cost-effective long-term investment for managing heat flow through building façades and improving overall energy efficiency. Enhanced insulation systems can deliver on average 25 per cent energy savings, with average cost premiums of US$35 per m^2 and payback periods of five to eight years. In Türkiye, roof insulation achieves up to 48 per cent of annual cooling energy savings in single-storey buildings, with payback periods between two and eight years (Asikoglu 2022). Another European study found that thermal insulation alone reduces building energy consumption by up to 40 per cent (Alrasheed and Mourshed 2023).

Glazing systems offer energy savings of 5–15 per cent and paybacks of three to seven years (Fereidani *et al*. 2021), while enhanced airtightness systems lower HVAC loads by around 18 per cent, achieving payback in roughly six years (Oak Ridge National Laboratory [ORNL] 2024). Thermal bridge reductions (i.e. reduced heat flow through building corners and openings) through continuous insulation eliminates structural heat transfer and can achieve up to 22 per cent energy savings at US$45 per m^2 premium with payback periods of five to eight years (BC Hydro *et al.* 2014).

Cool surfaces

Cool roofs and façades, which are surfaces that have been painted to increase their albedo (i.e. white and highly reflective) offer exceptional cost-effectiveness with minimal incremental costs and rapid returns on investment. New-construction cool roofs can deliver 15 per cent energy savings, adding a premium of only US$12 per m^2 and with a two-year payback period (Santamouris *et al*. 2022). Applying cool paints as retrofit applications can achieve up to 18 per cent energy reductions at a cost of US$18 per m^2 and offers payback in around 2.5 years (Bahmdad 2023).

Cool surface treatments bring the benefit of reduced surface temperatures, with international studies showing cooling load reductions of between 9 and 48 kWh per m^2 annually and roof surface temperature decreases of up to 7°C. The cool façades treatments provided around 12 per cent energy savings at costs of US$25 per m^2, while reflective paints achieved the shortest payback periods of 1.5 years at only US$8 per m^2 investment (Synnefa *et al*. 2007). Aside from cost-related benefits, roof lifespans can be extended by cooling treatments through reduced thermal stress and lower maintenance costs, with cool roofs lasting around 45 per cent longer than conventional alternatives.

Shading and solar control

Architectural shading systems deliver significant cooling benefits with moderate initial investments but substantial long-term savings. Fixed wall overhangs can provide around 25 per cent energy savings at US$45 per m^2 costs, with 3.5-year payback periods, and are particularly effective on south-facing orientations where energy savings reach 45 per cent (Alshamrani and Mujeebu 2016). Adjustable louvers can achieve 35 per cent energy reductions but can require higher upfront costs of around US$120 per m^2 and 6.5-year paybacks. External shading systems have been shown to reduce solar heat gain by 60–85 per cent, compared to 37 per cent for internal solutions.

Vegetative shading through strategic tree placement demonstrates exceptional cooling potential, with targeted sun-side plantings achieving 50–80 per cent cooling load reductions for low-rise buildings (Akbari 2002). Tree installations are more costly, at around US$200 per m^2 of building coverage, but provide 40 per cent energy savings, offering eight-year payback periods. Green façades (i.e. vegetated walls and surfaces) can offer 30 per cent energy reductions, although they are most costly at around US$250 per m^2 investment with 12-year paybacks (Perini and Rosasco 2013). Vegetated surfaces on and around buildings also offer co-benefits such as increased biodiversity, urban heat island mitigation, and air pollution reduction, making them a very important passive cooling measure.

Natural ventilation

Natural ventilation strategies provide economic returns by reducing or eliminating mechanical cooling requirements. Well-designed openings and building orientation can enhance air movement and deliver significant energy savings. Cross-ventilation designs achieve around 30 per cent energy savings at costs of around US$25 per m^2, with paybacks of about 2.5 years (Architecture Helper 2025). A review from Asia showed that natural ventilation techniques in buildings can achieve 40–50 per cent cooling energy reductions and can displace fan-driven mechanical systems that account for around 30 per cent of non-residential building electricity use (Zhang *et al.* 2021).

Hybrid ventilation systems, combining natural and mechanical ventilation strategies, offer around 35 per cent energy savings at US$85 per m^2 and six-year paybacks (Rey-Hernández *et al*. 2020). The benefit of natural ventilation is that it can reduce or even eliminate mechanical systems, has minimal ongoing maintenance requirements compared to mechanical alternatives, and can potentially provide improved indoor occupant comfort.

Thermal comfort benefits

Analysis of a compiled dataset of peer-reviewed studies on cooling strategies and measures shows that passive cooling technologies can reduce indoor temperatures by 1–7°C on average (Bhamare *et al*. 2019; Hu *et al*. 2023). Cooling potential varied by climate: hot-dry climates achieve up to 7°C reductions—due to favourable conditions for evaporative cooling and nighttime heat dissipation—while hot-humid climates achieve around 3–4°C reductions despite higher air moisture, which slows evaporation and heat dissipation. Vegetation-based solutions provide 2–6°C average cooling, and thermal mass systems (like Trombe walls) deliver 2–4°C reductions when coupled with night ventilation strategies.

Even simple shading delivers 1–3°C cooling and can cut annual cooling energy consumption by around 45 per cent by reducing solar heat gains – the heat absorbed from direct sunlight through roofs, walls and windows. The data indicate that strategically combining multiple passive measures—such as high-reflectivity roofs (2–4°C) with natural ventilation (5°C)—can achieve aggregate temperature reductions of 6–9°C, sufficient to eliminate mechanical cooling needs in many tropical and temperate buildings.

These temperature benefits translate into improved thermal comfort, reduced heat stress and greater resilience during heatwaves; this is particularly critical for vulnerable populations in low-income housing where mechanical cooling is unaffordable. Integrating gender-sensitive and climate-specific design guidance, including shading, ventilation and safe indoor spaces, into building codes and cooling policies can enhance health protection and energy equity (SEforALL 2022).

7.2 Economic and social value of urban-scale interventions

This section considers the economic and social benefits of passive cooling measures for buildings at the urban scale, emphasizing the cost-effectiveness of public investments that generate widespread community benefits.

Urban heat island mitigation

Large-scale implementation of cool surfaces and urban greening delivers substantial economic returns through monetized benefits that exceed implementation costs. For example, cool pavement strategies are cost-effective: in Austria, installing high-albedo[12] pavement surfaces costs around US$58 per m^2, while removing hard surfaces costs around US$18 per m^2 (International Institute for Applied Systems Analysis [IIASA] 2022). When applied city-wide, these measures reduce cooling demand and lower carbon emission by reducing reliance on mechanical air conditioning. A U.S. study, over a 50-year analysis period, estimated that cool surface adoption could result in around 3 per cent reductions in total GHG emissions in cold-climate cities such as Boston, and around 4 per cent in hot-climate cities like Phoenix – equivalent to 45 gigatons of CO_2 savings (AzariJafari *et al*. 2021).

Urban greening shows similarly favourable returns, with benefit-cost ratios consistently being above 1 (beneficial overall) across multiple jurisdictions. Comprehensive cost-benefit analysis of combined green and energy efficiency scenarios in Austrian municipalities demonstrates benefit-cost ratios of between 1.3 and 2.7, with net present values ranging from US$664 million to US$8.3 billion over 50-year periods (IIASA 2022). In Los Angeles, tree planting initiatives yielded US$7.30 in benefits per US$1 invested through carbon benefits, energy savings, air quality gains and stormwater management (Kunsch and Parks 2021).

Large-scale investments in cool surfaces and urban greening provide direct economic benefits that include reduced energy costs and increased property values. For example, Singapore saves an estimated 47 million Singapore dollars annually in city-wide energy costs due to the cooling effects of urban greenery (Ramsay *et al*. 2025). However, depending on location, the principal economic justification of large-scale passive cooling often lies in significant co-benefits from reductions in heat-related mortality. Studies from three cities in Austria estimate economic savings of 398 million, 2.5 billion and 6.1 billion Euros over 50 years from such reductions (IIASA 2022). Other monetized co-benefits included reductions in heat-related illness, hospitalizations and productivity loss, and the provision of a suite of urban ecosystem services. In Melbourne, maximum urban greening in a new suburb was valued at 7.1 million Australian dollars (1,500 Australian dollars per household), primarily from reduced mortality and electricity savings, with productivity gains contributing 12 per cent of the total value.

In New York, a study of benefits of green infrastructure showed property value premiums of 3–16 per cent for buildings with green features (e.g. green spaces, green walls and roofs), while ecosystem services including carbon sequestration (US$18,000 per 600 tons annually), stormwater management (US$27 million in avoided grey infrastructure maintenance) and air quality improvements (US$13.5 million annually in a New York county) provide additional economic justification (International City/County Management Association 2022).

Grid resilience and avoided infrastructure costs
Urban-scale passive cooling strategies also deliver substantial economic value through reduced peak electricity demand, enabling significant deferrals of power generation and grid infrastructure investments. Peak demand reduction is in the range of 8–50 per cent for individual buildings and 10–25 per cent city-wide (Ozkan *et al*. 2016). These reductions translate directly into avoided capital investments in generation capacity, transmission systems and distribution infrastructure that would otherwise be required to meet growing cooling demands.

The economic value proposition strengthens when considering avoided investments in generation capacity. In the USA, a 2–5 kW reduction per building (typical for comprehensive envelope and cooling system improvements) could avoid

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[12] Light-coloured, reflective surfaces, such as certain concrete or specially coated pavements, that reflect more sunlight instead of absorbing it like dark asphalt.

US$1,600–6,000 in generation capacity investments per building and US$240–900 annually in avoided carrying costs (i.e. fixed costs per customer for infrastructure maintenance) (ORNL 2022). When widely implemented, thermal energy storage systems coupled with passive cooling measures can offset the need for peaking power plants (i.e. power plants, typically run on fossil fuels, needed during periods of peak demand) and enhance grid stability.

7.3 The opportunity of nature-based solutions for passive cooling

Nature-based solutions offer cost-effective cooling with multiple environmental benefits. Green roofs can reduce cooling energy consumption by 35–85 per cent in hot climates (Jia *et al*. 2024) and by up to 75 per cent in temperate zones (Toronto and Region Conservation Authority 2007). In Mediterranean climates, green roofs lower roof maintenance costs by 75 per cent and cut energy use by up to 35 per cent.

A simulation study across multiple cities showed that when 90 per cent of buildings were covered with green roofs, indoor air temperatures decreased by 0.5°C and roof surface temperatures by 2°C, leading to around 8 per cent reduction in building energy use (Adilkhanova *et al.* 2024). In sub-tropical settings, green roof installation costs can be in the range of US$42–979 per m^2 over a 40-year life cycle, with extensive green roofs typically costing US$100–300 per m^2 (Chan and Chow 2013) with payback periods averaging 6.2 years nationally. Despite higher initial costs, extensive green roofs demonstrate total economy over their life cycle, with cost payback of 20 years (Canadian Institute for Climate Choices 2021).

Living wall systems deliver localized cooling benefits, reducing indoor ambient temperatures by an average of 6°C and achieving 18–20 per cent reduction in cooling loads. A study in the United Arab Emirates showed that green walls reduced the energy consumption from peak air conditioning by around 20 per cent and maintained consistently cooler internal surfaces with differences of 4–6°C during peak daytime hours (Haggag and Hassan 2015). Although more expensive — US$288–500 per m^2, with annual maintenance costs of around US$5 per m^2, and paybacks of 13–17 years — green walls increase property values and rental income (Haggag and Hassan 2015).

Together, these interventions demonstrate that urban-scale and nature-based passive cooling investments generate substantial private and public value – lowering energy demand, improving comfort and enhancing urban resilience.

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