The Cold Road to Paris

Mapping Pathways Toward Sustainable Cooling for Resilient People and Economies by 2050

WORLD BANK GROUP

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We appreciate your feedback; all remaining errors and deficiencies are ours.

BACKGROUND REPORTS

CONTEXT	Sustainable Cooling: The Context of a Roadmap. Background Working Paper. (Peters 2019a)
BUILDINGS	Primer for Space Cooling. (ESMAP 2020a) Compendium to the Primer for Space Cooling. (ESMAP 2020b)
URBAN	Primer for Cool Cities: Reducing Excessive Urban Heat – With a Focus on Passive Measures. (ESMAP 2020c)
INDUSTRY	Promoting the Adoption of Green Cooling Technologies and Practices: Insights from Industrial and Commercial End-Users. Background Paper. (IFC 2019)
TRANSPORT	Mobile Cooling: Assessment of Challenges and Options. (Ayres, Stankevich and Diehl 2020)
COLD CHAIN	Cold Chains in Developing Economies: A Techno-Socio-Economic Structural Development Challenge. Background Paper. (Peters 2019b)
RURAL COOLING	Rural Cooling: A Techno-Socio-Economic Structural Development Challenge. Background Paper. (Peters 2019c)
SYSTEMS	Integrated Cooling Systems: Harnessing Synergies and Co-Benefits Across Users, Technologies and Policies. Working Paper. (Heister and Peters 2020)
SUMMARY	Summary of Sustainable Cooling Background Papers. (World Bank 2020)

PREFACE

Cooling merits much greater attention—a fundamental paradigm shift—as a contributor to climate change and essential requirement for achieving multiple Sustainable Development Goals (SDGs) than it has received. The facts speak for themselves.

- Conventional cooling technologies, such as refrigeration, air conditioning (AC), and fans, account for more than 10 percent of fossil carbon dioxide (CO_2) emissions.
- More than 13 new cooling devices are deployed per second, and as the world becomes hotter, a vicious cycle is created as greenhouse gas (GHG) emissions rise along with demand for cooling.
- Despite this, more than 1 billion people face immediate risks from lack of access to cooling, which threatens SDGs for health (e.g., deaths from heat extremes, ineffective vaccines), food security (e.g., food waste due to lack of cold chains), clean energy, labor productivity, sustainable cities, and gender equality.
- Of these, 365 million people live in rural communities, battling extreme poverty and lacking access to water, electricity (SEforAll 2019a), and food cold chains for market connectivity. These conditions will worsen with increasing frequency of heatwaves. Immediate changes are needed across rural areas.
- A recent study suggested that, if global warming continues unchecked, the heat that will come later this century in some parts of the world will bring "nearly unlivable" conditions for up to 3 billion people (Xu et al. 2020).

A portfolio of initiatives is being introduced to reduce demand for cooling and deliver incremental efficiency improvements in cooling technologies. The Global Cooling Prize successfully set a challenge of providing affordable residential cooling solutions that will have less than one-fifth the climate impact of standard residential and room AC units available today and selected two winning teams (Kalanki, Winslow, and Campbell 2021). Countries from India to China and Rwanda to Trinidad and Tobago have published national cooling action plans, which include minimum energy performance standards, and under the banner of "cooling for all," projects are being developed that support marginalized communities by deploying essential cooling solutions for better health, economic development, safe food storage, and basic thermal comfort.

These interventions are essential and must be expanded, but they are insufficient. Given the growth in cooling demand, they will not deliver the required reductions in energy use, emissions, and pollution nor access to cooling for all who need it. In planning for 2050, the goal should be a sustainable cooling economy characterized by net-zero GHG emissions and near-universal access to cooling for all countries and development needs.

Modeling suggests that a "cooling for all" scenario, without accompanying step-changes in energy efficiency and technology interventions (with only business-as-usual incremental improvements), could result in an energy requirement of 19,600 TWh and double projections for cooling demand by 2050 (University of Birmingham 2018a). The projected energy demand volumes could exceed the International Energy Agency's forecast of total solar photovoltaic and wind generation in 2050.

To meet the targets defined in the Paris Climate Agreement and still provide the cooling required under the SDGs, energy consumed per unit of cooling would have to be reduced to about one-third of envisaged levels. The challenge that this represents will, to some extent, vary across sectors, but no sector is proposing a tripling of device efficiency from today's performance levels.

Alongside the simple total demand challenge, the additional stress that growth in universal access to cooling services will place on energy systems (time of use, peak demands, overall volume) must be placed in the context of broader fundamental structural changes to these systems—changes that the transition to renewables from fossil fuels are driving.

- Cooling cities in the Arab Gulf region already consumes more than 50 percent of energy supply in some cases, and 30 percent of total energy at peak times in California is from cooling demand.
- Transport and electrical energy systems are becoming interconnected because electrification is seen as the cornerstone of transport and thermal decarbonization. Cooling accounts for 6.4 percent of passenger transport energy consumption but could grow to 24 percent to 26 percent by 2050 as drive technologies improve, temperatures rise, and warmer regions motorize. This complicates other innovations; for instance, electric vehicles will use an increasingly large portion of battery life for cooling passengers (up to 50 percent for buses in hot regions) and batteries.

In parallel with accelerating the quick wins (e.g., deploying energy-efficient technologies or cool roofs) that can be secured today, we must build longer-term step-change strategies that will provide access to cooling—for thermal comfort, cold chains for food, and health—for those who need it in a warming world while minimizing the environmental impact of cooling. To do this, we must go far beyond incremental changes in energy efficiency technology. Delivering sustainable cooling will involve investing in a radical reshaping of how cooling is provided by designing more ambitious routes to mitigation and management of energy use and cooling demand. This must include:

- Understanding the comprehensive need for cooling.
- Prioritizing how to mitigate cooling demand through behavioral change, low-energy buildings, and cooling-informed design of new cities.
- Ensuring that we have an adequately skilled workforce to design, install, and maintain efficient, clean cooling systems.
- Recognizing the free, natural, and energy-waste resources that are available to help meet demand.
- Defining the right mix of energy sources, natural refrigerants, thermal energy storage, cooling technologies, business models, manufacturing, maintenance regimes, end-of-life management, and policy interventions and then optimally and safely integrating all available energy resources using holistic system approaches.

In short, we must create a sustainable cooling economy through cohesive, integrated, needs-driven, resource-smart, system-level strategies to mitigate the need for artificial cooling and provide access to cooling for all efficiently, cleanly, and sustainably while supporting safe, healthy living conditions and economic growth. This entails, among other actions, defining a new set of incentives and behavior changes that affect individual and organizational decisions—mitigating cooling demand, de-electrifying cooling where possible, storing energy for use on demand, balancing heating and cooling, and transitioning fully from fluorinated to natural or near–zero global warming refrigerants. Many future solutions, including innovative technologies and business models, will take decades to be fully developed at scale and will be contingent on near-term efforts.

This roadmap aims to provide an initial description of a long-term vision for the path to sustainable cooling. It introduces the many associated challenges and opportunities involved, describes the diverse community of actors and institutions to be engaged, provides an outline of actions to be taken now and in coming decades, and lists priority next steps. In doing so, it:

- Recognizes the enormity of the problem that we face when trying to meet the cooling challenges of sustainable development while addressing climate change.
- Describes a systems approach with potential for consensus across the broad portfolio of interventions and delivery partners.
- Aims to sustain the quick wins that we see as possible to achieve today while accelerating the needed step-change innovations and systemic changes so that short-term wins are aligned with long-term ambitions and long-term ambitions do not hamper short-term deliverables.
- Considers the unintended consequences, because it is likely that other parts of socioeconomic and environmental systems will shift as a consequence of cooling. We must plan as best we can for these consequences, identify emerging problems as early as possible, and create the capacity to mitigate anticipated and unforeseen harms as quickly as possible.

This roadmap is a first approach—a suggestion to the global community—to rally around a common vision, namely, to create a sustainable cooling economy by 2050. It is an invitation to take action and meet three goals: help limit global warming to 1.5°C, in line with the Paris Agreement on Climate Change; support the SDGs (and any further goals that may be established after 2030); and help societies prosper, adapt, and become more resilient to climate change.

This roadmap is aspirational, but it also embodies our hope that a roadmap process can and will be used as an instrument to build a global coalition of actors comprising, among others, industry stakeholders, governments, and other enabling organizations that will rapidly embark on the long road toward achieving sustainable cooling by 2050.

CONTENTS

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ABBREVIATIONS

AC	Air conditioning
CAAS	Cooling as a service
CO_2	Carbon dioxide
DFI	Development finance institution
GCF	Green Climate Fund
GEF	Global Environment Facility
GHG	Greenhouse gas
GWP	Global warming potential
HFC	Hydrofluorocarbon
IEA	International Energy Agency
IFC	International Finance Corporation
K-CEP	Kigali Cooling Efficiency Program
MEPS	Minimum Energy Performance Standards
MAC	Mobile air conditioning
MLF	Montreal Protocol Multilateral Fund
NCAP	National cooling action plan
NDC	Nationally determined contribution
ODS	Ozone-depleting substance
R&D	Research and development
SEforALL	Sustainable Energy for All
SDG	Sustainable Development Goal
UNEP	United Nations Environment Programme
WBG	World Bank Group

GLOSSARY

ABSORPTION COOLING

a process in which heat is used to drive a chemical cooling process through evaporation of a solvent that is absorbed (or adsorbed) by another medium and recovered with heat; also referred to as sorption cooling and refrigeration.

CHILLER

large machine that cools a process fluid (usually chilled water) which is distributed throughout a residential, commercial or industrial facility for the purpose of air conditioning, refrigeration and/or process cooling. Mechanical chillers use the vapor compression cycle whereas absorption chillers are powered by a heat source and operate without moving parts. Air-cooled chillers usually have a capacity of up to 300 tons of refrigeration and water-cooled chillers are preferred for capacities above 400 tons.

CLEAN COOLING

process or situation which delivers resilient access to cooling efficiently and sustainably without environmental damage and negative climate impact with the optimal use of natural and thermal resources throughout the lifespan of the cooling system; often used interchangeably with sustainable cooling (Peters and Chasserot n.d.).

CLIMATE ADAPTATION

process of adjusting to current or expected climate change and its impacts (Box 5).

CLIMATE CHANGE FEEDBACKS AND TIPPING POINTS

natural iterative processes that speed up or slow down a warming trend (feedback loop); critical thresholds which, when exceeded, can lead to accelerated and irreversible impacts (e.g., melting permafrost leads to release of large quantities of greenhouse gases).

COLD CHAIN

temperature-controlled supply chain involving a sequence of refrigerated production, pre-conditioning, storage, transportation and distribution activities and associated equipment and logistics designed and operated to maintain the quality and safety of temperature-sensitive products from point of production to final consumer.

COMMUNITY COOLING HUBS

integrated data-driven systems approach to meet a community's cold chain and wider cooling needs related to food, health, thermal comfort and safety in a highly accessible, efficient, affordable, resilient and economically, socially and environmentally sustainable manner (University of Birmingham 2019).

COOLING

any natural phenomenon, human activity, design, or technology that extracts heat or reduces temperatures and helps achieve reasonable thermal comfort for people, preservation of products and produce (medicines, food), or effective and efficient processes (data centers, industrial, agricultural production).

COOLING AS A SERVICE
delivers cooling to customers who pay for the service on the basis of the amount of cooling they actually use. A third party usually sells the service, funds capital, infrastructure and maintenance costs, and makes investment decisions based on lifecycle costs rather than equipment purchase price.

COOLING CENTER
cool site or air-conditioned facility designed to provide relief and protection during periods of extreme heat.

COOLING ECONOMY
an economy in which human activities critically depend on access to reliable, sustainable forms of cooling for enhanced productivity, health, safety, and comfort.

COOLING EFFICIENCY
effectiveness of converting energy into cooling, usually measured as the ratio of cooling output (in British thermal units) to energy input (in Watt-hours).

COOL ROOFS
designed to reflect more sunlight and absorb less heat than standard roofs thereby reducing the need and demand for cooling within a building.

DEMAND-SIDE MANAGEMENT
activities, including financial incentives and behavioral change through education, designed to encourage consumers to modify their level and pattern of electricity usage; often mandated by governments and implemented by electric utilities.

DIRECT EMISSIONS
greenhouse gases emitted at the site of—and directly caused by—the installation, maintenance, operation or disposal of cooling equipment; usually refrigerants and in some cases fossil fuel-related emissions from operating a cooling unit (e.g., in mobile applications).

DISTRICT COOLING
centralized production and distribution of cooling, typically delivered as chilled water via underground pipelines, to cool residential, commercial and office buildings within an urban district.

ENERGY-EFFICIENT BUILDINGS
buildings that are efficient in their use of energy and have reduced thermal loads through better site planning, building design, construction (or renovation), integrated building systems and processes that support longer-term efficient operation and maintenance.

ENERGY SERVICE COMPANIES
businesses that provide services with the aim of saving energy and improving energy efficiency.

ENERGY-SYMBIOTIC COOLING SYSTEMS
cooling systems that are integrated with the wider energy and environmental system.

GLOBAL WARMING POTENTIAL
measure of the global warming impact of atmospheric gases relative to carbon dioxide, which has a global warming potential of 1. Many refrigerants have a global warming potential of 1,000 and higher.

GREENHOUSE GAS
naturally occurring or anthropogenic gases that absorb and emit radiant energy at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. Anthropogenic greenhouse gases cause global warming.

HEAT (DATA) MAPS
a data visualization technique that shows the magnitude of a phenomenon through color-coding in two dimensions.

HYDROFLUOROCARBONS (HFCS)
fluorinated gases that are commonly used as refrigerants to replace ozone depleting hydrochlorofluorocarbons (HCFCs). Many HFCs are potent greenhouse gases that are being phased down by the Kigali Amendment to the Montreal Protocol (Box 1).

INDIRECT EMISSIONS
greenhouse gases emitted at a distant location and indirectly caused by powering and operating cooling equipment; usually emissions from a grid-connected fossil fuel power plant.

LIQUID AIR
air that is liquefied at minus 196°Celsius at atmospheric pressure. Re-gasification causes volume expansion, which can be used to drive a turbine or engine, and gives off usable, high value cold. Liquid air can be used to store energy.

LIVING LABS
in-field facilities to test and demonstrate a technology or process and train and support in-field experts; often linked to a research and technology center.

LOCK-IN
situation in which decisions and their long-term effects (e.g., emissions from installation of inefficient cooling equipment) are difficult or impossible to reverse, for example due to long equipment lifetime or market dominance of a technology for which better alternatives exist or may emerge.

MECHANICAL COOLING
devices that meet cooling loads through a mechanical process, in particular through vapor compression technology.

MINIMUM ENERGY PERFORMANCE STANDARD
policy tool that sets an energy efficiency floor for appliances.

MOBILE AIR CONDITIONING, MOBILE REFRIGERATION
devices that provide comfort cooling to passengers in vehicles or cooling for perishable goods in mobile applications; collectively referred to as mobile cooling.

MONTREAL PROTOCOL
international agreement to phase-out ozone depleting substances (Box 2).

KIGALI AMENDMENT
expands the Montreal Protocol to phase down hydrofluorocarbons (Box 1).

NATIONAL COOLING ACTION PLAN

a document, typically issued by a government, that describes strategies and actions to be undertaken to promote sustainable cooling practices (K-CEP n.d.4).

NATIONALLY DETERMINED CONTRIBUTION

formal submission by a Party to the Paris Agreement representing that Party's climate plans and actions to meet the agreement's temperature goals, including climate-related targets, policies and measures a government aims to implement in response to climate change and as a contribution to global climate action.

NET-ZERO GREENHOUSE GAS EMISSIONS

describes a situation where emissions and absorption of greenhouse gases from the atmosphere (by a sector, country or globally) are in quantitative balance (i.e. no anthropogenic greenhouse gases are added to the atmosphere). Absorption can be either through natural processes (reforestation) or through mechanical capture and storage.

OZONE-DEPLETING SUBSTANCES

chemicals that destroy the protective atmospheric ozone layer such as chlorofluorocarbons and hydrochlorofluorocarbons used in refrigerants.

PARIS AGREEMENT

legally binding global climate treaty adopted by 195 countries in December 2015 (in force since November 2016) within the United Nations Framework Convention on Climate Change. The agreement aims to hold the increase in global temperature to well below 2°C above pre-industrial levels while pursuing efforts to limit the temperature increase to 1.5°C. Also referred to as Paris Climate Agreement or Paris Agreement on Climate Change.

PASSIVE COOLING

systems that use building components and natural solutions (insulation, cool roofs, trees, water) to provide a cooling effect without using energy, as opposed to active cooling systems that use energy for cooling.

PHASE-CHANGE MATERIALS

substances that absorb or release significant quantities of heat or cold energy when they change phase. A basic phase change material is water, which absorbs heat as it changes phase from solid (ice) to liquid (water) and to gas (water vapor).

REBOUND EFFECT

describes a reduction in expected gains from a more energy efficient technology due to behavioral and systemic responses to improvements. For instance, lower energy consumption (and operating costs) can lead to increased use of cooling.

REFRIGERANT

substance used to transfer heat from inside a cooled compartment to the outside environment; typically a gas used in a vapor compression cycle.

ROADMAP

a coherent, prioritized, timebound plan that strategically organizes and allocates actions to achieve agreed-upon objectives.

ROOM AIR CONDITIONER

a small air conditioning unit used to cool a single room, normally with a vapor compression-based cooling capacity of up to 15 kilowatts or 4.5 tons of refrigeration.

RURAL COOLING

providing access to cooling in rural areas to meet the needs of rural populations for a variety of cooling applications.

SPACE COOLING

refers to the means that provide thermal comfort by maintaining the optimum temperature, humidity, and ventilation within the built environment.

SUSTAINABLE COOLING

cooling without negative climate and environmental impacts, in line with the objectives and targets of the Paris Agreement, Kigali Amendment and other relevant international agreements; often used interchangeably with "clean cooling" (defined above).

SUSTAINABLE COOLING EQUIPMENT

has a significantly lower environmental impact than current practices through a combination of reduced energy use and more climate-friendly refrigerants, thereby meeting or exceeding national and/or internationally agreed objectives and targets (Montreal Protocol, Paris Agreement) and contributing to the long-term goal of achieving sustainable, clean cooling. Also referred to as efficient, clean cooling system.

SUSTAINABLE COOLING INTERVENTIONS

actions that a country or government can take to regulate cooling and promote, support, encourage, or achieve sustainable cooling.

SUSTAINABLE DEVELOPMENT GOALS

adopted in 2015 as part of the United Nation's 2030 Agenda for Sustainable Development with the aim of providing a universal framework to "end poverty, protect the planet and ensure that all people enjoy peace and prosperity". Cooling is relevant to the majority of the Sustainable Development Goals (Table 3).

SUSTAINABLE SPACE COOLING

achieving human thermal comfort within buildings through energy-efficient building design, efficient cooling technologies and practices, and more climate-friendly refrigerants that collectively have a significantly lower environmental impact than current practices and are in line with or exceed national and/or internationally agreed objectives and targets (Montreal Protocol, Paris Agreement) and contribute to the long-term goal of achieving sustainable, clean cooling.

THERMAL COMFORT

condition of mind which expresses satisfaction with the surrounding thermal environment and is assessed by subjective evaluation (American Society of Heating, Refrigerating and Air-Conditioning Engineers, https://www.ashrae.org/technical-resources/authoring-tools/terminology).

THERMAL SYMBIOSIS

use of waste thermal streams from one process to provide valuable thermal energy to another process, thereby replacing primary energy consumption (e.g., use of waste heat from air conditioning to heat water).

THINKING THERMALLY

a holistic approach to energy systems that focuses on understanding thermal needs and developing the most efficient pathway to satisfying them; requires exploring available thermal energy sinks and sources and integrating solutions that store energy thermally.

TRANSPORT REFRIGERATION (UNITS)

maintaining goods at lower than ambient temperatures whilst they are in transit. Vehicles and containers for transport refrigeration.

TRI-GENERATION

process by which heat from an electricity and heat-producing plant (cogeneration) is used to generate chilled water using sorption cooling technology; also known as combined heat, power, and cooling.

URBAN HEAT ISLAND

urban area of significantly warmer temperatures than nearby rural areas due to human activity (e.g., heat-absorbing buildings, pavements, lack of vegetation, heat from energy use).

VAPOR COMPRESSION CYCLE

moves heat in a closed-loop cycle by compressing a refrigerant, shedding the resulting heat to the environment, and expanding the refrigerant to provide cooling. The main functional components of this globally dominant refrigeration and air conditioning technology are evaporator, compressor, condenser, and expansion valve.

WASTE COLD

cold energy released from processes or present in the natural environment, but unused and therefore regarded as a waste (or free) thermal resource.

WET-BULB TEMPERATURE

the lowest temperature to which air can be cooled by evaporation of water into the air at a constant pressure.

WHOLE-SYSTEMS APPROACH

a planning approach that integrates purposes, needs, impact-driven solutions and business models as well as socio-economic, political, and technical frameworks to accelerate deployment of sustainable cooling and cold chains.

“THE WORLD IS OFF-TRACK TO MEET THE 1.5°C OBJECTIVE OF THE PARIS AGREEMENT”

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EXECUTIVE SUMMARY

The world is off-track to meet the 1.5°C objective of the Paris Agreement. Without a radical change in global emissions mitigation, the world is heading for a 3.2°C increase in temperature by the end of this century (UNEP 2020, IPCC 2021). The rapid surge in demand for cooling resulting from this temperature rise will create a vicious cycle wherein rising temperatures will increase demand for cooling, which will increase use of energy and refrigerants, thereby increasing greenhouse gas (GHG) emissions and in turn further increasing temperatures.

The world is also off-track to meet the Sustainable Development Goals (SDGs) and adapt to rapidly increasing temperatures due to climate change (UN 2020b). Cooling does not solely address thermal comfort in residential buildings. Lack of cooling, combined with unreliable energy supply, can also hamper children's access to routine immunization; lead to severe decreases in economic productivity in sectors such as agriculture, construction, and manufacturing; and result in work-hour losses as high as 12 percent in the worst-affected regions and food loss of up to 40 percent in some markets. Rural communities are already experiencing severe impacts, and it is expected that this will continue in the absence of immediate changes, requiring greater access to cooling. The goal must be to ensure that basic needs are met for all in a warming world and within the limits of natural resources while mitigating future threats.

A paradigm shift is needed to achieve sustainable cooling—one premised on a clear vision and consistent plan of action by many partner organizations and governments on how to provide affordable access to clean cooling for all with minimal climate impact. Piecemeal improvements, pursued in conventional technological and organizational silos, will not be sufficient to reach this goal. Achieving sustainable cooling requires a global roadmap to enable fuller understanding of the multifaceted, complex consequences of cooling, raise awareness, integrate key stakeholders, and plan and coordinate actions on a global scale. Achieving sustainable cooling is a multidimensional, multisectoral challenge that will require us to address the interdependencies between economic, energy, technological, social, and political systems and devise the policies to address them.

This roadmap provides insights into the relationship between cooling and already-agreed-upon climate and development goals; presents the barriers, critical step-changes, and solutions needed to accelerate innovation and transformation; proposes aspirational targets and actions for each decade with the aim of achieving net-zero GHG emissions from cooling applications by 2050; considers financing solutions; and suggests a framework for governments and the global cooling community to take action.

THE COOLING COMMUNITY

Most of the thinking around cooling needs has been based on specific sectors and applications, including greater efficiency of air conditioning (AC) equipment for buildings, industry, and mobile needs; urban planning to reduce urban heat islands and protect residents from extreme heat events; building design and regulation to reduce cooling needs; and cold chains for health care and agriculture. This sector-specific focus has defined user communities and most solutions but will not be sufficient to meet climate and sustainability goals. A coordinated approach is needed and must be integral to responding at scale to meet the cooling challenge.

The global cooling community is as diverse as the range of cooling needs and solutions, which presents a challenge and an opportunity. It will be an immense challenge to bring together the different sectors and parties—many of which have entrenched views and interests—around a global roadmap, but there are also great opportunities to build on the many sources of knowledge, technical assistance, inventiveness, entrepreneurship, innovation, finance, policies, and political processes that can be deployed to meet the sustainable cooling challenge.

The Montreal Protocol community of companies, governments, international organizations, and others has been working together for decades and addressed the ozone-depleting refrigerant problem; and some highlighted the cooling challenge in addressing climate change. Since the adoption of the Kigali Amendment to the Protocol in 2016, several initiatives have sprung up to advocate and build knowledge foundations for and promote solutions toward sustainable cooling; these initiatives include the Kigali Cooling Efficiency Program (K-CEP), the United Nations Environment Programme (UNEP) Cool Coalition, the Sustainable Energy for All "Cooling for All" initiative, and the Global Cooling Prize. The climate community has become aware of the potential of cooling, with some governments (e.g., India) already working to implement national cooling action plans (NCAPs), although a broadly coordinated community organized around a global roadmap to guide implementation of the measures needed over the next three decades has not emerged.

ISSUES AND APPROACH

To design a roadmap requires consideration of the goals, potential solutions, critical step-changes enabling innovations and interventions, framework conditions, and barriers. The diversity of cooling markets and applications is reflected in the wide range of barriers and the correspondingly large number of categories of actions to address them. These barriers include the higher first cost of more efficient equipment; lack of consumer awareness of efficient cooling solutions; lack of skilled technicians for operation and maintenance; behavioral challenges such as the "rebound" effect; weak policy environments in the form of codes and standards; domination of large market segments by a small number of insufficiently dynamic global companies; and insufficiently understood and managed linkages between the many needs for cooling, cooling demand and resulting energy consumption, and unique challenges in some sectors, such as mobile AC.

A diverse range of actions has been proposed to overcome these barriers—actions that must be sequenced appropriately to be effective. Many future solutions, including innovative technologies and business models designed to meet roadmap targets, have long lead times and may take decades to develop fully and expand beyond what is currently considered feasible (e.g., IEA 2018), but most depend on near-term efforts, as well as a prompt start by a range of actors to create knowledge, build capacity, develop plans and policies, innovate, and generally prepare. The proposed roadmap actions fall into the following categories of interventions:

- **Dramatic improvements in technology and innovation** to achieve climate and universal access goals and identify solutions that do not depend on electricity.
- **Business models** that help overcome the higher initial cost of more efficient equipment and facilitate access by the rural and urban poor.
- **Policy reforms** to encourage accelerated innovation and market transformation by, among others, calling for performance standards to be strengthened rapidly but predictably.
- **Public and private finance** to support new technologies, expand successful business models, and support urban development and cooling action plans.
- **Capacity building** to help governments, businesses, and consumers understand and address cooling challenges, encourage solutions, and develop the skilled workforce that will be needed to install and maintain the growing number of cooling devices so that they operate efficiently and safely.

Systems approaches must be applied to development and implementation of sustainable cooling solutions to ensure that demand for cooling is minimized through passive measures and behavioral changes, and to manage cooling systems and energy systems to smooth load curves and create more room for intermittent renewable energy sources. These sustainable cooling solutions should also make full use of waste, free, and low-grade thermal energy sources and heat sinks; combine cooling loads from many diverse users into a single cooling system; and harvest social, economic, and environmental co-benefits wherever possible, including by integrating sustainable cooling into productive human activities.

COOLING AND SUSTAINABLE DEVELOPMENT

Adopted in 2015, the SDGs set out 17 targets promoting a sustainable future to be met by 2030. Providing access to sustainable cooling is crucial to meet many of the SDGs, as well as to ensure resilience for economies and populations and mitigate and adapt to climate change. These synergies are so strong that a comprehensive understanding of the role of cooling in meeting the SDGs in each relevant sector is a prerequisite for development of a cooling roadmap.

The need for vaccine cold chains to fight the COVID-19 pandemic is only the most recent example of the challenge of meeting the SDGs. The role of food cold chains in limiting food loss, supporting rural economies, and decreasing malnutrition is increasingly being recognized. Correctly managed, food cold chains can provide access for all to a safe, nutritious diet and reduce hunger while raising incomes for small farmers and those engaged in the fishing industry and reducing absolute and relative poverty. But increasing cooling to meet the SDGs must be done sustainably, without increasing GHG emissions (e.g., by lowering mechanical cooling demand, using passive cooling technologies and highly energy-efficient equipment, harnessing waste and free thermal resources and renewable energy, including in off-grid situations, avoiding GHG-intensive refrigerants, and changing behaviors).

The implications for energy systems, climate change, human well-being, and productivity of providing cooling are not sufficiently understood. Most discussions have focused on room AC equipment, without considering the full diversity of cooling needs and the holistic approaches necessary to make access to sustainable cooling part of bigger solutions. For instance, in India, 80 percent of economically active women work in agriculture (OXFAM 2018), so post-harvest food loss due to lack of cold chains hinders gender equality and rural women's empowerment. Cooling needs assessments, which link cooling to SDG targets, can help raise awareness of the contribution that cooling can make. Likewise, if the needed scale of cooling is underestimated, it can decrease ambition in policy, infrastructure, and technology development and have far-reaching social, economic, and environmental consequences.

ROADMAP OVERVIEW

This roadmap aims to connect actions with goals: bring GHG emissions from cooling applications in line with climate goals, adapt to increasing climate heat, and recognize the role of cooling in achieving the SDGs. These goals and related targets are not perfectly aligned, but they are reconcilable in a sustainability framework. Although the roadmap proposes reducing electric power use for cooling, it cannot resolve the inherent conflict between its net-zero GHG emissions target from cooling by 2050 and the impact that failure to decarbonize grid electricity could have on cooling sector emissions.

The roadmap uses a number of principles to organize and sequence proposed actions, in particular, the importance of time lags and preparing for future actions; avoidance of locking in future emissions because of inaction today; opportunities and urgency to generate quick, low-cost results; the need to reach scale to lower costs and generate transformational impacts; and the time it will take to bring cooling to remote, off-grid locations and solve difficult technological challenges.

Background reports that covered the four broad areas of cooling demand informed the construction of the roadmap: thermal comfort for living, learning, and working; food security and production; health services, safe storage, and transportation, including of vaccines and medicines; and industrial cooling and energy use. Accordingly, research reports for several user groups were prepared on buildings and space cooling, cooling and urban development, industrial and commercial cooling, cooling in transport, food and vaccine cold chains, and rural cooling. Each background report considered conditions in a sector and proposed a variety of actions to meet current and future cooling demand sustainably.

Taking a high-level perspective, the roadmap organizes typical, step-change interventions into three roadmap decades of action, from 2020 through 2050, and proposes road mark targets for the end of each decade as a measure of progress. These road marks should be understood as notional examples illustrating the type and scope of progress needed and must be further considered and discussed with stakeholders and modified in future versions of the roadmap.

“THE GOAL MUST BE TO ENSURE THAT BASIC NEEDS ARE MET FOR ALL IN A WARMING WORLD.”

THREE DECADES OF ACTION

PHASE 1 (2020-2030)

is characterized as the decade of readiness and quick results that emphasizes low-cost and high-impact opportunities, as well as measures to promote preparedness and avoid lock-in. During its first phase, the roadmap encourages actors to take time lags and innovation lags seriously and invest in cooling-informed planning and capacity. The need for early and urgent strategic actions to reduce short-term global warming rapidly in this decade is also recognized, with the aim of plateauing GHG emissions from cooling while avoiding lock-in of future GHG emissions from long-lived high-emission equipment and infrastructure decisions that increase future demand for cooling (e.g., urban expansions that increase heat in cities). Phase 1 also prepares the pathway for actions and scale-up investments in the subsequent roadmap phases and urges quick action to strengthen the vaccine cold chain in response to the COVID-19 pandemic.

PHASE 2 (2030-2040)

is the decade of market transformation and expansion. In addition to further measures to promote preparedness, this phase emphasizes access to cooling, food cold chains, and rural cooling and expanding clean space cooling. For the first time, a significant decline in GHG emissions will be achieved, and the knowledge and experience obtained from Phase 1, along with advocacy, advisory, and planning achievements, will enable policy actions and investments that lead to expansion of highly energy-efficient, low-GWP, clean cooling solutions. This phase will also see sustained introduction of food cold chain logistics into agricultural areas, which will benefit rural communities, protect health and livelihoods, and support productive economies for billions of people. This phase will require significant financial resources because of the large size of the cooling market and potentially higher-cost technologies being deployed, as well as strong public commitment and engagement to bring cooling to rural communities.

PHASE 3 (2040-2050)

will see the emergence of a sustainable cooling economy in which human activities will have access to reliable, sustainable forms of cooling for enhanced productivity, health, safety, and comfort. Full access to cooling for all who need and depend on it will be realized in Phase 3. Smart urban and rural design, zero-energy buildings, emissions-free mobile cooling, new technologies, and systems thinking will come together. The thermal energy symbiosis (e.g., tri-generation of power, heat, and cooling) will enable highly efficient cooling systems, combined with the use of renewables and waste thermal resources, to achieve net-zero GHG emissions by 2050. Phase 3 aims to be visionary with respect to proposed activities and in terms of achieving the net-zero emissions target from cooling sectors (while allowing for offsets) but not more so than the Paris climate goals, which are visionary and necessary.

FINANCE

Financing—from private and public sources—is a critical need in all cooling sectors and markets, particularly to overcome the first-cost barrier and support research and development (R&D), early-stage innovation, and business models that facilitate affordable universal access. The potential economic gains are large. For instance, the International Energy Agency Efficient Cooling Scenario is based on commercial adoption of more-efficient cooling equipment (at initially higher costs) that will produce net savings of almost USD3 trillion from 2017 to 2050. Public and private financing of early-stage technologies has been shown to be successful in the case of solar and wind technologies, yet only an estimated 0.04 percent of official development assistance is directed at cooling solutions.

Financial needs, challenges, and opportunities vary greatly across cooling sectors; applications; jurisdictions; and private, commercial, and public users. It is important to evaluate the financial settings within which sustainable cooling solutions are being planned to determine associated costs and benefits, as well as implementation and financial strategies. For instance, food cold chains and community cooling hubs can be commercially profitable and may have access to private financing, whereas cities may find it difficult to finance the mitigation of urban heat and sustainable cooling investments that benefit the general public. Several innovative business models have shown promise for meeting financial needs, such as cooling-as-a-service (CaaS) schemes and public bulk procurement (Dreyfuss et al. 2020; SEforAll 2018; 2020).

Awareness of the importance of cooling has grown among development finance institutions and philanthropic organizations (notably the Kigali Cooling Efficiency Program (K-CEP)), and greater attention has been paid to financing sustainable cooling interventions (e.g., from climate finance sources such as the Green Climate Fund (GCF)), although action to coordinate diverse sources of finance to encourage energy efficiency improvements in cooling equipment while phasing down hydrofluorocarbon refrigerants is urgently needed.

ROADMAP IMPLEMENTATION

A roadmap for sustainable cooling will necessarily evolve in stages, with increasing awareness, knowledge, support, and policy interventions driving technology research, new business models, capacity building, and greater integration of thermal demands into energy strategies. It will further require an ongoing flexible process to accommodate lessons learned and changing conditions.

There is no one-size-fits-all solution. Everyone will require cooling, although adaptation targets, priorities, goals, risk of heat impacts, and cooling demand will vary considerably across countries. As a starting point, countries must undertake robust needs assessments to better understand their capacity and cooling demand and to inform their cooling strategies and NCAPs (SEforAll 2019b; K-CEP n.d.4).

Recognizing the need to engage a broad cooling community is the starting point for implementation. The long-term benefits of sustainable cooling are clear but are not served by short-term commercial interests or by governments maximizing political support by sidestepping burdensome policies, which combined can lead to suboptimal noncooperative outcomes (e.g., market failure, unsustainable development).

Delivering a systems approach to cooling demand calls for establishing a common viewpoint on shared goals, coordinating delivery partners, fostering collaboration between government and industry, formulating policy supported by finance, influencing academic research, pushing innovation, developing new business models, and adopting systems solutions at scale.

The roadmap identifies the types of stakeholders and actors that must come together to implement proposed actions. To implement the roadmap, the global cooling community must take at least the following five steps.

- Reach agreement on a roadmap, its goals and targets, and priority interventions.
- Develop specific, detailed action plans (e.g., for countries and sectors).
- Assign roles to stakeholder actors and institutions and define the timeframe.
- Develop a tracking system for monitoring, assessing, and reporting on progress and challenges.
- Assign responsibility and a timeframe for revising the roadmap and related action plans.

As the landscape changes, it will be important to update and refine the roadmap and related action plans regularly. These updates must be linked to other international processes, such as the nationally determined contribution (NDC) process under the Paris Agreement, increasing levels of climate ambitions, adjustments to the Kigali Amendment, and possible revision of the SDGs after 2030.

The roadmap can be set up to facilitate agreements among stakeholders, including the cooling industry, national governments, and enabling organizations, who all stand to reap long-term benefits from co-operating on its implementation. These benefits are interdependent and include growth and access to new customers and markets from cooling-for-all programs for the cooling industry, enhanced resilience to climate change, socioeconomic development and co-benefits for developing countries, and increasing investments in poverty alleviation and global climate change mitigation and adaptation for development institutions (and their donors).

KEY CONCLUSIONS AND NEXT STEPS

This report came to conclusions, makes recommendations, and encourages urgent next steps that the cooling community may want to consider independently of the specifics of this roadmap. Some of these are:

SUSTAINABLE COOLING CHALLENGE

As we transition to renewable energy, it is important to recognize that cooling is essential to achieving development goals and is a rapidly growing contributor to energy demand. The barriers to achieving sustainable cooling by 2050 are high, and a hotter climate and economic growth will make them higher. A transformation in thinking, technologies, and business models is required to ensure that cooling can help meet global climate and sustainable development goals.

SIZE OF THE CHALLENGE

Partly because of the lack of adequate data, little work has been performed but is urgently needed to quantify the potential cooling volumes that will be required, and the associated energy demands and environmental impacts. We must learn the costs of delivering more efficient cooling and meeting the requirements of the SDGs and access to cooling for all while reducing GHG emissions from cooling to net-zero.[1]

SYSTEMS THINKING

A sustainable cooling economy will be possible only with much greater effort to promote holistic solutions and aggregate end uses to facilitate commercial scale. A systems approach calls for understanding and consideration of the interdependencies among highly intertwined economic, social, political, and environmental systems and the dynamic impacts that decisions made within the cooling sectors have on these elements.

1 • One exception to this is the modeling work that University of Birmingham (2018a) has undertaken.

THINKING THERMALLY

Solutions and strategies will require more than increasing the efficiency of electrically driven (vapor compression) technologies and renewable electricity generation. In a broad sense, thinking thermally first requires understanding the multiple cooling needs of urban and rural communities; the size, location, and availability of free, waste, and wrong-time energy resources; and system interdependencies. Then the right mix of novel energy vectors; thermal stores; efficient, clean cooling technologies; and novel business models and policy interventions to integrate these resources through optimized systems of systems must be defined. To think thermally requires taking a systematic seven-stage approach to cooling: planning cold, making cold, storing cold, moving cold, using cold, managing cold, and financing cold.

SUPPORT FOR INNOVATION

Technological innovation is essential for meeting many of the medium- and longer-term objectives of sustainable cooling but is among the most difficult activities to finance. Building on experiences with, for instance, the Global Cooling Prize and past successes in financing of renewable energy R&D, governments, in partnership with the cooling industry and other sources of innovation, should invest more to create the transformative cooling technologies and innovative business models needed to address the sustainable cooling challenge.

NEED FOR LEADERSHIP

Because the cooling industry is global and local, many solutions must be country specific yet coordinated internationally. Government leadership is required because governments can promote efficient cooling products and systems through policy reforms, such as labeling and minimum energy performance standards, bulk procurement of efficient equipment to decrease prices, and training programs for skilled technicians. NCAPs and inclusion of cooling in NDCs can help with international coordination and merit greater support.

COALITION OF ACTORS

As a first approach, this roadmap can be used to engage cooling stakeholders in discussions on goals, pathways, and actions toward a sustainable cooling economy by 2050. It can also be used to begin building the coalition of actors and commitments necessary to implement the vision of a global sustainable cooling roadmap. Organizations with the networks and interest to take on this challenge already exist in the global cooling community.

ONE

World Bank Group

THE COOLING DILEMMA

The world is off-track to limit global warming to 1.5°C and meet the objectives of the Paris Agreement. As reported in the United Nations Environment Programme (UNEP) 2020 Emissions Gap report (UNEP 2020), global emissions have continued to increase over the past 10 years, and even if all current unconditional commitments under the Paris Agreement are implemented, temperatures are expected to rise by 3.2°C by the end of the century, bringing even wider-ranging and more severe climate impacts.[2] Without near-term mitigation actions and strong commitments, there is a high likelihood that 4°C warming will be reached or exceeded this century, and there is a 10 percent chance of exceeding 5°C by 2100 (WBG 2014). Global action is therefore urgently needed. Collective ambition indicated by nationally determined contributions (NDCs) must be more than five times as high as current levels to deliver the greenhouse gas (GHG) emission cuts needed over the next decade for the 1.5°C goal to be reached (IPCC 2019, 2021; UNEP 2020).

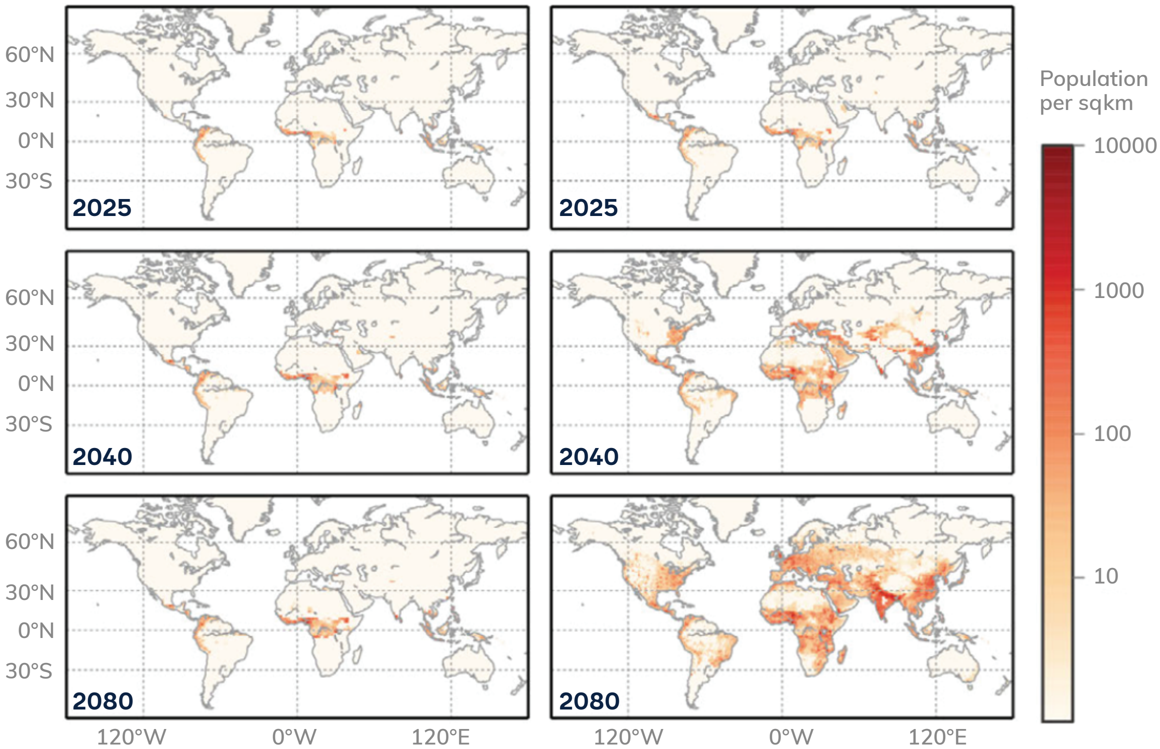
With current policy efforts, there is a significant threat of extreme heat. If global warming reaches 4°C, it is expected that 60 percent of the global land surface will be exposed to unusually high heat extremes by the end of the century. At 2°C warming, approximately 20 percent of the global land surface and tropical areas in South America, Africa, and Southeast Asia, where heat extremes are rare, will be exposed to unusually high heat extremes by the end of the century. Already in the 2020s, policy directions leading to 2°C warming will affect populations exposed to heat extremes differently than those leading to 4°C warming. With a 4°C scenario, it is anticipated that about 17 percent of the world's population (living mostly in the tropics) will experience unusual summer temperatures by 2025. By 2040, this increases to 50 percent (mostly in densely populated areas in Southeast Asia, the Americas, and the Mediterranean). By 2080, it is expected that 96 percent of the world's population will experience unusual summer temperatures and that 71 percent will experience unprecedented extreme temperatures. In a 2°C scenario, it is anticipated that about 11 percent of the world's population (living mostly in the tropics) will experience highly unusual summer temperatures by 2025 and about 25 percent by 2080 (Figure 1) (WBG 2014, 13). Both these scenarios present significant challenges to health, food security, and livelihoods. The shocks and stresses of increased warming will undermine current poverty reduction efforts and push new groups into poverty.

Climate change will also significantly increase humidity. Ambient humidity is an important aspect of cooling because high humidity limits water evaporation, reducing the body's ability to cool by shedding heat through perspiration. A wet-bulb temperature of 35°C marks the upper physiological limit for humans, but serious health and productivity impacts can occur at much lower values. Weather station data show that some subtropical locations have already reported wet-bulb temperatures of 35°C and that the frequency of extreme humid heat has more than doubled since 1979 (Raymond, Matthews, and Horton 2020).

2 • The COVID-19 global pandemic has caused a short-term decline in emissions, but there is considerable uncertainty as to whether this is simply a short-term blip or signals a gradual longer-term reduction (UN 2020a).

In the tropics and parts of the mid-latitudes, the frequency of extreme wet-bulb temperature events may increase by a factor of 100 to 250 (about double the frequency change projected for temperature increases alone) (Coffel, Horton, and de Sherbinin 2018). By 2080, there may be 150 million to 750 million person-days of exposure to wet-bulb temperatures higher than those seen in today's most severe heat waves, and wet-bulb temperatures above 35°C could exceed 1 million person-days. The regions that are expected to be the most affected, such as West Africa and northeast India, have limited cooling infrastructure and low levels of climate adaptability. The increase in temperature and humidity poses a severe threat to human health and productive activities outdoors, such as agriculture and energy infrastructure.

FIGURE 1: World Population Experiencing Unusual Summer Temperatures in a 2°C and 4°C World



Source: WBG 2014.

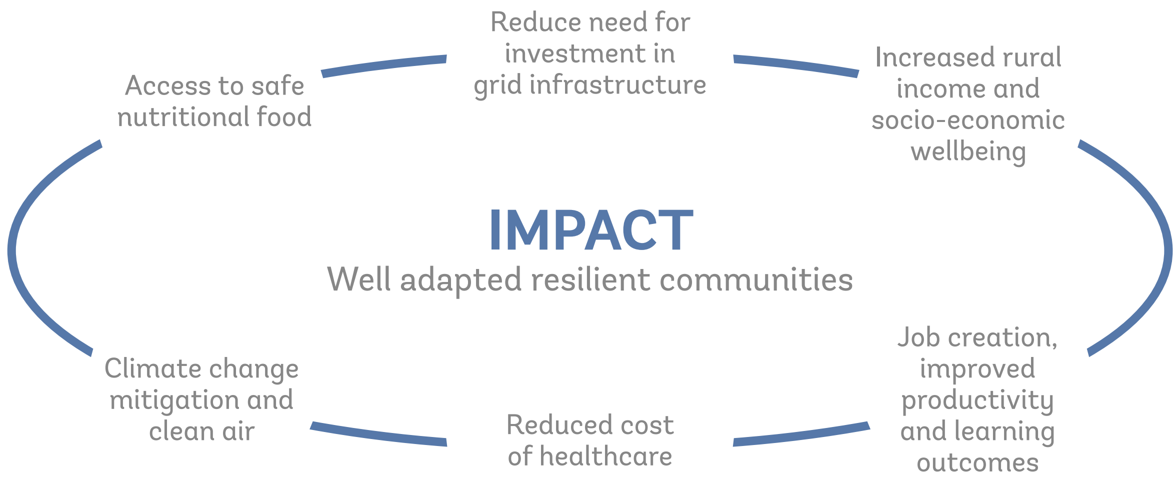
COOLING AND CLIMATE CHANGE

Cooling is of particular importance to this agenda because business-as-usual cooling creates a vicious cycle: as the world gets hotter and more humid, greater demand for cooling—such as air conditioning (AC), refrigeration, food and medical cold chains—increases GHG emissions, which in turn increase temperatures and make access to cooling even more critical. Access to sustainable, clean cooling is crucial because it can ensure that increasing energy demands are met in ways that help lift people out of poverty and boost their prosperity without further endangering them by increasing heat impacts of rising emissions.

Climate-friendly cooling, defined as cooling with low-global-warming-potential (GWP) refrigerants and very efficient equipment, whose potential is largely untapped, can help meet GHG mitigation goals. A warming world will increase use of cooling equipment, including cold chains to ensure food safety, refrigeration for vaccines, cooling of data centers, and ensuring comfort and productivity in homes, institutions, and workplaces.

Clean cooling involves providing resilient cooling to all who need it while limiting environmental damage and climate impacts. Cooling that is sustainable and resilient will support well-adapted, resilient communities (Figure 2). It necessarily incorporates thinking to mitigate demand for mechanical cooling where possible and ensure minimized, optimal use of natural resources, design for circularity, and repurposing of waste heat and cold (thermal symbiosis)[3] throughout the lifespan of the cooling system. Clean cooling meets cooling needs while helping achieve society's goals for GHG reduction, climate change mitigation, natural resource conservation, and air quality improvement. Likewise, it must be accessible, affordable, financially sustainable, scalable, safe, and reliable in order to deliver the societal, economic, and health goals of the United Nations Sustainable Development Goals (SDGs).

FIGURE 2: Effect of Sustainable Cooling: Resilient Communities



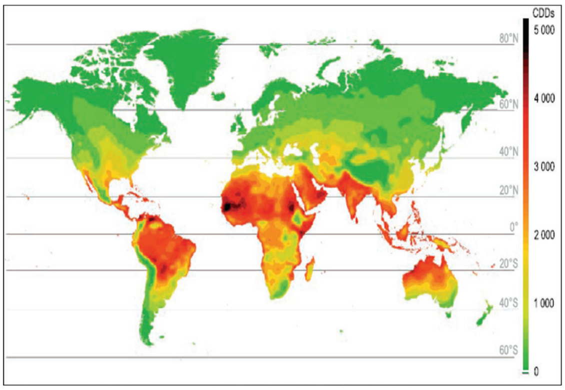
3 · Examples of thermal symbiosis include harnessing the waste heat of a supermarket chiller cabinet to provide hot water, using industrial waste heat to drive sorption cooling for AC, and harnessing the waste cold of liquified natural gas regasification.

There is an increasingly urgent need for actions to achieve sustainable cooling. As Nobel Laureate Mario Molina explained, there is growing recognition that "Speed must become the key measure of all climate mitigation strategies" to avoid self-reinforcing climate change feedbacks and tipping points (Molina, Ramanathan, and Zaelke 2020). "Speed" is defined as measures that can begin within 2 to 3 years, be substantially implemented in 5 to 10 years, and produce a climate response within the next decade or two. A second, closely related rationale for speed is the lock-in problem associated with short-term purchases of refrigeration and AC equipment for buildings, industry, and transportation.[4] Once installed, such equipment could be used for 15 years or more, even as much more efficient alternatives become available. A significant proportion of emerging cooling needs will be in urban development and supply chains that have yet to be built, providing an opportunity to deliver cooling in carefully planned, integrated energy systems. It is projected that 13 to 18 cooling devices will be deployed per second until 2050.

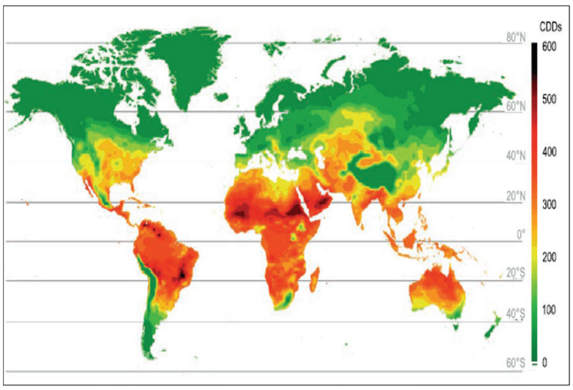
As global warming increases, cooling is an essential adaptation measure to provide relief from extreme heat. Heatwaves are one of the deadliest natural hazards and disproportionately affect the poor and vulnerable; 1.1 billion people face immediate risks from lack of access to cooling, including 680 million slum dwellers living in hotter-climate urban areas where electricity services are unavailable, intermittent, or too expensive. In addition, about 365 million people live in poor rural areas without access to cold chains for food and medicine (SEforAll 2019a). More frequent heat extremes (Figure 3) will lead to as many as 3 billion people being exposed to temperatures beyond human tolerance (Xu et al. 2020). Adding to the distress, the projected heat-exposed regions often overlap with regions with the highest levels of air pollution. Thus, in the absence of substantial reductions in air pollution, many people will suffer a double burden of heat and air pollution (Marginean, Sillmann, and Aunan 2017).

FIGURE 3: More Heat: Increase in Cooling Degree Days through 2050

Mean annual average cooling degree days
2007–17



Increase in cooling degree days under baseline scenario relative to historical cooling degree days
2016–50



Source: IEA 2018.

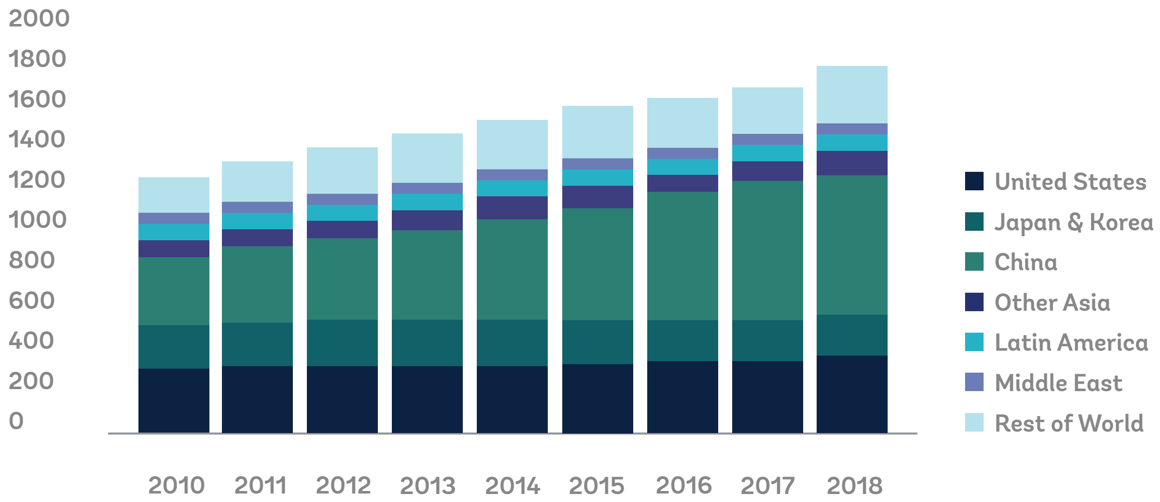
4 · SEforAll (2019a) estimates that 2.2 billion lower-middle income consumers may soon be able to purchase the most affordable cooling appliances, which are likely to be inefficient and energy intensive in use.

Lack of cooling can have severe health impacts. The World Health Organization estimates that, despite global vaccination efforts, in 2019 an estimated 19.7 million children did not receive routine immunizations, including temperature-sensitive diphtheria-polio-tetanus vaccines, largely because of inadequate refrigeration and unreliable energy supply (WHO 2020). Heat and humidity are growing problems for human health and are limiting human endurance and survival. Cities are particularly vulnerable because they are warming at twice the average global rate because of the urban heat island effect, a phenomenon by which air temperatures are substantially higher than in rural areas. This affects health in several ways: increasing air pollution, reducing water quality, and increasing flood risk by affecting rainfall patterns. The key direct impact of urban heat islands on human health is exposure to extreme heat, which can increase risk of hospitalization and death, because high heat exposure exacerbates existing respiratory and minor illnesses. Older people and those with preexisting health conditions in urban centers are particularly at risk (Heaviside, Macintyre, and Vardoulakis 2017). Rising temperatures, in combination with the urban heat island effect, make it likely that health problems will continue to increase in urban centers. Building materials that absorb solar energy and radiate heat, urban designs that trap heat, and a relative lack of vegetation and tree canopy increase urban heat. Rising temperatures are of increasing concern for cities in developing and developed countries, because they put significant stress on urban systems and affect many aspects of urban life.

Ambient heat without access to cooling reduces human productivity. Lack of cooling imposes a “productivity penalty” on businesses and developing economies that could become much worse as the planet warms. Outdoor and indoor exposure to heat in the construction, agriculture, and manufacturing sectors, among others, results in annual socioeconomic losses that are expected to increase rapidly. A rise in temperature could result in a 2.2 percent decrease in global work hours, which equates to roughly 80 million full-time jobs and global economic losses of USD2.4 trillion (ILO 2019a; Taylor 2019). In India, every degree above average temperatures translates to a 3 percent loss of output in manufacturing—large enough to explain the entire reduction in India’s economic output in hot years (EPIC 2018).

Many countries in hotter climates have exceptionally low rates of household AC. Only 4 percent of households in India have AC (IEA 2018); this number is expected to quintuple by 2050, still leaving the majority of households without modern cooling service. Globally, an estimated 5 billion cooling appliances and systems are in operation, including 2.6 billion AC units (stationary and mobile) and 2 billion domestic refrigerators and freezers (IIR 2019). Households in India, China, Brazil, and Indonesia are poised for an explosion in demand for cooling appliances as income levels rise and the world warms (Figure 4). Fans offer some protection from extreme heat and are one of the most widely used non-refrigerant-based pieces of cooling equipment, especially in low- and middle-income countries. More than 1 billion rural and urban poor people experience significant health and economic harm because of the lack of access to cooling, and more than 2 billion people in lower-middle-income countries can afford only the lowest-cost air conditioners and often have unreliable access to power to run them or can afford to do so for only limited periods.

FIGURE 4: Estimated Air Conditioner Stock in Selected Regions, 2010–19 (million units)

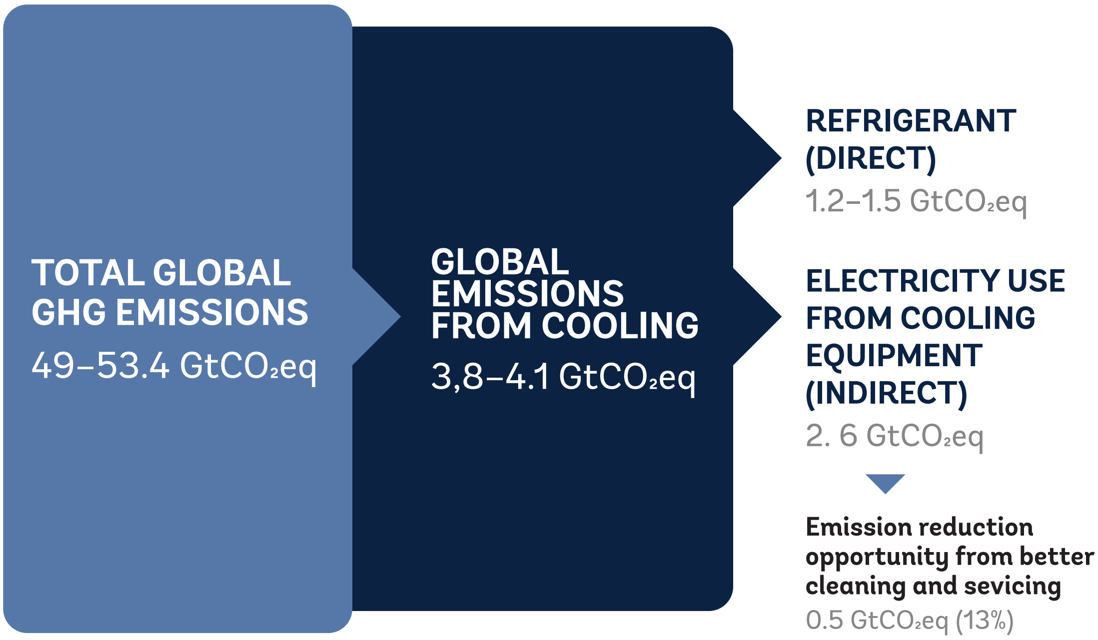


Source: IEA n.d.

Cooling affects the electrical infrastructure. The cooling sector (refrigeration and AC) consumes about 20 percent of electricity used worldwide (IIR 2019). Energy demand for cooling, if left unchecked, could more than double by 2050 and rise even higher if estimates of providing affordable access to cooling for all people that need it are accurate (IEA 2018). The impact of cooling demand on climate change is closely related to its implications for affordable, clean energy (SDG 7). For instance, space cooling is a major contributor to peak energy demand, representing an average of 14 percent of peak demand globally in 2016 and more than 50 percent in many large cities in developing nations. If cooling efficiency remains unchanged, additional power generation capacity of 2,500 GW will be needed to meet cooling demand by 2050—at a cost of about USD1.7 trillion. A 30 percent increase in the energy efficiency of room air conditioners alone could avoid the need to build 1,500 medium-size peak power plants by 2030 and up to 2,500 by 2050, leading to global savings of up to USD3 trillion through 2050 (Abhyankar et al. 2017). The growth in demand for power that added space cooling creates also makes it more difficult to decarbonize electricity systems by adding renewable energy.

The world may be able to avoid close to 1°C in warming by 2100 if energy efficiency in the cooling sector can be maximized while simultaneously phasing down hydrofluorocarbons (HFCs) contained in refrigerants (Dreyfus et al. 2020). According to the Montreal Protocol Technical and Economic Assessment Panel, about 80 percent of the climate impact of cooling equipment is from indirect emissions (i.e. carbon dioxide (CO_2) emissions from fossil-fuel electricity generation) and 20 percent from direct emissions of HFC refrigerants (UNEP 2018b). Emissions resulting from poor installation and maintenance further complicate the challenge in many developing nations, where trained service personnel are typically in short supply. Effective maintenance and optimization could result in emissions savings of up to 30 gigatonnes of CO_2 equivalent by 2050 (0.5 gigatonnes per year) (K-CEP 2018) (Figure 5).

FIGURE 5: Total Global Emissions from Cooling (Annual)



Source: K-CEP 2018.

Today's conventional cooling technologies (refrigeration, AC, fans) account for over 10 percent of global fossil CO_2 emissions (more than 7 percent of total global GHG emissions), which is about half the global emissions from transportation and twice the emissions from aviation and maritime combined (K-CEP 2018; GCI n.d.; Olivier and Peters 2020). If left unchecked, emissions from cooling are expected to double by 2030 and triple by 2100, driven by heat waves, population growth, urbanization, and a growing middle class (K-CEP n.d.1).

The Kigali Amendment, an international agreement signed in 2016, initiated a phase-down in the use of HFCs, which are potent GHGs used as refrigerants (Box 1). The agreement amends the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer—a remarkably successful example of public–private cooperation in addressing a global environmental threat. The Kigali Amendment commits many countries to substantial reductions, or a phase-out, in their use of HFCs and authorizes funding to assist developing countries in achieving their requirements, but it does not directly address the need to increase the energy efficiency of cooling equipment to reduce power requirements. The potential contribution to mitigating the rate and magnitude of warming by replacing refrigerants and increasing the energy efficiency of cooling equipment is even larger; close to 1°C of global warming could be avoided by 2100 and, if attained, could help keep the global temperature increase within the outer limit set in the Paris Agreement (Dreyfus et al. 2020).

BOX 1: KIGALI AMENDMENT REDUCES CONSUMPTION OF HYDROCHLOROFLUOROCARBONS (HFCS)

The Kigali Amendment was adopted on October 15, 2016, as the fifth amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer and entered into force on January 1, 2019; as of June 2021, 122 countries (including China) had ratified it—the United States announced its intention to ratify the Agreement in 2021.

The Kigali Amendment requires countries to phase down HFCs, beginning in 2019 for developed countries and 2024 for most developing countries. Its initial phase-down schedule will achieve more than an 80 percent reduction in HFC consumption by 2047. Most developed countries began the phase-down in 2019, and most developing countries will freeze consumption and production in 2024 and begin the phase-down in 2029. Developing countries susceptible to high ambient temperatures will freeze consumption in 2028 and begin to phase down in 2032.

HFCs, which do not destroy stratospheric ozone but are potent climate pollutants, are alternatives to chlorofluorocarbons and to the hydrochlorofluorocarbons that replaced chlorofluorocarbons, both of which are ozone-depleting substances and powerful climate pollutants. In the absence of interventions, it was projected that rising annual HFC emissions would contribute a warming equivalent of about 20 percent of carbon dioxide emissions in 2050. Accelerating reductions in HFCs and other short-lived, high-global-warming-potential pollutants could avoid up to 0.6°C of warming by 2050 (CCAC n.d.).

Energy generation from fossil fuels must be reduced by 70 percent to achieve the SDGs while staying within the GHG emission limits set by the Paris Agreement and meet the increasing demand for cooling. This would require a 300 percent increase in energy efficiency (University of Birmingham 2018a). The cooling industry has steadily increased the energy efficiency of cooling equipment in recent years, but these changes have been incremental and insufficient. More needs to be done to meet the SDGs. Initial needed actions include:

- Sharply reducing GHG emissions from refrigerants and energy use to meet the Paris Agreement and Kigali Amendment goals by 2050.
- Increasing productivity in poor countries through smarter agriculture to feed millions more.
- Modernizing manufacturing to provide decent work and more jobs; integrating energy services and logistics to increase economic efficiency; and strengthening supply chains for medicines, vaccines, and health.
- Providing greater support to developing countries in providing access to cooling for millions of people to adapt to the effects of climate change, particularly the severe impact of increasing heat stress on vulnerable people.
- Protecting natural resources and combating environmental degradation and its impacts.
- Building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation.

Today's more efficient AC models are not the most popular because of their higher initial cost. The upfront cost of efficient cooling equipment using low-GWP refrigerants is often higher in markets where this equipment is not yet the standard technology, although the overall lifecycle cost of these more efficient AC models is usually lower than that of models using conventional technology and high-GWP refrigerants because of their better performance, lower maintenance costs, and other factors. Nevertheless, from the end-user perspective, particularly those with low income, the initial price is often the deciding factor when purchasing new equipment. Price is therefore an important element in determining whether a technology will be successful.

Solutions must be found to overcome higher investment cost, split incentives, heterogenous markets, and the high transaction costs of managing small, dispersed interventions to increase the deployment of sustainable cooling technologies. Examples for such technologies include high-efficiency inverter AC systems, absorption cooling technologies, district cooling, ice thermal storage, and integrated cold chains, which can reduce food waste and improve the lives of farmers.

SUSTAINABLE COOLING AT THE WORLD BANK

Cooling is a global challenge but one with a disproportional impact on developing countries. Lack of access to adequate cooling and the need for and deployment of new and specific cooling solutions will affect developing countries, economically and socially, much more than advanced economies. Cooling directly and indirectly affects the World Bank's development and environmental objectives, including its work on eliminating poverty and advancing the SDGs, increasing financing for climate mitigation and adaptation, strengthening resilience, and promoting sustainable mobility (World Bank 2018).

Cooling should be prioritized in World Bank advisory, lending, and policy operations. Addressing cooling already has a history in World Bank Group (WBG) operations of increasing energy efficiency of buildings and appliances and in infrastructure design, and the importance of cooling in health, agriculture, water management, urban planning, transportation, disaster relief and preparedness, and industrial modernization is being increasingly recognized. The multisectoral and global nature of potential solutions cuts across many areas of its operations, research, technical assistance, and external engagements. Accordingly, the WBG is well positioned to contribute to the economic, social, and policy analysis needed to justify and plan action on cooling and bring its clients integrated, systems-based solutions. In addition to its client country focus, the WBG is a knowledge broker, disseminates best practices, and facilitates the exchange of experience between practitioners and policy makers around the globe.

Sustainable cooling is an area where the interests of consumers, industry, and governments intersect with the global public goods agenda (e.g., reducing GHG emissions, phasing out prohibited refrigerants, reaching the SDGs). In this area, the WBG can play its traditional role as a convener and facilitator, bringing value through its economic and policy analysis and its experience in drawing together different agendas and interests and advancing them toward global, regional, and local action that will ultimately contribute to a common goal. Given its traditional work on the Montreal Protocol and with the global cooling industry and its two decades of climate change advocacy and action, the WBG is well placed to assist the international community and its client countries in addressing the domestic and global challenges of providing sustainable cooling.

Meeting these challenging objectives will require finance, which implies that development finance institutions (DFIs) have an important role to play. As noted, higher first cost—despite significant savings over time—is a major barrier to adoption of climate-friendly, energy-efficient AC. Innovative financial instruments and blended finance are among the promising responses, complemented by supportive policies and regulations. There are additional barriers to finding and matching early-stage, innovative technologies with potential users in developing countries and to financing and scaling their deployment—a challenge that the WBG's International Finance Corporation (IFC) is addressing through its TechEmerge program for cooling innovations. About 35 percent of all energy for cooling is consumed in large commercial buildings such as hotels, shopping malls, and hospitals, which typically use old, inefficient, incorrectly sized, poorly maintained industrial chillers. Cooling for transportation is another sector with potential for quasi-commercial finance.

The WBG can work with many public and private sector partners to enhance their efforts to achieve sustainable cooling, but a paradigm shift is needed to achieve political commitment and provide the public and private sectors with the financial resources needed for investments in sustainable cooling. It is estimated that only 0.04 percent of total official development assistance is being directed at cooling solutions (K-CEP n.d.1). Access to sustainable cooling finance "must grow quickly and substantially enough to meet the increased need for cooling services" (SEforALL 2019a).

THE ROLE OF THE ROADMAP

A complete roadmap would consist of a coherent, prioritized, timebound, global plan that strategically organizes and allocates actions to achieve sustainable cooling and agreed-upon objectives. The need for, as well as the implications and complexities of achieving, sustainable cooling have only recently been recognized and are still emerging. It is therefore premature to expect a roadmap of great specificity and detail that the entire global cooling community can agree to and will support. Instead, this report represents a first step and is presented for consideration of principle elements and as input for discussions with stakeholders and the global cooling community as a basis for a future consensus on a global roadmap to achieve sustainable cooling by 2050.

The objectives of this roadmap report are therefore limited to:

- Developing strategies and pathways to identify and plan actions to meet the need for sustainable cooling as a key step toward achieving climate mitigation and adaptation goals and many of the SDGs.
- Introducing the challenges and opportunities associated with actions to move toward sustainable cooling, including within WBG operations.
- Characterizing the action space and partnerships within which WBG projects, financing, and support can have catalytic impacts on the sustainable cooling agenda and leverage global actions.
- Proposing immediate priorities, the actions needed now, and the future directions of actions to achieve universal access to cooling while moving toward net-zero GHG emissions from cooling.
- Identifying engagement modalities with the global cooling community to reach an agreement among partners on a future version of a global roadmap, related stakeholder actions, and their coordinated implementation.

"COOLING IS A GLOBAL CHALLENGE BUT ONE WITH A DISPROPORTIONAL IMPACT ON DEVELOPING COUNTRIES."

TWO

Annie Spratt / Unsplash

THE COOLING COMMUNITY

A globally coordinated approach is integral to responding at the scale needed to meet the cooling challenge. The goals that drive sustainable cooling (climate goals and SDGs) are global priorities. The overarching policies to achieve the goals contained in the Paris Agreements, NDCs, and the Kigali Amendment are internationally agreed upon and supported. The national policies, regulations, and incentives that guide the design and deployment of sustainable cooling solutions, and the industries that deliver them, are interdependent and globally connected. Hence, delivering a sustainable cooling transformation requires international coordination and a globally concerted effort. From the standpoint of efficiency and effectiveness, it is therefore necessary to take stock of ongoing efforts and identify the stakeholders in the global cooling community that are already contributing to meeting the challenge and can provide leadership.

The global cooling community is as diverse as the range of cooling needs. This represents a challenge inasmuch as ways must be found to bring together many different parties and interests; it also presents an opportunity because these many different parties and interests are potential sources of technical assistance, innovation, resources, finance, and political support. The activities are as diverse as the organizations involved and include building and urban design, technology development, energy, logistics systems, policy reform, business model innovation, advocacy, consumer behavior change and communication, capacity building, and finance. Although collectively this is impressive, much greater effort and resources are being invested in some sectors and activities (e.g., those related to increasing the efficiency of AC and refrigeration equipment) than others, particularly activities related to providing access to cooling in poor rural areas and slums.

The Montreal Protocol community (Box 2) actively coordinated efforts by governments, the chemical industry, cooling manufacturers, environment groups, and science and technical experts that successfully phased out use of ozone-depleting substances (ODSs). The addition of the Kigali Amendment in 2016 (Box 1) expanded and extended this process by including reduction of HFCs, which are being widely used as refrigerants, and thereby providing additional impetus to the low-GWP, efficient cooling agenda (UN 2016).

BOX 2: LEARNING FROM THE SUCCESSFUL MONTREAL PROTOCOL

The Montreal Protocol, which virtually every nation on Earth has ratified, has been widely heralded as the most successful global environmental agreement in history. In 1987, a subset of developed countries agreed to a 50 percent reduction in the use of ozone-depleting substances (ODSs), with a 10-year grace period for developing countries (UNEP n.d.). The Protocol has subsequently been amended and adjusted multiple times to accelerate and broaden the reduction and to provide financial support to developing countries to enable them to reach these goals.

Thanks to the Protocol, the Antarctic ozone hole, which resulted from the release of ODSs into the atmosphere, is on track to recover. The world has also avoided substantial warming because the chemicals that the Protocol has banned are also potent contributors to global warming. The extraordinary degree of cooperation between governments; chemical companies responsible for producing substitutes; and a wide-ranging, diverse set of private sector users, including refrigeration and air conditioning, electronics, automotive, and aviation, partly explains the Protocol's success (Andersen and Sarma 2002; Andersen and Zaelke 2004).

The Ozone Secretariat, hosted by the United Nations Environment Programme, supports the Protocol's implementation. The Protocol's Multilateral Fund, overseen by an executive committee and supported by a secretariat and a technical and economic assessment panel, provides grants to developing countries to support the phase-out of ODS. Implementing agencies, including the United Nations Development Programme, United Nations Environment Programme, United Nations Industrial Development Organization, and World Bank, support developing country governments in executing Multilateral Fund projects.

Efforts to promote coordination of actors that focus on sustainable cooling have also increased (Table 1). In 2017, a number of philanthropies came together to create K-CEP (Box 3) and quickly established a large collaborative network of international organizations, nongovernmental organizations, research institutions, businesses, and expert advisors to support the Kigali Amendment of the Montreal Protocol and the transition to efficient, clean cooling solutions for all (K-CEP n.d.2).

BOX 3: KIGALI COOLING EFFICIENCY PROGRAM (K-CEP)

K-CEP is a unique philanthropic initiative created in the wake of the adoption of the Kigali Amendment, in which 17 foundations and individuals initially pledged USD51 million to increase the energy efficiency of cooling in developing countries. While supporting the objectives of the Kigali Amendment, as an independent philanthropic initiative, K-CEP defines strategies and makes funding commitments more rapidly and with less process than donor-administered funds. It has four programmatic focus areas: strengthening for efficiency; policies, standards, and programs; finance; and access to cooling.

A few of K-CEP's notable activities include support for Sustainable Energy for All's access to cooling programs, national cooling action plans, and technical assistance for inclusion of cooling commitments in nationally determined contributions. K-CEP also supports the World Bank Energy Sector Management Assistance Program to promote inclusion of efficient cooling in new World Bank Group investment projects and mobilize additional financing.

COOLING STAKEHOLDERS

Taking a systems approach to cooling demands a radical program of consensus-building among intervention delivery partners involving multiple sectors, many with entrenched cultures and vested interests, and seeking to establish a common viewpoint on shared timebound goals. To be successful, such a program will require formulating multiple parallel, coordinated pathways. The roadmap will need to drive government and industry cooperation, align policy with finance, shape academic research agendas, and accelerate the transition of innovation to market and widespread adoption at scale.

The capacity of actors and supporters to implement roadmap actions are an important factor in making realistic plans and generating intended outputs and outcomes. The roadmap identifies key stakeholders and actors for proposed actions, although assessing their willingness and capacity to act will depend on systematic, extensive engagement with the global cooling community and relevant stakeholders. The present approach to a sustainable cooling roadmap is therefore preliminary, to be revised after consultations with the global cooling community on the resources available and support needed for implementation of the roadmap.

The categories of stakeholders and partners most relevant for engagement and critical for the success of a consensus roadmap are the cooling industry, governments, and networking organizations. Key market players relevant for the sustainable cooling agenda include equipment manufacturers; chemical companies; heating, ventilation, and air conditioning service companies; energy companies; utilities; and major users of cooling (e.g., mobile cooling and refrigerated transport).

THE COOLING INDUSTRY

Viewed as a whole, the cooling industry is much larger and more diverse than might initially be thought. Many actors are involved in developing, marketing, installing, operating, and maintaining cooling equipment, as well as the policy environment relevant for innovation and product selection.[5] Although there are many players, a small number of global actors whose interests frequently span several sectors tend to dominate major markets. This has arguably been a barrier to technological innovation, market introduction, and promotion of advanced, efficient, climate-friendly technologies.

The cooling market consists of about 3.6 billion pieces of installed cooling equipment, with annual sales of around 350 million units (Peters 2018; 2019a). Projections from the Green Cooling Initiative anticipate sales of about 19 billion pieces of equipment between now and 2050 (700 million units per year by 2050) and a market size of 9.5 billion installed units. Global annual sales of cooling equipment are estimated to be worth USD140 billion in 2018 and USD270 billion by 2050 (Peters 2018). These figures encompass a wide variety of applications (e.g., cooling used in industrial facilities alone is a USD14 billion business that employs 15 million people supplied by more than 20 major companies and expected to reach USD25 billion by 2025 (Global Market Insights 2019)). According to the International Energy Agency (IEA), about 41 million chillers are in use around the world, with a capacity of 3,350 GW; most of these are in commercial buildings and central plants for large residential blocks and district cooling systems (IEA 2018). The largest share is in the United States, although demand is growing rapidly in China and other developing nations (IEA 2018; 2019a; 2019b). The global food and beverage industry chiller market is expected to reach USD2.5 billion by 2022, largely driven by growing demand for processed and frozen goods in the Asia-Pacific region (Allied Market Research 2017).

5 · The Clean Cooling Landscape Assessment (University of Birmingham 2018b) contains a comprehensive overview of the actors and activities that are involved in the cooling product cycle and must help provide clean cooling.

3.6 BILLION
PIECES OF INSTALLED COOLING EQUIPMENT

Mobile cooling is cooling through vehicle AC equipment (e.g., cars, buses and coaches, trains) and transport refrigeration equipment for cooling of cargo space in vans, trucks, shipping containers, and the like. Mobile cooling accounts for 31 percent of total cooling emissions, despite consuming only 25 percent of the energy used for all cooling applications. Mobile cooling primarily consumes fossil fuels and accounts for a higher share of CO_2 equivalent emissions from refrigerant leakage, equipment manufacturers, and disposal (37 percent of the sector's GHG emissions) than other cooling sectors. By 2050, emissions from mobile air conditioning (MAC) equipment are estimated to increase by almost 70% (from 1,264 to 2,129 million tons of CO_2 equivalent per year) under the base case (constrained access) and to almost 3,000 million tons under the expanded growth scenario (Ayres, Stankevich, and Diehl 2020).

Production of refrigerants is also a large industry, with dozens of plants to meet diverse needs and applications, and a critical source of innovation to develop gases with low or zero GWP and to operate equipment efficiently.

GOVERNMENT ENTITIES

Governments include national, state, and local authorities. National governments are in the best position to assess a country's cooling needs and priorities and prepare strategic plans. Various government departments, including energy, industry and commerce, environment (national ozone offices), investment, and international cooperation, share responsibility for cooling measures. Their involvement is relevant to advancing the sustainable cooling agenda by, for example, preparing national cooling plans and linking climate strategies, including NDCs, policy reforms, regulations and standards, interministerial coordination, public education and awareness, and training of technicians. This sharing of authority is often associated with a lack of clear responsibility and overall coordination, a challenge that countries are beginning to address through NCAPs.

Governments at all levels have a major role to play in bringing about sustainable cooling, particularly because they have responsibilities with respect to health and agriculture through the cooling-related delivery of vaccines and cold chains for farming and fisheries. They regulate electricity prices, which if artificially low, effectively subsidize the use of inefficient AC equipment. Pricing that reflects the higher cost (and pollution) associated with peak demand can improve the economics of efficient equipment. Utilities in countries with generating capacity shortages can justify financial incentives for early retirement of inefficient appliances and their replacement with high-efficiency units.

National agencies are sources of technical assistance and advisory services to state and local governments and to private sector actors in developing countries. They execute and provide support to national and subnational initiatives and promote learning and knowledge sharing, capacity building, and risk taking in innovation and pilot projects, sometimes in collaboration with international organizations and initiatives. Government testing and labeling programs are critical to raising consumer awareness of the benefits of efficiency, ideally combined with minimum energy performance standards (MEPS) to drive inefficient equipment out of markets. Government entities own and occupy substantial building space, which creates the potential to lead by example and use purchasing power to lower costs and prices through bulk procurement.

Cities and other authorities with subnational jurisdiction have substantial responsibility and a host of options to avoid urban heat islands, decrease cooling demand, increase efficiency, and protect vulnerable people exposed to extreme heat.[6]

NETWORKING ORGANIZATIONS

Networking organizations include international organizations; development agencies; coordinating bodies; and research, expert, and advocacy groups. Given the magnitude of the challenge, it is fortunate that numerous organizations and groups are making significant efforts to promote sustainable cooling. Multiple international organizations have made significant commitments to cooling-related initiatives, and philanthropies and nongovernmental organizations have made notable efforts to promote more efficient cooling and protect vulnerable populations from heat.

The Food and Agriculture Organization of the United Nations has a program on food loss and waste and publishes two indices—the Food Loss Index and the Food Waste Index—that help track the magnitude of the loss (FAO n.d.1). The World Health Organization has an initiative supporting innovative cooling methods for transportation and storage of vaccines (WHO 2012). The International Federation of Red Cross and Red Crescent Societies has produced and distributed a guidebook to help cities prepare for heat waves (New York Times 2019). The Rocky Mountain Institute (RMI) has played a leading role in developing and implementing the Global Cooling Prize competition (Kalanki, Winslow and Campbell 2021). The Natural Resources Defense Council has been working with national and city officials in India to support cooling action plans and city heat action plans (Jaiswal 2019). The Collaborative Labeling and Appliance Standards Program (CLASP) helps developing countries develop and implement programs to promote more efficient appliances, including in a testing and labeling program and adoption of MEPS.

K-CEP is unique in supporting and funding fast action for sustainable cooling, including programs at the World Bank (2019a). And multilateral development banks and international financial institutions such as the Green Climate Fund and the Global Environment Facility (GEF) are becoming increasingly interested in cooling.

Reflecting the increasing political understanding of the crucial role of cooling in the future, heads of state and governments at the G7 Summit in 2019 launched the Biarritz Pledge for Fast Action on Efficient Cooling, which has a goal of transforming the global cooling sector and decreasing emissions by coordinating efforts to increase the energy efficiency of air conditioners and other cooling equipment in parallel to the phase-down of HFCs, thus maximizing the climate benefits of the Kigali Amendment to the Montreal Protocol.

6 · See generally C40 (2016) and SEforAll (2018; 2019a). The World Bank has published a primer on measures cities can take to protect residents from extreme heat (ESMAP 2020c).

In addition to the individual cooling-related activities of public and private entities, there are multiple initiatives that promote sustainable cooling and facilitate coordination and collaboration among organizations. Table 1 lists selected organizations and initiatives, their missions and activities, which encompass advocacy, raising awareness, providing technical assistance, promoting coordination and collaboration, encouraging technological and business innovation, and supporting financing of sustainable cooling initiatives. The WBG is a partner in four initiatives: K-CEP, SEforALL's Cooling for All program, UNEP's Cool Coalition, and the Climate and Clean Air Coalition.

TABLE 1: Selected International Initiatives Promoting Sustainable Cooling

INITIATIVE	CHARACTER AND MISSION	ACTIVITIES
Kigali Cooling Efficiency Program[7]	Philanthropic collaboration of 17 foundations and individuals. Help developing countries transition to energy-efficient, climate-friendly, affordable cooling (Box 3).	Grants to partner organizations for research, advocacy, pilot projects, capacity building, and access to clean and efficient cooling; Nationally Determined Contributions support facility. www.k-cep.org
Cool Coalition	Coalition of over 100 partners hosted by the United Nations Environment Program. Connect wide range of actors (governments, cities, international organizations, businesses, finance, academia, civil society) to facilitate knowledge exchange, advocacy, and joint action for a rapid global transition to efficient, climate-friendly cooling.	Sharing scientific case for action and promoting collaboration; securing high-level political commitments; advocating for more innovation, greater investment, better information, and greater capacity; supporting national cooling action plans; working on pathways to zero emissions from cooling. www.coolcoalition.org
Climate and Clean Air Coalition	Partnership of governments, intergovernmental organizations, businesses, scientific institutions and civil society. Protect the climate and improve air quality through actions to reduce short-lived climate pollutants.	Reduction of hydrofluorocarbon consumption and leaks; high-level political leadership (e.g., efficient cooling initiative at 2019 G7 Environment Ministers meeting); initiatives on hydrofluorocarbon alternatives and energy-efficient cooling. www.ccacoalition.org
Sustainable Energy for All **Cooling for All program**	Program launched by Sustainable Energy for All, an international organization supporting access to affordable, reliable, sustainable, and modern energy. Generate evidence, partnerships, policy and business solutions necessary to provide sustainable cooling for all and reduce energy demand to achieve this.	Research, publications, issue briefs, knowledge sharing, events, and advocacy, with emphasis on Sustainable Development Goals; Chilling Prospects annual report; #ThisIsCool campaign. www.seforall.org/cooling-for-all

7 · In August 2021, K-CEP changed its name to Clean Cooling Collaborative (www.cleancoolingcollaborative.org).

INITIATIVE	CHARACTER AND MISSION	ACTIVITIES
International Energy Agency	Intergovernmental organization of 30 OECD member countries and 8 associated countries. Shape secure, sustainable energy future for all through research and policy advice on energy generation and use and energy efficiency.	Research, publications, data collection on cooling scenarios, technologies, energy use, energy efficiency potential. www.iea.org/fuels-and-technologies/cooling
Institute for Governance & Sustainable Development	Research and advocacy institute Promote just and sustainable societies and protect the environment by advancing the understanding, development, and implementation of effective and accountable systems of governance for sustainable development.	Research projects, analysis, publications, networking and education on Montreal Protocol-related issues and short-lived climate pollutants. www.igsd.org
International Institute of Refrigeration	Independent intergovernmental organization of 59 member countries (founded in 1908). Gather and disseminate scientific and technical knowledge in every sector of refrigeration to improve quality of life for all while respecting the environment and taking into account economic imperatives.	Research, publications, events; efforts to become a major global player in implementation of sustainable refrigeration in all its uses. www.iifiir.org
Centre for Sustainable Cooling	Consortium of academic institutions. Work with governments, industry, development agencies and nongovernmental organizations to solve the cooling challenge, namely, to sustainably accelerate access to cooling for all who need it.	Developing systems that integrate technological, policy, social, economic, energy, finance, and business pathways to manage cooling demand and deliver sustainable solutions that help the most vulnerable in society. www.sustainablecooling.org www.clean-cooling.ac.uk
Global Cool Cities Alliance	Non-profit organization. Accelerate global transition to cooler, healthier cities by advancing urban heat island mitigation policies and programs that promote efficient, comfortable buildings and healthy, resilient cities.	Cultivating partnership with cities, governments, and companies on cool roof and pavement programs; Million Cool Roofs Challenge (competition for effective, sustainable, replicable models to expand deployment of cool roofs). www.globalcoolcities.org www.coolroofschallenge.org

INITIATIVE	CHARACTER AND MISSION	ACTIVITIES
Green Cooling Initiative	Membership network initiated by the German Association for International Cooperation (GIZ). Transform cooling sector by promoting natural refrigerants and helping implement climate-friendly sustainable cooling in emerging and developing countries.	Policy advice, technology transfer, capacity building, data collection, publications, training, demonstration projects, advocacy for natural refrigerants. www.green-cooling-initiative.org
Global Cooling Prize	Initiative by Rocky Mountain Institute (RMI) and partners. Help solve climate threat from growing air conditioning demand through prize competitions that promote rapid technology innovation.	Awarded prizes for room air conditioning systems with less than one-fifth the climate impact of standard residential air conditioning. www.globalcoolingprize.org
Collaborative Labeling and Appliance Standards Program (CLASP)	International nonprofit organization. Improve energy and environmental performance of appliances and equipment used every day, accelerating transition to a more sustainable world.	Research and resources on efficiency standards; advocacy and policy advice (specifically on minimum energy performance standards); market acceleration initiatives; technology competitions (e.g., off-grid cold chain challenge). www.clasp.ngo
Basel Agency for Sustainable Energy (BASE) **Cooling-as-a-Service (CaaS)**	Initiative launched by BASE, a Swiss not-for-profit foundation and specialized partner of United Nations Environment Program. Increase investments in clean and efficient cooling by mainstreaming the CaaS business model.	Research, advocacy, tools, training, implementation support on CaaS business model. www.energy-base.org www.caas-initiative.org

INITIATIVE	CHARACTER AND MISSION	ACTIVITIES
Global Food Cold Chain Council	Initiative of cold chain equipment manufacturers. Increase access to food cold chains; reduce food waste; encourage solutions, policies, and actions on access to sustainable food cold chains; participate in international climate policy.	Industry coordination, advocacy, development of standards and practice. www.foodcoldchain.org
Global Cold Chain Alliance	International alliance of cold chain users and service providers. Expand cold chain industry; lead development of cold chain.	Events, research, publications, training, advocacy; fighting food loss and waste. www.gcca.org
European Partnership for Energy and the Environment	Association of refrigeration, air-conditioning, and heat pump industry in Europe. Increase understanding of refrigeration, air-conditioning, and heat pump sector; support safe, environmentally and economically viable technologies; contribute to development of effective European policies to achieve long-term sustainability agenda.	Programs on energy efficiency, refrigerants, and markets; policy and position papers; awareness and advocacy (e.g., #CountOnCooling campaign). www.epeeglobal.org www.countoncooling.eu

THREE

Sergei Akulich / Unsplash

ISSUES AND APPROACH

Designing a roadmap for cooling for all requires knowledge of the goal, potential solutions, critical step-changes that enable innovations and interventions, framework conditions, and barriers. The preceding sections introduced the goal and the many actors that can and should be engaged to implement solutions. This section reviews the barriers, challenges, and potential actions (interventions) specific to each type of actor. Subsequent sections focus on what must be done, and when, and the importance of short-term actions to achieve universal long-term climate-friendly access to cooling. Concluding sections address financial challenges and implementation needs.

As the preceding sections described, the sectors and actors relevant to cooling needs, products, and services are extraordinarily diverse. The range of barriers, challenges, and potential solutions to achieve a sustainable cooling economy is correspondingly varied and encompasses the need for demand mitigation through design or behavioral change, integration of a broader portfolio of energy resources, technological innovation, new business models, training programs for equipment installers and technicians, capacity building for urban planning, and additional sources of finance.

KEY CHALLENGES

Barriers to sustainable cooling include:

- **Not thinking thermally.** When choosing among cooling options, many people continue to default to electricity (and batteries) as energy source, whereas most of our energy services are thermal; thermal storage and direct thermal-to-thermal conversion of energy might better serve the transition to renewables (e.g., district cooling using rivers or lake water and using ice to store cold).
- **Not going back to first principles** to mitigate the demand for cooling by design, for example by building designs that minimize cooling needs, rather than meeting them using mechanical processes, which, even when efficient, consume more energy.
- **Lack of priority** of building owners and other stakeholders for cooling demand management and mitigation within energy systems.
- **Lack of research investment.** Even though cooling accounts for 20 percent of global electricity demand and 10 percent of CO_2 emissions and is one of the fastest growing sectors for energy demand, much less research investment is being made in step-change innovations than in other sectors or industries.
- **Lack of data and credible forecasts** for the future scale of cooling needs, including costs, benefits, and climate impact.[8] There is also a lack of good-quality baseline data in many countries on equipment stocks, equipment sales, and refrigerant inventories—the basis for understanding the scale of the challenge and the efficacy of any measures proposed.

8 • IEA (2018) was a significant corrective effort but was limited to analysis of mechanical AC for buildings.

- **Lack of awareness.** Few users of cooling equipment are fully aware of their emissions' impact, energy consumption, maintenance requirements, or operating costs over time. There is also sometimes a lack of awareness about availability of much more energy-efficient equipment with lower environmental impacts.
- **Limited analysis** of implications of climate change for cooling needs and associated energy demand and costs. Based on current trends, in coming decades, there is potential for increases of 3°C to 4°C in global average temperatures—conditions that would exceed human survivability in many locations on many days of the year (Arnell et al. 2015).
- **Lack of skills.** In many countries, there are insufficient numbers of trained technicians to maintain cooling equipment in efficient working order, compounded by new emission-reducing technologies that require greater skills.
- **Behavioral issues.** Greater use of AC may partially offset efficiency improvements that reduce power demand—a "rebound" effect; conversely, initiatives such as the Cool Biz program in Japan have shown that it is possible to reduce power demand by promoting voluntarily raising thermostats and adoption of less formal office attire.
- **Higher first cost and affordability.** Consumers often resist paying more to buy efficient cooling equipment and are constrained in developing economies by the affordability of this equipment. This is a problem because more efficient equipment often has a higher purchase price, even if the total cost of ownership is lower once lower running costs are taken into account.
- **Weak policy environment.** Because of lack of capacity or resistance to regulating consumer choice, many governments have yet to adopt MEPS, building energy codes, and other measures effective in promoting more energy efficient and climate-friendly cooling.
- **Market structure.** A small number of global companies with significant market power and limited incentives for innovation dominate many segments of the cooling industry.
- **Unique challenges in the transport sector,** including a lack of focus on cooling power demand and its implications.
- **Need for systems-level thinking and an integrated approach.** Integrated systems thinking to look more broadly at ways to meet cooling needs shows great promise, but limited tools are available to plan systems, and no large-scale demonstrations have been completed.

SYSTEMS-LEVEL THINKING AND INTEGRATED APPROACHES

A key consideration when developing roadmaps is interdependencies and synergies between actions. Certain actions may produce outputs that are required inputs for other actions that may occur at the same time but more often occur later. It is important to identify the critical step-change innovations and interventions required to unlock a broader portfolio of progressive solutions. The roadmap uses these chains, or clusters of actions, as pivotal elements around which other actions can be organized and prioritized over the three decades between 2020 and 2050 using additional criteria.

Current cooling development interventions focus on adopting low-risk, convenient, sector-siloed approaches to deliver quick incremental efficiency wins. Over the long term, providing sustainable cooling will require integrated approaches using bundles of technologies (and revenue streams) and leveraging all energy resources.[9]

This must include recognizing the synergies between thermal sources and sinks; being able to add value from system optimization; identifying new economic values to be captured; and, ultimately, ensuring resilience and optimizing energy management across transport and the built environment.

Systems design approaches in the cooling industry currently focus on individual appliances and integrated installations (e.g., a store refrigeration system or, at the larger end of the scale, a district space cooling project). Considerable efficiency gains may be unlocked by taking a holistic approach to assessing space cooling and refrigeration needs at a community, regional, or national level and exploring how economies of scale, waste resource opportunities, and synergies between processes can be best unlocked. An example of an emerging concept that embodies such thinking is a community cooling hub (Debnath et al. 2021), which would serve multiple needs (e.g., food storage to enable shipping produce to higher-value markets, temperature control of vaccines, and mushroom cultivation). When multiple needs are served, the potential for financial sustainability is substantially greater. This concept also offers the potential to use the food cold chain to support COVID-19 vaccination logistics.

Figure 6 shows the ladder of intervention, which depicts progressive cooling innovations—or step-changes—from the introduction of current energy efficiency improvements to future technology leapfrogging by developing countries. These innovations are less technical and require holistic changes in thinking on cooling needs and the energy and environment context, which underpins and guides technical innovations. In the context of a roadmap of actions, operationalizing these step changes is the task of governments, the cooling industry, development organizations, and other stakeholders.

9 · For detailed information on current and future cooling technologies, see University of Birmingham (2015; 2018b) and Appendix A.

FIGURE 6: Ladder of Opportunities and Step-Change Interventions

NOW

1

Ensuring lowest GWP and highest energy efficiency of current technologies–main-tenance, best in class adoption.

2

Active steps to reduce demand for cooling. Mitigate need (building design, passive cooling, food packaging). Behavioural changes.

DEVELOP

3

Think thermally, rather than default to electricity – turn waste heat and cold into a value.

4

Think system and how to aggregate services, create integrated trading platforms.

5

Needs-driven, leapfrog to new technologies.

Disruptive innovation, demand aggregation

SHORT-TERM INTERVENTIONS FACE SIGNIFICANT CHALLENGES:

Consumers don't want to pay more to buy efficient cooling equipment (although they would benefit from lower lifecycle costs), governments don't want to burden consumers and domestic manufacturers with challenging standards and higher costs, and cooling manufacturers are slow to innovate and scale up rapidly, because they don't see a market.

While important to quickly take the first two steps on this ladder, it is also necessary to prepare for the next steps, which will involve systems integration, disruptive technologies and leapfrogging in developing countries – before building out new cities and in-vesting climate and development dollars into the "wrong" cooling and energy infrastructure.

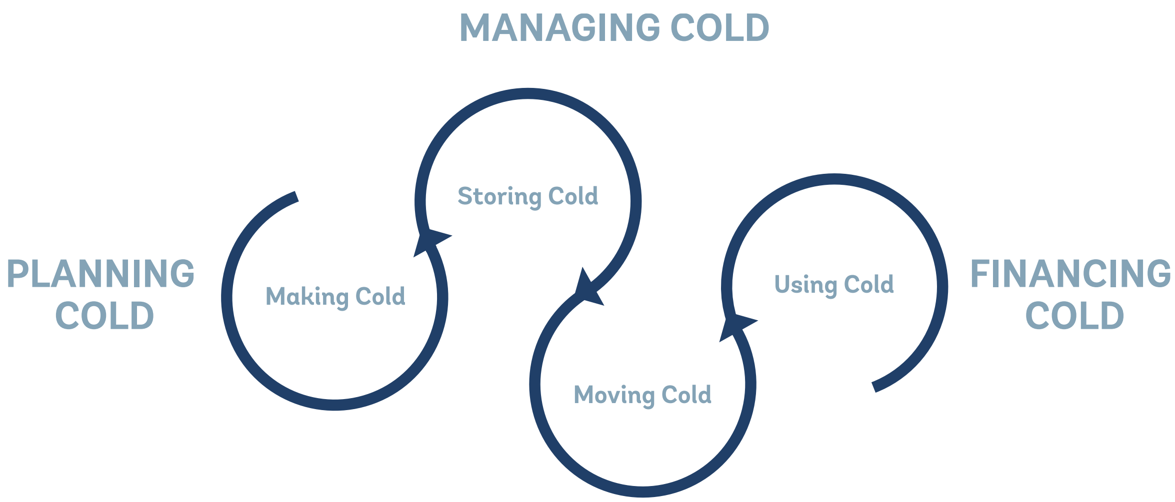
Today, there is still a chance to avoid the lock-in of old-world in-frastructures in young countries, which will be inadequate and too expensive in the long-run to address the climate problem while serving the cooling needs of the populations. Doing so now may prevent large costs and climate damage in the future.

Source: Adapted from University of Birmingham (2018b).

"Whole systems" can be difficult to understand, contain many interdependencies, and can be difficult to study in the real world, but powerful computer simulations can be used to identify the factors that have the biggest impact. Planning cooling for infrastructure illustrates some of the considerations relevant in a whole-systems approach (Figure 7):

- **Making cold:** Harness unused or "waste" resources, such as cold-water bodies, "wrong time" renewable energy (wind, solar), waste cold (liquefied natural gas) and heat, and ambient heat sinks (ground source, sky cooling). Explore opportunities to harness free cooling and synergies between processes, waste resources, and cooling needs that can reduce the cooling required.
- **Storing cold:** Store energy thermally, in physical mass (thick walls), or phase-change materials (ice) to make use of cyclical changes in ambient heat sinks and the supply of (electric) energy at lower costs by including e-vehicles and e-logistics.
- **Moving cold:** Use new energy vectors and materials to move thermal energy (e.g., liquid air or nitrogen can be used for cooling and can generate mechanical energy).
- **Using cold:** Reduce cold loads by lowering cooling demand (insulation), increasing equipment efficiency, and replacing refrigerants with high GWP. Highlight behavior-change and demand-mitigation strategies likely to be effective while maintaining required service levels. Modal shifts can substitute for cooling solutions, with much lower energy use (e.g., transporting vaccines using airborne drones over rough terrain).
- **Managing cold:** Make cooling systems smart for real-time monitoring of cooling needs and performance (sensors), load adjustments (controls), and integrated system management and storage (communication). Deliver cooling only where and when it is needed while optimizing system-wide impacts. The key is to ensure correct installation and maintenance of cooling units; if this is not achieved, inefficient energy use and refrigerant leakage rates above 25 percent are possible, and safety provisions may be violated.
- **Financing cold:** Focus on ensuring access to cooling but also improving human decision making and encouraging behavior modification (e.g., through pay-for-use, instant visibility of system status and consequences, integration of external costs and benefits (carbon pricing), and markets for alternative energy vectors (e.g., waste heat).

FIGURE 7: Whole-Systems Approach to Cooling



Source: University of Birmingham (2018).

KEY QUESTIONS, INTERVENTIONS, AND ENABLERS

The process of evaluating needs and defining solutions will require action at most levels, from the global to the very local. Most countries will not have the capacity or resources to focus on technological innovation, and many in need of cold chains for health and agriculture will require external assistance. In one country, the priority may be the fisheries sector, whereas in a neighboring country, it may be health in urban slums. Business models and cooling applications that work in one market may not be easily transferable to another. Thus, some initiatives (e.g., development of innovative technology) should and are being undertaken as international collaborations, whereas many others require identification of country-specific needs, priorities, and solutions. This is the role of NCAPs and why they should be linked to NDCs, as K-CEP (n.d.4) outlines in its Principles for National Cooling Plans. Table 2 lists some of the questions to be asked and options to be considered in evaluating the most effective measures to address a range of cooling needs.

TABLE 2: Whole-Systems Approach: Questions and Options

QUESTION	INTERVENTION AREA	KEY AREAS OF INVESTIGATION AND PRIMARY ENABLERS
How do we use cold? **How much cold do we need?**	Cooling load	Needs assessment, including climate adaptation
		Behavioral change
How do we reduce the need for cold?		Green buildings
		Sustainable development and urban planning
How do we manage cold?		Monitoring and controls, trading platforms, system resilience
How do we make cold?	Technology and innovation pipeline	Energy resources, including resource mapping
		Efficiency and optimization of vapor compression cycle technologies
		Non-vapor compression cycle technologies
		Hybrid systems
How do we store and move cold? **How do we manufacture cold systems?**	Systems and infrastructure	Energy storage, energy vectors
		Demand aggregation and management

QUESTION	INTERVENTION AREA	KEY AREAS OF INVESTIGATION AND PRIMARY ENABLERS
How do we finance cold?	Economy	Business models
		Transactional energy models
		Financing models
		Lifecycle analysis and circular economy
How do we ensure enough people for a cool industry?	People	Training and skills development
How do we accelerate access to cooling for all sustainably?	Policy and regulation	Governance, standards, protocols, benchmarking and certification, incentives
Stakeholder engagement and communication	Cooling community	Consumers, farmers, industry, manufacturers, energy companies, financiers, entrepreneurs, academics, policy makers, planners

UNINTENDED CONSEQUENCES

Introducing more affordable and readily available means of cooling in food supply chains and the built environment is not just a matter of adding cooling to the status quo; it may cause major shifts in societies and cultures, as well as in the wider environment and eco-systems. These could sometimes have unintended negative, as well as positive, effects. It will be important to anticipate emerging problems as early as possible, plan for them, and create the capacity to mitigate harm quickly.

For example, a cold chain will help reduce food loss, which is a major source of CO_2 emissions. About 9.7 million hectares are deforested annually for food production; reducing food loss through cold chains can ensure less land is deforested by increasing the proportion of food that reaches the market from existing farm production (FAO 2013). It could also allow farmers in developing economies to transition from staple to high-value (but temperature-sensitive) horticulture, and refrigerated food supply chains will over time allow farmer cooperatives to process food at the farm. There are also potential negative consequences. The shift to higher-value crops could lead to more water-demanding produce. Although this shift would add value for farmers, the absence of proper environmental measures without advance planning could increase local CO_2-equivalent emissions, pollution, and packaging demand and have implications for waste streams and resource use.

Refrigeration in the home can change cooking styles and patterns, especially if coupled with more processed food and the convenience products that cold chains enable. Refrigerators and microwaves have become more common in kitchens, and traditional cooking appliances and methods are no longer as widely used. Over time, this affects kitchen architecture and the design of new buildings, as well as cooking skills, indigenous diets, and health. Domestic refrigeration can also reduce the frequency of shopping, which can affect local marketplaces. On the plus side, reduced frequency of shopping and refrigerating bulk cooked meals has the potential to increase the time available for other productive activities, which is of particular benefit for women.

Once factored into architectural practice, the availability of AC radically alters how buildings are designed and can result in a loss of building traditions that address local environmental conditions. Air conditioners can also spread disease without adequate fresh air integration and cleaning of filters and systems. Passive cooling (e.g., through shading and natural ventilation) is often abandoned.

There will always be “unknown unknowns,” but drawing on a broad, cross-disciplinary analysis of the impacts of artificial cooling, we can at least begin to anticipate many of the possible consequences related to introduction of cold chains and widespread adoption of AC across the developing world.

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COOLING AND SUSTAINABLE DEVELOPMENT

The SDGs (UN n.d.) are the international community's principal vehicle for addressing a broad range of fundamental concerns that underpin inequalities and inequities in human society and our unsustainable relationship with planet Earth. Adopted in 2015 by all 193 member states of the United Nations General Assembly as a successor to the Millennium Development Goals, the 17 SDGs set ambitious targets to be met by 2030, along with associated indicators against which progress can be measured. The SDGs are a route to achieving a better, more sustainable future for all, regardless of current economic development status, and are intended to be delivered with no one left behind.

The SDGs are closely intertwined with the climate change adaptation and resilience goals, especially if temperatures rise above the Paris target of a 1.5°C increase. Providing cooling sustainably and advancing on the SDGs will mean that economies and people must adapt to climate change and become more resilient to the impact of extreme heat. These synergies are so strong that a comprehensive understanding of the relationship between the SDGs and the use of cooling in each relevant sector is a prerequisite for development of this roadmap. The need for vaccine cold chains to fight the COVID-19 pandemic is only the most recent example.

Cooling has strong gender links. In each sector, access to cooling must be considered in the context of impact on gender equality. As an example, in India, 80 percent of economically active women are in the agriculture sector, comprising 33 percent of the agriculture labor force and 48 percent of self-employed farmers (OXFAM 2018). Post-harvest loss due to lack of cold chains materially affects women, slowing their empowerment and emancipatory societal processes in rural areas. Likewise, domestic refrigeration frees up time for women—often the primary housekeepers—by reducing the need for daily shopping and food preparation.

The SDGs, and the contribution sustainable cooling can make to reaching them, should be central to the development agendas of all nations and are critically important for the future of human societies and well-being, but progress against goal indicators has been uneven, with several failing to advance significantly. There is a need in many cases to increase national focus on and deepen commitments to achieving the goals, accelerate delivery actions in implementation, and increase efforts in previously neglected and unrecognized areas where significant gains can be made. One such area is the provision of cooling.

BOX 4: "COOLING FOR ALL" NEEDS ASSESSMENT

Most discussions about the future of cooling have focused on room air conditioning equipment, without considering the full diversity of cooling needs and the holistic approaches necessary to provide access to sustainable cooling for all. The implications that cooling demand has for energy systems, climate change, clean air, economics, well-being, and workforce development are not fully understood. Underestimating the scale may limit ambition in policy, infrastructure, and technology development and could have far-reaching social, economic, and environmental consequences.

For a country, city, or community to ensure that their population's cooling needs are met, they must first understand what those needs are. The "Cooling for All" needs assessment, developed by Heriot-Watt University and Sustainable Energy for All, is a tool for governments, development institutions, and nongovernmental organizations to measure the full spectrum of cooling needs. By assessing all cooling needs, the full scope of demand can be understood systemically and measured fully. A roadmap or cooling action plan to provide access to sustainable cooling for all can then be developed. Such an assessment is crucial to the planning and investment required to ensure access to cooling sustainably—minimize demand, aggregate services, and harness new and renewable technologies.

SUSTAINABLE DEVELOPMENT GOALS

Several studies (University of Birmingham 2018a; SEforAll 2018) have raised awareness of the importance of cooling in achieving the SDGs. It will be impossible to meet many of the SDG targets without attention to cooling. Conversely, achieving the SDGs means increasing the supply of cooling—and potentially increasing associated GHG emissions if cooling is not delivered sustainably (by lowering cooling demand using passive cooling technologies, highly efficient equipment, and renewable energy). Attempts at quantifying the cooling demand that would enable the SDG targets to be met are underway, such as the Cooling for All Needs Assessments led by SEforAll and Heriot-Watt University (Box 4).

In a development context, four broad areas of cooling needs must be understood: food security and production; thermal comfort for living, learning, and working; health services and safe storage and transportation of vaccines and medicines; and industrial cooling and energy use.

- **Food, nutrition, and agriculture—for food security, safety, connectivity, and rural income:** We must understand the additional cooling and cold chain requirements—from pre-cooling at the farm to domestic refrigeration—if all people are to have access to an affordable, nutritious, safe diet and income from agriculture and fisheries is to be sufficient to keep workers out of absolute and relative poverty. Related SDGs advanced by access to cooling include 1 (end poverty), 2 (end hunger), 7 (energy access), 9 (infrastructure, industrialization, innovation), 12 (consumption, production), 13 (climate change), and 14 (oceans, marine resources).
- **Human comfort and safety:** for living, learning, working, and mobility: We must understand to what extent the population has access to the space and mobility cooling necessary to maintain safety and productivity outdoors in rural areas and in the heat islands of cities, at home, in education, in the work environment, and while moving between each. Related SDGs advanced by access to cooling include 4 (education), 7 (energy access), 8 (economic growth, employment), 9 (infrastructure, industrialization, innovation), 11 (safe, resilient, sustainable cities), and 13 (climate change).
- **Health services:** for safe medical clinics and secure transport and storage of vaccines and medical products: We must understand how much unbroken cold chain is needed to provide medicines and health care products (an urgent problem for COVID-19 immunization) and what is required to equip health care centers with the cooling they need to deliver adequate health services. Related SDGs advanced by access to cooling include 3 (healthy lives), 7 (energy access), and 13 (climate change).
- **Industrial cooling:** for processing, inclusive manufacturing, and data centers: We must understand how much cooling is required for food processing (including marine), pharmaceutical factories, industrial needs, data processing and communication, and increasingly, product distribution centers. Related SDGs advanced by access to cooling include 9 (infrastructure, industrialization, innovation).

RELATIONSHIP BETWEEN COOLING AND SDGS

A prerequisite to development of an SDG delivery-focused roadmap for the introduction of sustainable cooling is a comprehensive, needs-assessment-based understanding of the relationship between the SDG targets and the use of cooling in each relevant sector—today and in the future. In most case, the impacts of cooling on SDG targets are strongly positive, but there are some potential negative implications as well, as Table 3 shows.

TABLE 3: Effect of Sustainable Cooling on the 17 Sustainable Development Goals (SDGs)

#	SDG	POSITIVE EFFECTS	POSSIBLE NEGATIVE EFFECTS
1	End **poverty** in all its forms everywhere	Cold chains enable economic growth for agricultural and fishing communities, and space cooling is critical for comfort and productivity in a warming world.	Overfishing, overproduction. Food loss becomes food waste.
2	End **hunger**, achieve food security and better nutrition, promote sustainable agriculture	Cold chains are critical to reduce food loss and waste and increase the nutritional value of food that reaches people.	Loss of traditional food processes and redundancies. Food storage can lead to food waste, more packaging.
3	Ensure **healthy** lives and promote well-being for all at all ages	Medical cold chain, health services, nutrition, thermal comfort, reduced heat stress, mobility	Unhealthy lifestyle changes (more meat consumption?)
4	Ensure inclusive, equitable quality **education** and promote lifelong learning opportunities for all	Thermal comfort in schools and colleges is important for productive learning environments in hot and warming climates.	Behavior changes
5	Achieve **gender** equality and empower women and girls	Refrigeration services in poor rural communities are especially relevant for women in agricultural and fishing communities.	Greater working expectations of women from partners
6	Ensure availability and sustainable management of **water** and sanitation for all	Prevent food loss and reduce water used from irrigation.	Horticulture and evaporative cooling consume a lot of water.
7	Ensure access to affordable, reliable, sustainable, modern **energy** for all	Sustainable cooling reduces energy use, transitions demand from electricity to thermal resources, reduces peak demand, enables more-reliable energy access.	Mechanical cooling consumes a lot of energy
8	Promote sustained, inclusive, sustainable economic **growth**; full and productive employment; and decent **work** for all	Space cooling can increase human productivity in hot locations, increase profits, provide skilled jobs.	Need to ensure technician training to avoid damage to cooling system

#	SDG	POSITIVE EFFECTS	POSSIBLE NEGATIVE EFFECTS
9	Build resilient **infrastructure**; promote inclusive, sustainable industrialization; foster **innovation**	District cooling and other solutions as part of resilient infrastructure. Management of thermal energy demands, use of waste energy.	Lifecycle impact of cooling infrastructure on other systems and resources.
10	Reduce **inequality** within and between countries	Increasing cooling (cool cities, cold chains) in developing countries reduces international inequality based on gender, wealth, or location.	Access to cooling for only a few can increase inequality (e.g., large farmers producing cash crops).
11	Make **cities** and human settlements inclusive, safe, resilient, and sustainable	Space cooling, heat-informed urban design and construction to minimize heat islands, storage of and access to nutritious food reduce heat stress, increase resilience.	More mechanical cooling can make urban heat islands hotter, noise from cooling units.
12	Ensure **sustainable** consumption and production patterns	Low-global-warming-potential refrigerants, energy-efficient cooling solutions, reduced food loss and less deforestation, circular economy.	Refrigeration increases plastic packaging use.
13	Take urgent action to combat **climate change** and its impacts (incl. 13.1: strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries)	Cooling already contributes about 10% to global warming. Sustainable cooling emits no or minimal energy-related and refrigerant emissions. Access to cooling as part of adaptation strategy.	Fossil fuel use for mechanical cooling will increase greenhouse gas emissions.

#	SDG	POSITIVE EFFECTS	POSSIBLE NEGATIVE EFFECTS
14	Conserve and sustainably use **oceans**, seas, and marine resources forsustainable development	Seafood cold chain can reduce fish loss (25% of fish caught) and catch numbers. Habitat conservation.	Could affect jobs and income of low-earning fishing communities. Must be managed sustainably.
15	Protect, restore, and promote sustainable use of terrestrial **ecosystems**, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss	Cold chains reduce food loss and can reduce pressure to clear forests for agriculture. Food loss has direct impact on degradation of land resources through agriculture.	Cold chains can lead to more intense food production, more chemical and water use.
16	Promote **peaceful** and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, inclusive institutions at all levels	Access to cooling can reduce resource conflicts, rising food prices, water shortages, heat stress, and migratory pressure on rural populations; help maintain peace.	Must have inclusive production and manufacturing to avoid creating greater economic inequality and dependency.
17	Strengthen means of implementation and revitalize global **partnership** for sustainable development	Implementing roadmap for sustainable cooling requires global action and builds partnerships.	Can change economic landscape.

COOLING AND ENERGY

In the context of sustainability and energy (SDG7), current technologies and processes used to deliver cooling in all sectors are primarily fossil fuel based for energy sourcing, use high-GWP refrigerants, use unsustainable resources for their construction and operation, would not meet sustainability criteria in a whole-life-cycle analysis, and are not aligned with the principles of a circular economy.

A study conducted at the University of Birmingham (2018a), provided the first evidence-based analysis using global modeling of equipment penetration, the size of the challenge, and the implications of achieving universal access to cooling. Various scenarios were developed and compared with an implied energy budget calculated from the IEA's 2°C scenario.[10] The Cooling for All scenario, without step-change energy efficiency or technology intervention (business-as-usual incremental improvements), reviewed in the report resulted in an energy requirement of 19,600 TWh—three times the IEA budget for cooling of 6,300 TWh (IEA 2018) and double the current projections for cooling demand by 2050. The energy demand volumes that the study projected could exceed the IEA's forecast for total solar photovoltaic and wind generation in 2050.

To stay within the IEA budget and still provide the cooling required under the SDGs through this convergence pathway, energy consumed per unit of cooling would have to be reduced to about one-third of the levels envisaged. The challenge that this will represent will, to some extent, vary according to sector, although no sector is currently proposing a tripling of device efficiency by 2050 from today's levels. Although the details of the numbers in the Cooling for All scenario, such as penetration levels, energy consumption, and solution choices, might have some statistical dispersion, given the quantum gap between current demand projections and those included in the Cooling for All scenario, the conclusions are likely to be correct. Therefore, to avoid conflicts with climate goals, it is essential that only technologies and processes be used that provide cooling sustainably while pursuing the contributions that cooling can make to SDG targets.

COOLING AND ADAPTATION

As a further challenge, when planning for cooling demand to meet the SDGs, it is necessary to also consider the future impact that global temperature increases will have on society in the absence of adaptation to climate change. Without transitioning to energy-efficient clean cooling, meeting the increased cooling demand from climate change will itself accelerate climate change through fast growth in CO_2 emissions (Box 5).

10 • A set of policy, technology, and economic measures resulting in the amount of CO_2 released to the atmosphere being consistent with a significant probability of limiting global temperature increases to 2°C.

BOX 5: COOLING AND CLIMATE ADAPTATION

Global temperature increases will affect cooling demand in at least two main ways:

- **Changes to ambient temperatures:** expected to manifest in the form of higher average temperatures and more cooling degree days and consecutive days of high extreme temperatures that must be mitigated using refrigeration and air conditioning equipment.
- **Reductions in food production capability:** caused by temperatures, ice melt, and flooding reducing the amount of productive land, safe and productive environments for animals, and therefore food available to feed a growing population, making farm-to-fork cold chain losses less acceptable.

At the sector level, ambient temperature changes are likely to affect cooling demand in the following ways:

- **Stationary space cooling:** affected through increased air conditioning, more operating hours (if cooling degree days increase), and higher cooling capacity (if temperatures become substantially higher).
- **Industrial and commercial refrigeration:** affected through increases in equipment deployment (e.g., air conditioning use in animal husbandry) and need for greater cooling power to offset higher ambient temperatures.
- **Mobile cooling:** affected through increases in transport refrigeration deployment because cold chain coverage must be near 100 percent, with higher loads for mobile air conditioning equipment and transport refrigeration because of higher ambient temperatures. This could significantly affect energy consumption and vehicle range. Insulation may improve, but this may increase energy use and emissions if it substantially reduces payloads or increases weight.
- **Domestic refrigeration:** affected through a need for greater coverage to reduce postpurchase food loss. Minor potential impact from higher ambient temperatures.

As an example of the need for more cooling to support meeting the SDGs, the International Labour Organization estimates that, by 2030, the equivalent of 2.2 percent of total working hours worldwide will be lost every year (ILO 2019b) because it is too hot to work outdoors or workers must work at a slower pace. In parts of Africa, productivity loss may reach 5 percent. Other challenges often accompany heat stress because it is more prevalent in countries without decent working conditions, such as a lack of social protection and high rates of informality and working poverty. As such, excessive heat levels will exacerbate inequality between rich and poor countries and between rich and poor within the same country. Box 6 shows how the lack of cooling affects key SDGs.

BOX 6: CHILLING PROSPECTS

Projections of growth in conventional cooling and prospects for efficiency improvements typically neglect the need for substantial additional cooling to address a range of development needs. More than 1 billion people are at grave, often life-threatening risk from lack of cooling, the vast majority in Asia and Africa (SEforAll 2018). Those at risk face diverse challenges in a wide range of development objectives:

- **Zero Hunger and Sustainable Agriculture (SDG 2):** Up to 50 percent of food is lost after harvest in developing countries because of inadequate refrigeration and food cold chains. Lack of adequate cold chains is responsible for about 9 percent of loss of perishable foods in developed countries and 23 percent in developing countries, with approximately 1 gigatonne of carbon dioxide equivalent in 2011 attributable to insufficient cold chains (Dreyfuss et al. 2020). Replicating best practice with respect to food loss, an objective that cold chains support, could save an amount of food sufficient to feed an additional 1 billion people. Food loss and waste contributes an estimated 4.4 gigatonnes of carbon dioxide equivalent (8 percent of global GHG emissions and more than the annual emissions of all but two countries) (FAO n.d.2).
- **Good Health and Well-Being (SDG 3):** It is estimated that heat waves cause the deaths of 12,000 people annually around the world (SEforAll 2018), and more than 166,000 people died from extreme temperatures between 1998 and 2017 (CRED 2018). The World Health Organization (2014) estimates that there could be 90,000 additional deaths annually from heat by 2030 and 250,000 by 2050. The lack of adequate cold storage and refrigerated transport contributes to more than 1.5 million vaccine-preventable deaths each year. This has taken on even greater significance with the coronavirus and expectations that a vaccine will play a key role in ending the pandemic. To be fully effective, distribution of such a vaccine must be global, which increases the importance of cold storage to reach rural populations in many developed countries.
- **Decent Work and Economic Growth (SDG 8):** Integrated cold chains could quadruple or quintuple the incomes of poor rural farmers by reducing waste and enabling a switch to higher-value produce. Higher temperatures will decrease labor productivity and cause up to 6 percent gross domestic product (GDP) loss annually and as much as 12 percent in South Asia and West Africa. The International Labour Organisation projects that heat stress will reduce global GDP by USD2,400 billion by 2030, affecting agricultural and construction workers in particular (ILO 2019b). It is estimated that labor productivity loss for low- and lower-middle-income countries due to high temperatures is about nine times as high as for high-income countries and that we may already be seeing economic losses of as much as 2 percent of global GDP as a result of greenhouse gas emissions (Chavaillaz 2019).
- **Sustainable Cities and Communities (SDG 11).** More than half of the world's population lives in urban areas, a level expected to reach 70 percent by 2050. An estimated 680 million live in urban slums with little or no cooling to protect them during heat waves. Pavements and roofs account for more than 60 percent of urban surfaces and are typically made of dark materials that absorb more than 80 percent of incoming sunlight, converting it into heat. As a result of this urban heat island effect, cities can be as much as 2°C hotter than surrounding areas. The use of air conditioning adds to the problem by dumping heat outside. Use of reflective materials could mitigate the impacts of climate change.

Even if global warming could be limited to 1.5°C above preindustrial levels by 2100, the accumulated financial loss due to heat stress is expected to reach USD2,400 billion by 2030, and if not enough is done to mitigate climate change, these costs will be much higher as global temperatures rise even higher toward the end of the century (ILO 2019b).

The most urgent goal is to ensure that the basic needs of all are met in a warming world while living within our natural resource limitations and mitigating future risks to our survival on the planet. Sustainable cooling must be about establishing strategies today for climate adaptation and to future-proof society. The sooner we recognize this fully and invest accordingly in step-change interventions to mitigate the impact of a warming world and provide access to environmentally and socially sustainable cooling for all who need it, the better humans will fare in the 21st century.

"MEETING THE INCREASED COOLING DEMAND FROM CLIMATE CHANGE WILL ITSELF ACCELERATE CLIMATE CHANGE."

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ROADMAP OVERVIEW

Roadmaps define actions and connect them with goals. The goals of this roadmap are threefold: bring GHG emissions from cooling applications in line with climate goals, adapt to rising climate-induced temperatures, and recognize the role of cooling in meeting the SDGs. The roadmap considers numerous actions, spans several sectors, and is sequenced over three decades.

ROADMAP GOALS AND TARGETS

The GHG emissions goal is aligned with the Paris Agreement, which aims to keep global warming within 1.5°C. To do so requires that GHG emissions from all human activities and sectors reach almost zero by 2050. This roadmap therefore uses net-zero by 2050 as the GHG emissions target for the cooling sectors, allowing for offsetting of emissions that cannot be eliminated from cooling applications. GHG emissions from cooling include direct and indirect emissions from power generation for cooling and emissions of refrigerants used in cooling equipment. The roadmap's emissions target thus incorporates the HFC phase-down target under the Kigali Amendment of the Montreal Protocol.

In accordance with the adaptation objectives of the United Nations Convention on Climate Change, the adaptation goal builds on the realization that people and human activities must adapt to global warming and become more resilient to climate-induced heat waves and their impacts. In so far as we are unable to keep the planet cool, cooling human-used spaces, food, medicines, and materials is an essential adaptation option. Even if the Paris goals are met, cooling will remain important for many needs other than human comfort, including industrial applications and for food and health. This roadmap therefore uses bringing cooling services to all people that are at risk of heat impacts and need cooling—as spelled out by SEforAll (2018; 2019a)—as an adaptation target.

Many SDGs are linked to cooling and cannot be achieved without sustainable, affordable cooling services. There are strong overlaps, conflicts, and symbiosis between the adaptation goal and many of the SDGs; and both types of goals require interventions far beyond cooling. Cooling needs assessments have therefore been proposed to quantify the amount of cooling needed to help meet the SDG targets (SEforAll 2019b), but results were not yet available to prepare this roadmap.

Not all aspects of the three roadmap goals and their respective targets are aligned. On a basic level, expanding access to cooling and reducing GHG emissions are in direct contradiction if fossil fuels and GHG-intensive refrigerants are used. Addressing these conflicts, the roadmap strategy assumes the following: adaptation and the SDGs are not less important than GHG mitigation; cooling will increase anyway, albeit more slowly than the rise in global temperatures and reaching the SDGs may demand; less-efficient, more-polluting technologies will be locked in if current trends continue; and expanding cooling with sustainable technologies need not increase net GHG emissions and could even decrease them (e.g., a sustainable (non-fossil fuel) cold chain will reduce food waste and land use, thus avoiding GHG emissions). The roadmap strategy therefore treats these goals as equally important and proposes balancing target conflicts at the level of actions.

There is a particularly potent possible conflict and potential synergy between decarbonizing the electric power system and decarbonizing cooling that this roadmap cannot resolve. Although we should aim to transition to more thermal solutions for cooling where possible, electricity will still be needed for large numbers of mechanical cooling applications (and currently accounts for up to 80 percent of GHG emissions from cooling). Reaching the roadmap's GHG mitigation targets will therefore depend on progress in energy generation from renewable sources. This conflict is evident from recent trends, with global deployment of solar photovoltaic generation not able to match the capacity required for new room AC units.[11] Linking cooling more directly to renewable energy and increasing overall technical efficiency addresses this conflict only partially. The GHG targets that this roadmap uses must therefore be considered with the caveat that electric system emissions are largely outside the control of the cooling community. Although the roadmap allows excess GHG emissions to be offset, this strategy will have limits given the need that all sectors and countries must reach net-zero emissions to meet the climate goal of the Paris Agreement and considering the uncertainties and potentially high costs of carbon removal technologies (Dyke, Watson, and Knorr 2021).

Actions on cooling can result in powerful synergies. Deploying better cooling solutions can simultaneously lower GHG emissions, increase resilience, and help meet certain SDGs. However, those who invest in sustainable cooling usually benefit from only a portion of these advantages, which suggests significant underinvestment and "wrong" investment in some cooling sectors. Hence the need for public intervention to increase investment in cooling and ensure that cooling solutions are increasingly clean, efficient, and sustainable.

ROADMAP PRIORITY ACTIONS BETWEEN 2020 AND 2050

Mapping out, prioritizing, and sequencing the actions that should be undertaken until 2050 to reach roadmap targets is a difficult undertaking and fraught with uncertainty. To do so, the roadmap is subdivided into three phases, one for each decade between 2020 and 2050. Subtargets are suggested—and priority action areas proposed—for each decade to focus and organize the roadmap actions. These subtargets are suggested as notional landmarks to measure progress at the end of each decade; they are not prescriptive and should only be understood as examples that illustrate the type and scope of progress that is needed. The priority areas and actions were drawn from the sectoral background work for this roadmap. The roadmap itself and the proposed actions and targets presents an approach to mapping a global response, which must be further considered, reviewed, and refined in consultation with the global cooling community and other stakeholders and possibly modified in future versions of the roadmap.

A leading theme describes each of the three roadmap decades: Phase 1 (2020-2030) is characterized as the **decade of readiness and quick results** and Phase 2 (2030-2040) as the **decade of market transformation and expansion**; Phase 3 (2040-2040) describes the **emergence of the sustainable cooling economy**. The chart in Figure 8 shows the strategic roadmap priorities and actions, their sequence, and their interdependencies over time; and it outlines the innovations in technology, business, and financial models and the socioeconomic and policy thinking necessary to deliver access to cooling for all who need it while limiting impacts on climate and natural resources.

11 • In 2017, a record year for global deployment of solar photovoltaic generation, 94 GW of capacity was added, and the full load power draw from all new room AC units sold added about 106 GW to the global grid. 2018 was again a record year for solar photovoltaic, with 104 GW of capacity added, but global sales of AC units amounted to a potential power draw of 115 GW.

FIGURE 8: Roadmap of Priority Cooling Actions and Step-Changes 2020 through 2050

Integrated roadmap to drive the innovation in technology, business and financial models, socio-economic and policy thinking to deliver access to cooling for all who need it while limiting the impact on climate and natural resources

2020–2030
Readiness and Quick Results
Build technological, regulatory foundation. Avoid lock-in. Cheap wins.

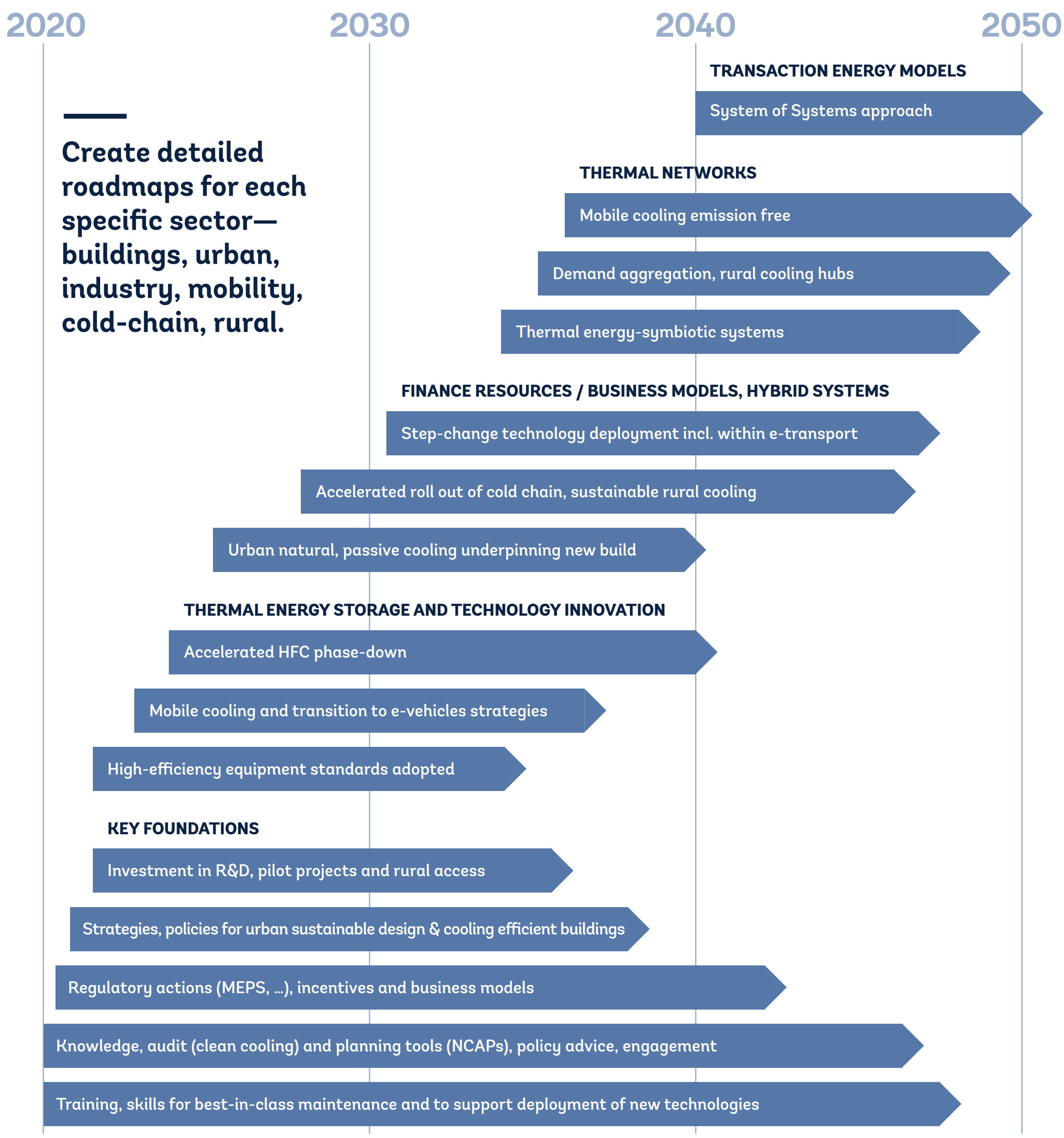
2030 TARGETS
Avoid lock-in of inefficient cooling technologies, take actions that are low cost – with the target of plateauing GHG emissions from cooling.

2030–2040
Market Transformation and Scale-up
Cool cities. Rural access to cooling.

2040 TARGETS
Scale up efficient cooling in buildings and cities, bring cooling to rural populations – while achieving a significant decline in GHG emissions.

2040–2050
Emergence of the Sustainable Cooling Economy
Net zero challenge. SDGs.

2050 TARGETS
GHG-free mobile cooling, full access to cooling – achieve net-zero GHG emissions (incl. offsets) by 2050.



In Phase 1, readiness actions have the greatest priority in activities to improve and build the technological, capacity, systemic, auditing, and regulatory foundation for sustainable cooling. Phase 1 is characterized by actions to avoid lock-in of low-cost, inefficient cooling technologies and actions, with the target of plateauing GHG emissions from cooling. Phase 2 focuses on expanding efficient cooling in buildings and cities and bringing cooling to rural populations; this phase will, for the first time, lead to significant declines in GHG emissions. Emergence of the sustainable cooling economy in Phase 3 addresses energy-symbiotic cooling infrastructure, zero-GHG-emissions mobile cooling, and full access to cooling for rural productivity and for all people at risk of climate heat while returning GHG emissions from cooling (including offsets) to net-zero by 2050.

The actions proposed for each phase support these themes, but this does not imply that certain actions would not need to be undertaken and sustained during other phases or the entire lifetime of the roadmap and possibly beyond. The roadmap is frontloaded with near-term actions because of the urgency of interventions and preparations needed now and because of greater uncertainties in later roadmap years. Hence, it is a rolling plan that must be reviewed, updated, and concretized regularly.

This roadmap must generalize, using specific actions as examples; it does not provide specific details on, for example, incentive schemes, business models, and technologies. This information is available in the background reports for this roadmap and other publications. Although this section contains a brief overview of the roadmap according to sector, development of detailed sector and country roadmaps of actions, linked to this global roadmap, should be considered as part of next steps.

ROADMAP ACTIONS ACCORDING TO SECTOR

This roadmap is based on background research conducted for different user groups and cooling sectors that suggests priority areas of intervention and sector-specific actions, most of which are clustered in the early years of the roadmap (World Bank 2020). Actions suggested in background reports are summarized in Appendix B.

The report on the **building sector** (ESMAP 2020a; 2020b) advocates for an integrated approach of reducing electrical loads for cooling using passive cooling, equipping and serving cooling loads with efficient and low-climate-impact technologies, and optimizing and controlling cooling loads to ensure that cooling is delivered only where and when needed. The strategy is built around opportunities to accelerate access to sustainable space cooling, including leveraging the full potential of passive cooling, addressing consumer first-cost bias, establishing effective policy and regulatory frameworks, developing institutional and professional capacity, enabling access to finance, raising awareness of the benefits of sustainable space cooling and energy efficiency in buildings, accelerating technology innovation, and capturing the opportunity to reduce emissions from energy use while replacing high-GWP refrigerants with low-GWP or natural refrigerants.

Interventions to address market barriers and advance sustainable space cooling are grouped into three overarching strategies: establishing a supportive policy and regulatory environment, creating financial instruments and business models to make sustainable cooling affordable, and increasing awareness and capacity to improve technology. A sample roadmap is presented that consists of the following steps: elevate cooling as a priority area, establish policies to stimulate market demand for sustainable space cooling, expand awareness of and stimulate energy-efficient building practices, and apply cross-cutting market enablers (financial and other instruments that accelerate market transition).

The report on **urban cooling** (ESMAP 2020c) indicates that the choices cities make when deciding where and how to build and develop their urban areas and which technologies and materials to use can lock them into patterns of excessive urban heat for decades. Technical solutions for cool cities include solar-reflective and permeable green surfaces (roofs, walls, pavements, trees, parks, water features), heat-resilient planning (urban design, building infrastructure, heat-generating technology, transport), and energy efficiency (thermal insulation, district cooling). Building codes and planning regulations can promote all of these measures.

The report proposes a framework for an inclusive, integrated approach to help cities develop locally appropriate cooling strategies by taking stock, engaging stakeholders, gathering and analyzing data, and developing policy. The report presents more than 20 policies, programs, and examples from cities around the world grouped into four categories—awareness raising, leading by example, incentives, mandatory activities—and recommends the following roadmap actions: develop a cooling action plan; identify heat-vulnerable areas and populations; demonstrate urban cooling strategies with pilot projects; engage the public; lead by example (to create local capacity); make urban cooling measures the standard (building codes, urban design principles); consider incentives; expand reflective surfaces, water, green spaces (urban forestry); invest in cooling-informed infrastructure (thermal networks) and integration with electricity supply (load management); and work with other cities.

The report on cooling in **industrial and large commercial facilities** (IFC 2020) discusses systemic hurdles that commercial decision makers face in procuring efficient cooling equipment, considers the role of regulatory measures for company decision making, provides examples, and presents possible solutions, including:

- Develop guidance notes, tools, and training on risks, impacts, and cost of heat stress; optimal replacement or upgrade of cooling equipment; life-cycle costing of energy-efficiency investments; improvement in procurement practices; computer-aided load analysis, including passive building measures to right-size cooling equipment; and use of the IFC-sponsored EDGE tool for cooling (a green building certification system focused on making buildings more resource-efficient).
- Optimize use of cooling by aligning organizational structure, employee incentives, and external contracts with energy and cooling efficiency goals; engaging with the energy utility to establish savings goals and negotiate rate incentives to manage cooling systems; and conducting preventative and predictive maintenance for heating, ventilation, and AC equipment.
- Introduce financial incentives to accelerate replacement of inefficient cooling systems that use hydrochlorofluorocarbons or HFC-based refrigerants.

The report on the **transport sector** (Ayres, Stankevich, and Diehl 2020) discusses new solutions for cooling in ground transportation (cars, busses) and transport refrigeration units (refrigerated trucks, shipping containers). The report covers the dominant technologies, alternative technology options, and potential for new business models and recommends regulatory interventions to increase efficiency and reduce GHG emissions from mobile cooling:

- Generate data and improve assessment of equipment stock.
- Work with specialized (international) organizations to create or enhance international standards for new and used cars and transportation of perishable food.
- Increase transparency of energy use and emissions (e.g., by including AC in vehicle testing protocols).
- Develop and implement a skills program in the automotive sector (e.g., handling of refrigerants).
- Provide guidance on equipment specifications and modal shifts for policymakers to address increasing heat and demand for cooling.
- Understand the impacts of MAC and temperature-controlled logistics in the transition to electric mobility and e-logistics.

The report on **agricultural and food cold chains** (Peters 2019b) in developing economies discusses the challenges of reducing food loss by expanding cold chain capacity quickly and affordably while minimizing GHG emissions from energy and refrigerant use. The report connects these challenges with opportunities to increase agricultural productivity and rural incomes by providing access to cold chain logistics and cooling for productive purposes. The report's recommendations include:

- Understand the implications of cold chain development for global nutrition, feeding the world, and protecting smallholder farmers simultaneously.
- Improve monitoring tools and data collection on food loss along the cold chain.
- Develop tool kits for assessment of mobile and stationary cold chain needs within an integrated system.
- Set industry targets for reducing food loss and phasing out high-emission technology.
- Encourage market supply of affordable, sustainable on- and off-grid cooling equipment.
- Support research to map sustainable cold chain technology and economic and development scenarios.
- Engage stakeholders to define cold chain strategies, investment needs, and risk sharing.
- Develop adaptable cold chain business models and mobile data platforms able to serve small agricultural producers by matching supply and demand, controlling service quality, and facilitating payments.

Access to rural cooling is discussed in a companion report (Peters 2019c) that links rural cooling and cold chains and emphasizes the contribution of rural cooling to the SDGs. It discusses systems approaches to food security, connectivity, and rural incomes; thermal comfort for living, learning, working, and connectivity; and health services, including safe storage and transportation of vaccines and medicines. The report makes the following recommendations:

- Invest in the medical and vaccine cold chain to prepare for COVID-19 vaccination.
- Conduct a needs assessment for rural cooling in different countries and include access to rural cooling in NCAPs.
- Develop strategies for an integrated cold chain (including for medicines and vaccines) and rural cooling (community cooling hubs).
- Encourage development and piloting of cooling technology and business models to meet rural communities' needs, including for agricultural, medical, and health applications and human comfort.
- Invest in "living labs" and pilot community cooling hubs.
- Share knowledge about cooling interventions, case studies, and off-grid cooling applications with rural communities.
- Develop standards, guidelines, policies, and regulations for rural cooling; village-level production; health care and community facilities; medical cold chains; and thermal comfort and related equipment in homes, workplaces, and schools.
- Create (financial) incentives for private sector investment in rural cooling and support business models and private-public partnerships to organize rural cooling facilities that have productive purposes and meet human needs.

PRIORITY STAKEHOLDER ACTIONS

Table 4 shows three types of priority interventions (actions) that each stakeholder group (actors) should undertake by 2025 to advance the sustainable cooling agenda.

TABLE 4: Stakeholder Actions: Urgent Interventions (2020–25)

ACTORS	ACTIONS 1	ACTIONS 2	ACTIONS 3
Governments	Recognize urgency and principles of sustainable cooling economy Assess cooling needs to meet socioeconomic goals Develop national cooling action plans and include them in nationally determined contributions Set emissions and energy limits to meet Paris Climate Agreement targets	Ensure that energy policies and financial mechanisms recognize and support thermal energy approaches Encourage efficiency (e.g., minimum energy performance standards) and cooling demand reduction	Support research and development, centers of excellence, knowledge and technology transfer Undertake system-level demonstration projects for technology and business model innovations
Development finance institutions	Facilitate cross-sectoral approaches to clean, efficient cooling Advise and assist developing country clients Maximize finance for investments and impact	Provide financing to cities to support development and implementation of needs-driven, system-wide (buildings, mobility, urban design) sustainable cooling strategies	Provide financing to rural communities and logistics providers for sustainable cold chain and community cooling
Energy sector	Optimize flexibility of electric networks by encouraging and managing thermal loads (e.g., cold storage)	Harness natural and waste thermal resources	Evaluate thermal demands of mobile air conditioning and mobile refrigeration on energy grids

ACTORS	ACTIONS 1	ACTIONS 2	ACTIONS 3
Cities	Use cooling-informed urban design to reduce urban heat Develop heat action plans and create “cool” spaces Mitigate demand for artificial cooling	Develop and enforce building energy code to reduce demand for artificial cooling	Plan and invest in smart thermal networks (cross-city and micro-grids)
Agricultural and rural community	Provide training on clean cold chain technology and related business models	Ensure that cold chains have low climate and environmental impacts	Develop community cooling hubs including supportive business, finance, economic models
Cooling industry	Deliver equipment to market that meets the Global Cooling Prize criteria	Train enough technicians in clean, efficient cooling technologies to meet future refrigeration and air conditioning needs	Increase research and development investment Create pipeline of sustainable cooling innovations (including step-change solutions)
Businesses	Practice life-cycle cost analysis Set whole-life equipment performance targets Reform procurement process and purchase decisions	Drive behavior changes Use incentives for demand mitigation Develop and pilot sustainable cooling business models	Harness waste thermal streams and integrate thermal energy storage to manage energy demand

ACTORS	ACTIONS 1	ACTIONS 2	ACTIONS 3
Banks, financiers, investors	Use climate and Sustainable Development Goal–informed audits to assess sustainability of investments in cooling projects	Create financial instruments to support clean cooling businesses (e.g., cooling-as-a service, bulk procurement)	Create "cooperation-competition" funds with manufacturers to support early-stage research and technology development
Nongovernmental and philanthropic organizations	Sponsor advocacy campaigns Create and disseminate knowledge Increase stakeholder capacity for implementation of sustainable cooling	Provide catalytic funding for high-impact demonstration projects	Track and report progress toward achieving sustainable Cooling for All goals
Academia	Improve needs assessment methodology and sustainable cooling assessment templates, including consideration of effects on adaptation, society, and gross domestic product	Study and pilot integrated system designs (community cooling hubs, smart thermal networks, open-source thermal energy systems)	Invest in basic cooling-related research and training Develop step-change, manufacturing, and supply chain innovations
Consumers of cooling services	Use alternatives to cooling, natural cooling solutions, and behavior changes to reduce demand for artificial cooling	Drive demand for clean, highly efficient cooling technologies by considering energy and emissions targets and cooling performance in purchasing decisions	Conduct regular maintenance and responsibly dispose of used refrigerants and cooling appliances

"THE ROADMAP IS FRONTLOADED WITH NEAR-TERM ACTIONS BECAUSE OF THE URGENCY OF INTERVENTIONS."

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ROADMAP PHASE 1 (2020–2030)

The first decade of the roadmap is the decade of readiness and quick results. Box 7 shows examples of targets that could be pursued during this decade. Phase 1 features three strategic priorities, which are prioritized because they offer a way to reduce short-term global warming rapidly while laying the groundwork and freeing up government capacity for action and expansion of investments in the second phase of the roadmap:

- **Getting ready**: Actions that are required early because future actions depend on them.
- **Avoiding lock-in:** Actions that must be undertaken to preempt installation of long-lived high-emission alternatives.
- **Investing in low-cost results:** Actions that can be undertaken at relatively low marginal costs, with the potential to avoid high GHG emissions.

BOX 7: INDICATIVE TARGETS FOR 2030

- Greenhouse gas emissions from cooling applications have stabilized.
- Hydrofluorocarbon consumption is at least 10 percent below baseline in most countries.
- Air conditioning units meeting Global Cooling Prize specifications are in the market at competitive prizes.
- Newly installed air conditioning equipment uses less than half the energy of average new equipment in 2020.
- Most major cities use cooling-informed urban planning.
- Mobile air conditioning units use low-global-warming-potential-refrigerants and are 50 percent more efficient than 2020 models.
- Diesel-powered mobile refrigeration has been eliminated from new trucks.
- Cold chain mobile data platforms and rural cold hubs have been successfully piloted.
- The vaccine cold chain has global reach.
- Most countries have national cooling action plans and drive cooling efficiency with strong minimum energy performance standards.
- There is no shortage of skilled cooling technicians.

The background work on the roadmap identified many actions that fall into these priority categories. Analysis of the action database and its linkages highlights the importance of actions necessary to prepare for broad-based, strategic implementation actions in later years. A surprising number of these actions fall into the readiness category. There is also evidence of opportunities to reduce GHG emissions from certain cooling activities quickly before technology or market lock-in has taken hold. Some of these actions (e.g., awareness-raising and capacity-building programs) are underway, but need to be expanded and accelerated, especially at the global level. Others should start soon. Several will have short-term outputs; others must continue in the long term to produce results, although as the sector recommendations show, current activities are insufficient and not well embedded in mainstream sectoral work, and only some countries are implementing them.

Overcoming the barriers that have shaped today's cooling industry and revolutionizing cooling markets requires a revolution in thinking and capabilities. Since the invention of the vapor compression cycle, the common understanding of cooling is of consumers meeting their cooling needs by purchasing a cooling appliance (e.g., refrigerator, air conditioner) from equipment manufacturers that have a rapidly growing market for such products. Even in large facilities, where cooling is provided centrally, cooling is usually not considered in the context of energy systems and climate needs, and cheaper first-cost solutions are often preferred over lower life-cycle costs, resulting in inefficient energy use and high GHG emissions. Many recommended actions are designed to correct this market failure (often with negative GHG abatement costs) and go beyond energy efficiency by taking environmental concerns and system synergies into account.

GHG emission reductions and contributions to the SDGs are difficult to attribute to readiness actions, whose impacts can be great but depend on subsequent actions resulting in behavioral, technical, and investment changes and which have greatly varying costs. Costs and primary impacts are much clearer for energy efficiency and demand avoidance actions under the lock-in and low-cost categories, where uncertainties mainly revolve around their longer-term contribution to market transformation.

READINESS ACTIONS

There are surprisingly many readiness actions that should be strengthened or commenced in the first roadmap period. Many can and should be initiated promptly, with achievable outputs by 2025; others can start later and may need to be extended beyond their initial period (e.g., an action could continue into subsequent roadmap periods). Particularly urgent are knowledge and planning tools, advocacy and stakeholder engagement.

Knowledge about cooling is insufficient to fully support evidence-based sustainable cooling strategies. Available data (e.g., at GCI (n.d.), IEA (n.d.), SEforAll) is fragmented and not easily comparable across countries. A cooling data initiative is needed as a concerted effort by research and advocacy organizations to create common datasets (e.g., heat maps, technology options, costs) and (visualization) tools across cooling needs, technical applications, business models, and policy actions. Related academic research, analysis, and ground testing are also needed, including through centers of excellence and living labs. Knowledge facilities, needs, and gaps should be analyzed, followed by investment in cooling knowledge, and sustained over the long run. Box 8 shows some of the data and research needs that the background reports for this roadmap identified.

BOX 8: KNOWLEDGE TOOLS

- Measure losses at various stages of the cold chain
- Improve data about equipment stocks
- Collect case studies on innovative procurement
- Create detailed heat data maps of cities
- Establish human-centered metrics for urban planning
- Benchmark energy use of buildings
- Fill in knowledge gaps for promoting market growth of off-grid space cooling
- Aggregate cooling demand in buildings
- Create living labs for cooling research
- Assess cooling needs of countries and sectors
- Create purpose-driven business models

Planning tools and policy advice are needed to assist planners and policy makers. Tools for sustainable cooling needs assessments (e.g., those based on SDG and GHG targets) are being designed and must be vetted and customized (SEforAll 2019b). The existing technology landscape assessment must be kept updated to track emerging alternatives, costs, impacts, and risks and integrated into planning tools (University of Birmingham 2018b). Developing country parties to the Montreal Protocol Kigali Amendment are preparing HFC phase-down plans, and some have developed NCAPs. Both deserve support, including through financing and implementation plans and inclusion in the NDCs under the Paris Agreement. This will help focus and coordinate actions between and within countries and strengthen political resolve (K-CEP 2019). City administrations need tools and expertise to facilitate heating- and cooling-informed urban design and planning, which is critical to avoid locking cooling-intensive infrastructure into future urban expansions and new cities. Such tools should be provided in conjunction with knowledge generation and technical assistance actions and supplemented by policy advice. Evidence-based advice on policy tools (e.g., MEPS, appliance labeling), delivery vehicles (e.g., CaaS), and incentives (financial, enforcement) will be critical in planning implementation of NCAPs. These actions should be increased over the first roadmap period and should lead to solid outputs by 2025 (with respect to needs assessment and NCAPs) and 2030 (those addressing urban plans and cooling policies). Table 4 and Box 9 show examples of near-term policies and regulatory actions for sustainable cooling.

BOX 9: POLICIES FOR SUSTAINABLE COOLING

- Create and enforce enabling regulatory environment, industry standards, and sector protocols for sustainable cooling and cold chains
- Develop and enforce standards for new and older cars
- Plan urban spaces to minimize heat build-up and retention
- Integrate resilience and urban cooling at planning and site level
- Integrate building energy-efficiency requirements and solar-reflective roofs and walls into building codes
- Establish policies (e.g., tax credits, access to credit) to stimulate market demand for energy-efficient building practices
- Use energy performance standards, appliance testing and labeling to steer consumers to more sustainable purchasing decisions

Awareness raising and advocacy will be equally important and should be directed at policy makers and market participants to coordinate their expectations, behavior, and decisions. The role of cooling in energy security and supply management, human productivity and health outcomes, GHG mitigation and adaptation to climate change, and achievement of various SDGs is not well understood or appreciated. Experience from other programs (e.g., cookstoves, energy efficiency) shows that shaping behavior through advocacy will be a long-term effort that should be introduced as early as possible and is expected to stretch across all roadmap periods.

Stakeholder engagement is at the core of any roadmap (see Section 10), because success will depend on long-term coordination of supply and demand expectations, policy plans (e.g., MEPS), and commercial decisions (e.g., on innovation, investments) that are supported by well-timed (financial) incentives and capacity building. Systematic engagement of stakeholders and actors with the capacity to implement roadmap actions must underpin planning and implementation of coordinated actions over the entire time horizon of the roadmap, although in the short-term, immediate engagement would involve focus on:

- Partnerships with sector-specific **global advisory organizations** (including nongovernmental groups) and their technical experts to promote and include cooling concerns in their work with national partners and in international and national standards, which in turn will influence permitting, production, procurement, and innovation, for instance standards for automotive testing (to include use of AC) and transportation of perishables using cold chains.
- Engagement of **governments**, who control domestic regulatory and incentive actions and can influence international coordination and recommendations. Governments are instrumental in upgrading regulatory standards in their home markets (e.g., MEPS, cold chain product and process standards) and have the capacity to implement them through incentives and enforcement, with strong impacts on manufacturers' production and innovation decisions, in particular if policies and standards are internationally coordinated. But governments need reassurance that domestic manufacturers and consumers can cope with higher standards and may need external assistance with this.

- Engagement with **industry,** manufacturers, and commercial associations will be essential to ensure that innovative technologies and business models support policy action—and to close the supply-demand loop. Manufacturers are key actors in choice of refrigerants and the efficiency of their products but have only recently made efficiency a priority. Although many company research and development (R&D) departments have technologies to support sustainable cooling, these will not be brought to market if market and policy risks dominate company strategies and decisions. It is therefore critical to align commercial expectations with government policies and plans to reduce market and innovation risks—and in turn reassure governments that the equipment and business models needed to meet stringent sustainable cooling requirements will be available.
- Engagement should also include **cities** and other subnational bodies with a significant role in planning and implementing sustainable cooling action.

New business models to meet future cooling demand sustainably will be needed and are emerging. A prominent example is CaaS, which is being piloted (Climate Finance Lab n.d.). CaaS is a pay-per-service model for clean cooling systems, which eliminates upfront investment in clean cooling technology for customers who pay per unit of cooling they consume, strengthening incentives for efficient consumption and, on the technology provider's side, for installation and maintenance of the most efficient equipment possible. An example is the Rwanda "Coolease" program, a partnership between the Rwanda Business Development Fund, Rwanda Green Fund, UNEP United for Efficiency initiative, and Basel Agency for Sustainable Energy. The program finances installation of energy efficient cooling equipment that uses low-GWP refrigerants. Commercial and industrial clients make monthly payments, and the technology provider commits to providing maintenance.

Incentives, in particular financial incentives, can be effective in promoting adoption of high-efficiency, low-GWP cooling equipment; governments, utilities, and other organizations can use them. Incentive instruments should be carefully prepared beginning in the roadmap's first phase, because they can have budget implications, must target specific market segments and circumstances, may be difficult to administer, and might work only under specific country conditions and regulations. Incentive instruments typically lower the first-costs hurdle for consumers, may increase return on investment for commercial buyers, or may redistribute financial or equipment performance risks. Some amount to subsidies, others (loans) redistribute first costs over a longer period (benefiting from lower lifecycle costs), and others offer guaranties or insurance. Some may facilitate specific business models, such as energy service companies, or require specific conditions. For example, property-assessed clean energy–type financing attaches repayments of loans for building-efficiency upgrades to property-assessed taxes (or fees), separating credit risk and aligning benefits and repayments by making both transferable with the sale of a property, which makes property-assessed clean energy dependent on a well-functioning property tax system. Box 10 lists examples of incentive instruments and new business models.

BOX 10: INCENTIVE INSTRUMENTS AND NEW BUSINESS MODELS

- **DEMAND AGGREGATION:** Aggregate demand to decrease acquisition cost of sustainable space cooling equipment, increase market confidence, and spur greater adoption
- **DEBT SUBSIDY:** Reduce first cost of sustainable space cooling using debt subsidy and risk mitigation instruments
- **DEMAND-SIDE MANAGEMENT:** Manage peak cooling loads using utility-led demand-side management and financial measures
- **COOLING AS A SERVICE (CAAS):** Implement CaaS business model, including for district cooling projects
- **PROPERTY-ASSESSED CLEAN ENERGY AND ENVIRONMENTAL UPGRADE FINANCING:** Leverage these approaches to lower the first cost of energy-efficient construction
- **ENERGY SERVICE COMPANIES:** Catalyze investment in sustainable space cooling by developing energy service company capabilities
- **ENERGY SERVICE AGREEMENTS:** Expand access to financing for sustainable space cooling by developing (managed) energy service agreements (a derivative of the energy service company model)

More **technical innovation and dissemination** will be needed to decrease GHG emissions dramatically in the face of rapidly increasing demand and achieve sustainable cooling by 2050. Investment in R&D and technical innovation is a broad portfolio that includes increasing the coefficient of performance of heat pumps and absorption and adsorption refrigeration systems; developing liquid refrigerant-free refrigeration technologies (e.g., thermo-chemical and solid-state); improving thermal energy storage, including improving insulation material at nanoscale for cool storage; understanding new sources of waste and excess heat (e.g., electric vehicles, hydrogen, carbon capture and storage) and designing circularity into new integrated energy systems; and considering improvement in cooling and recovery of waste heat in integrated thermal network, including in electric vehicles.

Researchers and manufacturers need time to develop, test, and prepare these technologies. Incentives are needed to encourage innovation and make these technologies available for deployment and expansion during the second and third roadmap decades. The Global Cooling Prize and similar initiatives already respond to this need, but other public and private actions must join them before 2025 to create the innovations and market demand that determine which technologies and business options will be available to implement sustainable cooling solutions. As has occurred in other sectors, data collection and connectivity, which could be built into new cooling equipment rather than retrofitted, will enable new cooling business models. It is therefore important to provide incentives for the cooling industry and service providers early, during the first roadmap decade, to develop and pilot integrated technical and business solutions, which must be ready to expand access to cooling in future years.

Technician training will be needed to support the expected large increase in cooling demand, equipment installation, and maintenance. India alone may need as many as 100,000 additional heating, ventilation, and AC technicians. In many developing countries, servicing of AC units is a seasonal job performed by inadequately trained handymen. A higher-skilled workforce will be needed as more technically complex, data- and system-connected equipment, possibly filled with flammable or otherwise dangerous refrigerants, becomes more widely available; these higher skills are needed to comply with stricter installation, operating, monitoring, inspection, and servicing requirements, including handling, collecting, and disposing of refrigerants as well as to assure continued high efficiency operation. Technician training, some already supported by the Montreal Protocol Multilateral Fund (MLF), will take time, and governments and industry actors should step up training efforts in the first roadmap decade so that a sufficient number of skilled technicians will be available when sustainable cooling solutions must be expanded after 2030.

Access to cooling contributes in many ways to achieving the SDGs and to climate change adaption, and more and more people will depend on it to survive future heatwaves (SEforAll 2018). Cooling access must therefore be researched and piloted in the first roadmap decade to develop the solutions and enabling instruments that can bring cooling to slums and rural areas and to be prepared to respond to sometimes urgent needs (e.g., in support of food security or vaccination campaigns, as in the COVID-19 health crisis) (Box 11). Meeting many of these cooling needs will require new business models, as well as public coordination and funding, the magnitude of which is not clear, partly because the cooling needs to meet adaptation and sustainable development goals are not yet well understood; partly because the interconnections between (rural) energy and production systems are complex (e.g., in off-grid situations); and partly because technical and organizational solutions and business models for rural cold chains, cold-dependent production, and cooling for comfort and community purposes are only now being developed.

In India, for instance, the National Centre for Cold-chain Development is exploring how integrated community cooling hubs can help farming communities reduce food loss, increase incomes, and meet rural cooling needs in an affordable, sustainable way; this concept is based on the idea of integrating food cold chains with other cold-dependent services (Debnath et al. 2021). The background work for this roadmap therefore suggests increasing R&D, including in cooling equipment, digital supply chain technology, linkages with data-driven business models, piloting of access solutions for at-risk city dwellers and for rural cold chain corridors and village communities, improving the regulatory environment, and developing delivery and financing structures to be ready for deployment in the second roadmap decade.

BOX 11: SUSTAINABLE COOLING, COVID-19, AND OTHER HEALTH THREATS

- Distribution of **vaccines** requires effective medical cold chains, which are lacking in many parts of the world. An estimated 20 percent of targeted health care facilities in countries that Gavi, the Vaccine Alliance supports lack cold chains; where there is equipment, 20 percent is broken, and 50 percent is poor performing or of an older generation. In India, to immunize 60 percent of the population (more than 840 million people) over a 3-month period to achieve herd immunity would theoretically require a vaccine cold chain almost nine times its current capacity for the 390 million annual doses.
- Poor indoor and outdoor air quality weakens health in ways that contribute to vulnerability to the virus. Unconditioned spaces can place thermal stress on people that may be directly life threatening and decrease their resistance to infection (ASHRAE n.d.).
- **Passive cooling** measures with good air flow will reduce risks from trapped particles. Air conditioning can increase risk of exposure to the virus if systems lack good air exchange and filters, which can trap virus particles and must be exchanged with caution. It is believed that an outbreak of the virus in China among restaurant diners in January was due to distribution of particles from the ventilation system (New York Times 2020).
- **Cooling centers** to protect health during heat events can result in at-risk groups of people congregating and provide a route for transmission of the virus. The U.S. Centers for Disease Control and Prevention (2019) recommends that cooling centers be equipped with air exchange systems and located in buildings with tall ceilings and ceiling fans with upward airflow rotation combined with upper-air ultraviolet germicidal irradiation disinfection systems.

Ultimately, **government action** will drive implementation of most aspects of the cooling agenda. A supportive, reliable policy and regulatory environment—with NCAPs and HFC phase-down plans, implementation pathways and financing plans, technology promotion and MEPS, piloting of new business models and public–private partnerships—will be needed in most countries to gain the confidence of the private sector and institutional investors. This is a long-run challenge, with many country-specific details to be considered, but governments must start this process in the first roadmap decade to be prepared for implementation from 2030 onward.

Finding the right **financing** solutions for sustainable cooling is important. Governments, DFIs, and the private sector should prepare new financing instruments and make adequate funding available. There are currently no instruments dedicated to financing access to sustainable cooling. The MLF is limited to the phase-down of ODSs and now also HFCs. The GEF and other sources of climate finance typically focus on energy efficiency and GHG mitigation. The Adaptation Fund and similar sources are insufficient to support access to cooling at the scale needed. Some major institutions (e.g., GCF, World Bank) have begun to develop financing windows for cooling. Access to cooling can also be built into existing development finance arrangements with donor support. This work must grow and lead to substantial financial flows to underwrite the contribution of sustainable cooling to the SDGs and to achieving the Paris Climate Agreement goals by 2050.

ACTIONS TO AVOID LOCK-IN

Lock-in occurs when long-lived or irreversible, climate-polluting technologies are used rather than lower-carbon options that are available now—or soon will be—thereby locking in high levels of GHG emissions for many years to come. Lock-in can have many causes, among them higher first costs or risks associated with a newer technology, habitual decision making and unsophisticated procurement, lack of knowledge or skills for newer technologies, and disregard for negative external effects.[12] Lock-in is a particular concern if it is permanent or leads to large “unnecessary” emissions over many years (in the form of infrastructure investments or long-lived equipment, such as chillers).[13] In some cases, lock-in can be avoided by low-cost interventions. Most actions to avoid lock-in are specific to sectors and cooling applications.

Urban development carries a particular lock-in risk. With the urban heat island effect, large cities with substantial areas of dark pavement and roofs can be 2°C hotter than surrounding areas (Santamouris 2014). Even in developed countries, this can damage the health of populations without access to effective cooling. In response, cities have prepared heat emergency plans and promoted tree planting and lighter colored pavements. Beyond such short-term retrofit measures, heat-informed urban planning and design can substantially mitigate heat generated and retained in cities (e.g., wind flow, water bodies, infrastructure that minimizes the need to run engines and air conditioners). The lay-out of a heat-informed city reduces demand for artificial cooling and increases city resilience and livability (ESMAP 2020c). Furthermore, cooling-informed planning can optimize a city’s energy infrastructure and use waste and free energy for cooling; examples of this are district cooling plants that use cold water as heat sinks, waste cold from liquefied natural gas expansion, tri-generation (power, heat, and cold), and ice storage to balance power grid loads.[14] Conversely, urban spaces planned without heat-mitigating features will not only increased demand for AC and more energy consumption and GHG emissions, which will be difficult to reverse, but will also lack the infrastructure to meet this demand efficiently.

Avoiding this outcome for fast-growing new cities in developing countries requires collaboration with city planners to generate local spatial knowledge and share heat-informed urban design principles. In Asia, Singapore is in the vanguard of such planning. Creating a center of excellence for heat- or cooling-informed urban planning to build capacity and assist city administrations would greatly help cities avoid future heat lock-in; the sooner this action is taken, the greater the mitigation impact will be, particularly when combined with immediate actions such as green buildings and reflective roofs.

New building construction is another area for early action. Green buildings, designed and constructed to minimize cooling demand (and energy consumption), will avoid lock-in of unnecessary high cooling demand for many decades to come. Early action (by 2025) in this area requires awareness raising and decision tools, as well as upgrading building standards to be cooling informed and incorporate passive cooling practices into construction, plus possible added (financial) incentives. For example, the IFC Green Buildings Market Transformation Program sets metrics-driven definitions of what constitutes a green building, rewards property developers for building green, facilitates compliance with building regulations, and promotes direct investment in green buildings (IFC 2017).15 The program’s centerpiece is the EDGE tool https://edgebuildings.com, which can be used to promote sustainable cooling in building design and construction.

12 • Appliances are often replaced when repairs are needed, with an emphasis on minimizing costs and without a focus on the range of alternatives and full life cycle costs, which is a behavioral and economic issue.

13 • Optimal investment decisions made under myopic business conditions can lead to substantially different outcomes than long-term economic considerations and would require a case-specific analysis.

14 • City planning and regulation can also facilitate solar installations.

15 • IFC’s cumulative investment in green buildings is greater than USD3 billion.

Mobile cooling in cars, buses, trucks, and transport refrigeration units is not only fuel intensive, but also inefficient, and refrigerants in vehicles are prone to leakage. Refrigerated trucks usually use diesel fuel to run their onboard refrigeration unit, which should be minimized and eliminated. Stringent emissions standards for new vehicles will lead to better vehicle insulation and temperature management, integration of cooling and vehicle engine power, thermal energy storage, and more battery-powered trucks.

Cooling in vehicles and public transport to enhance comfort and safety will become more prevalent and influence passengers' choice of transportation modes. With a vehicle lifetime of 15 years or more (and re-traded into developing country markets), GHG emissions from MAC are an on-going liability for many years ahead. Choices between individual and public transport systems and related investments will also have long-lasting impacts on mobile cooling emissions. Cities and public transport authorities can promote public transport by offering greater thermal comfort in buses and trains and reduce emissions through modal shift. Long investment cycles require integrating public transport preferences early in the development of urban and countrywide infrastructure plans, particularly in hot climates, where decarbonizing mobile cooling in passenger vehicles will be challenging.

Early (regulatory) action in developed countries will have positive spillovers in developing country markets. Cooperation on testing of vehicles for export, possibly by eliminating low-efficiency, high-emission vehicles, may enhance this effect. MAC fuel efficiency can be improved by increasing transparency and incorporating MAC use into vehicle fuel efficiency test cycles or indirectly through off-cycle credits. MAC energy efficiency improvements of more than 50 percent are possible, and costs are modest. In addition, innovative technologies such as secondary loop MAC units allow a greater choice of affordable low-GWP refrigerants (e.g., HFO-1234yf) while reducing the refrigerant charge and leakage rate (saving money on service and fuel) and avoiding further build-up of HFC banks and refrigerant disposal (Dreyfus et al. 2020). Addressing MAC efficiency early in the first roadmap period will also accelerate the transition to electric mobility by stretching battery range. With the right incentives and its innovative capacity, the automotive industry is in position to manage a quick transition. Background work on transportation cooling suggests that early action must be taken to increase efficiency (Ayres, Stankevich, and Diehl 2020). An effective strategy will include developing emissions and product standards for existing and new cars in developed and developing countries, which could be achieved through established national and international standardization and testing organizations,[16] and promoting cooperation between vehicle exporters and importers to enforce stricter standards.

Accelerated **HFC phase-down** beyond the targets in the Kigali Amendment—and possibly an agreement to adjust the Kigali timeline—should be pursued to avoid lock-in of unsustainable HFC technology. Quick introduction of low-GWP or natural refrigerants in new cooling equipment (replacing hydrochlorofluorocarbons and HFCs) in fast-growing markets will avoid further build-up of HFC banks in equipment and for servicing. Governments should mandate the collection and destruction of obsolete high-GWP refrigerants. While desirable, measures to quickly strengthen and accelerate the Kigali Amendment will be difficult because parties are only beginning to implement it, and further technological and cost improvements are needed. This action is therefore included as a powerful option for the second half of the decade (after 2025).

16 · Such as the United Nations Economic Commission for Europe-sponsored Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be used for Such Carriage.

ACTIONS WITH LOW COSTS

Some relatively quick low- or negative-cost actions should be undertaken in the near term. These typically involve behavioral changes and promotion of market-available, energy-efficient cooling equipment.

With rising incomes and warming climates, new **room air conditioners** are rapidly being installed, and many are much less efficient than what is already available even in developing country markets (IEA 2018). At typically lower first cost for buyers, these AC units will substantially increase power demand and, over time, increase expenses for consumers. Much of this additional demand occurs during peak periods, when power generation is most expensive and polluting, which drives the need for new power plants. Given that inverter technology AC units are about 30 percent more energy efficient, with a payback period of about 3 years, the economic cost of eliminating older models from the market is negative. Evidence suggests that much greater efficiency gains are possible and that scale production will drive down costs. In addition, equipping new units with low-GWP or natural refrigerants will dramatically reduce the problem of rapidly increasing HFC banks and the need to reduce HFC consumption from a high baseline in compliance with the Kigali Amendment.

There is evidence that it is well worth increasing the efficiency of AC units in the market immediately, which could be done using effective instruments and expanding pilot projects already underway. Governments, development banks, and utilities (via mandated demand-side management) have run energy efficiency programs before and possess relevant experience.[17] Some of the multiple methods and instruments available to promote AC efficiency, and that usually target the demand side, are listed below. They can be tailored to various market conditions and should be upgraded or phased in early to become effective before 2025.

- Stringent **MEPS**, which eliminate market access for substandard products, are remarkably effective. Underwritten by a testing and certification program to ensure compliance and an appliance labeling program to inform consumers, MEPS can and should be raised over time to drive further product improvements.
- Competitive **bulk procurement programs** can be a powerful incentive for manufacturers to decrease production costs and innovate, as India's program demonstrates.[18] The public sector does not have to organize them, as a cooperative buyers' club model in Morocco shows (Andersen et al 2020; IGSD and UNEP 2020). These programs typically purchase equipment with demanding energy-efficiency and performance parameters and possibly low-GWP refrigerants, setting examples for other buyers to procure only cooling equipment that is certified as clean and efficient.
- Given lower lifecycle costs of efficient AC units, **performance and cost awareness** may be a sufficient incentive to redirect decisions. Cost information that explains potential savings to buyers can be included on product labels.
- Some programs use **financial incentives**, usually a subsidy that lowers the first cost of efficient units to compete with lower-priced inefficient units. Subsidy programs are expensive but can be worthwhile if they are limited in time and form part of a strategy to raise MEPS.

17 • Examples from the World Bank include the India Energy Efficiency Scale Up Program, which examined efficient ceiling fans and business models for super-efficient AC, and the Mexico Efficient Lighting and Appliances project, which focused on efficient residential appliances.

18 • India has competitively procured 100,000 room air conditioners at greater efficiencies than available in the market (Singh and Gurumurthy 2019).

- **Financial structuring** involves loans with payback installments that lower monthly payments to match the operating costs of an inefficient unit. There are many ways to achieve this—through utility bills, bank loans, or consumer credit cards and secured using various ownership models.
- Various **business models** have sprung up around financial structuring and equipment ownership, from energy service companies to CaaS, which also provide other services (e.g., maintenance). These businesses deserve support to facilitate quick market penetration, optimal operation, and continuous improvement of AC equipment.
- Under certain circumstances, supplemental measures to support the supply side may help encourage policymakers to raise MEPS and make demand-side actions more effective. The MLF supports certain developing country producers and users of ODSs in their transition to substitutes, enabling governments to introduce and enforce restrictions on banned substances in a cooperative process. A recent World Bank project pilot has expanded this concept to the manufacture of energy-efficient AC equipment.[19] Supply-side actions alone may be insufficient but, if designed to enable demand-side actions, can be highly effective.

Optimal installation, monitoring, inspection, and systematic **maintenance** of existing cooling equipment and systems can dramatically reduce refrigerant leakage and power consumption (or maintain energy efficiency), which in turn could lead to 30 percent or more reductions in ODS and GHG emissions.[20] Better maintenance is a low-cost action that some countries may be able to promote or introduce as part of permitting requirements and CaaS-type business models. Action on maintenance will create immediate jobs for newly skilled technicians trained to support rapid growth in the deployment of cooling equipment.

Changes in **consumer behavior** with respect to use of cooling can be encouraged through awareness raising and education campaigns and supported by technology and incentives. Setting a higher default temperature in office buildings and influencing social norms (e.g., dress code) have been shown to reduce cooling demand at minimal loss of comfort. Such low-cost actions can be taken immediately. In addition, integrated smart data technology (enhanced with financial incentives) allows users to operate cooling equipment in a way that helps balance power grid loads. Making cooling part of a wider system is demanding but possible, particularly in cities, during the first roadmap decade. For instance, in the United Kingdom, 300 Asda supermarkets earn extra revenue by helping balance the grid by operating their commercial refrigerators as a virtual cold battery pack—freeing up 13 megawatts of power at peak times (Ambrose 2019).

Installation of **reflective surfaces** and **cool roofs** is another low-cost action that can reduce artificial cooling needs and is recommended for rapid deployment (ESMAP 2020c). Cities can make rules that will allow and encourage building owners to deploy this simple measure and, with immediate effect, reduce heat build-up inside their building by a few degrees, increase comfort, and lower reliance on fans and AC. Cool roof pilots are underway (encouraged by the Million Cool Roofs Challenge)[21] and will be ready to be expanded by 2025. City administrations can also choose lighter building materials for pavements and new construction, and even-better reflective materials are being tested and introduced.

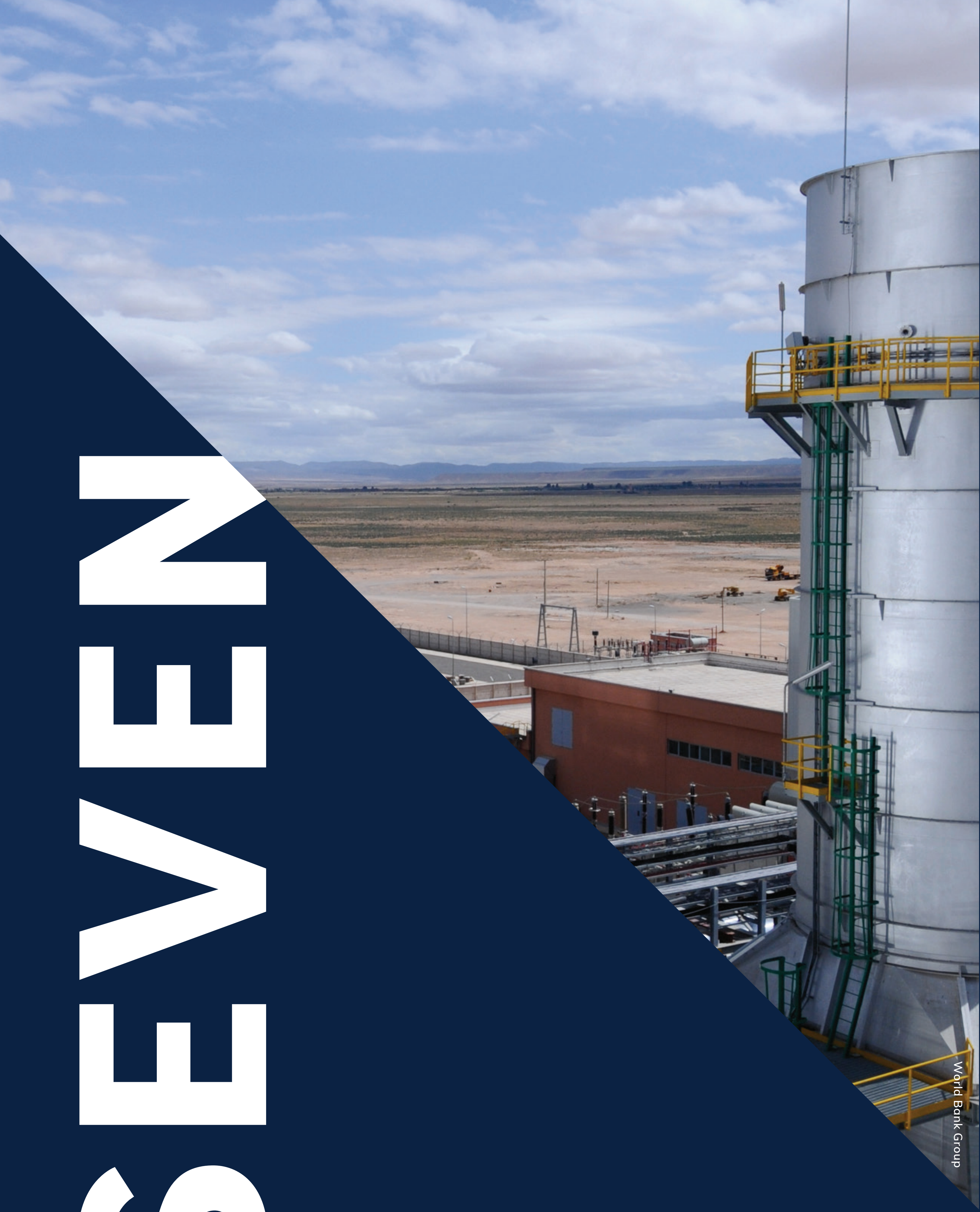
19 • Supporting Market Transformation to Higher Energy Efficient, Lower GWP Refrigerant Room Air-Conditioners (AC) through Manufacturing Readiness (P166806).

20 • Electricity savings of up to 20 percent (700 TWh annually) are possible if equipment has not been maintained for a long time, leading to emissions savings of up to 0.5 gigatonnes of CO_2 equivalent per year (Dreyfuss et al. 2020).

21 • A global challenge to accelerate access to affordable, sustainable cooling through rapid deployment of cool roof materials. Ten finalists have been selected (www.coolroofschallenge.org).

"OVERCOMING THE BARRIERS THAT HAVE SHAPED TODAY'S COOLING INDUSTRY REQUIRES A REVOLUTION IN THINKING AND CAPABILITIES."

SEVEN



World Bank Group

ROADMAP PHASE 2 (2030–2040)

BOX 12: INDICATIVE TARGETS FOR 2040

- Greenhouse gas emissions from cooling are 50 percent below 2030 levels.
- Global hydrofluorocarbon consumption is 50 percent of baseline.
- An accelerated Kigali hydrofluorocarbon phase-down schedule is in place.
- Obsolete refrigerants are being collected and destroyed.
- Highly efficient cooling systems using 20 percent of electricity per cooling unit of new 2020 equipment, at costs not more than 130 percent of 2020 prices, are available.
- Cooling-as-a-Service-type business models supply 40 percent of residential and commercial cooling.
- 60 percent of cooling loads in cities are managed to balance the electricity load curve.
- Thermal energy use in new cooling sites grows by 10 percent per year.
- Solar-reflective coatings, photovoltaic surfaces, green spaces, and water cover 50 percent of suitable city surfaces.
- Food cold chains with farm-to-fork e-commerce connect 35 percent of major cities with surrounding agricultural areas.
- Value-added agricultural productivity has doubled since 2020.
- Food loss in areas with food cold chains is halved.

The second decade of the roadmap is the **decade of market transformation and expansion**. Box 12 shows indicative targets that could be pursued during this decade. Phase 2 must see large investments in efficient clean cooling to meet increasing demand for comfort cooling and enable vulnerable populations in cities and rural areas to access cooling to protect their health and livelihoods while—for the first time—achieving a significant decline in GHG emissions from cooling, despite continued growth in demand. Phase 2 of the roadmap is based on the following two priorities in addition to the capacity-building and readiness work that must continue or be carried over from Phase 1.

- **Expand clean space cooling:** Actions needed to dramatically reduce the energy and emissions footprint of AC in buildings.
- **Increase access to cooling:** Actions needed for greater resilience to heat to protect vulnerable populations in rural areas and city slums and begin building the infrastructure that will be needed to enable and maintain productive economic activities for billions of people in developing countries.

In Phase 2, actions must build on the results of the previous decade. By 2030, the beginning of Phase 2, the readiness infrastructure and the capacities that key actors need to enable expansion must be in place. Based on the knowledge, advocacy, and advisory work of the previous decade (and because of more frequent heat waves), governments will understand why cooling matters for action on climate and for sustainable development of their economies, and— building on the readiness efforts of Phase 1—they will have the tools and willingness to act.

If key developing and developed countries implement Phase 1 of the roadmap, the situation in 2030 may be described by the following achievements, on which Phase 2 builds.

- Implementation of NCAPs and NDCs, which contain actions on cooling efficiency and HFC phase-down, guides government actions. Policies and regulations (e.g., MEPS) and (financial) incentives are in place; standards are being strengthened and predictably enforced.
- Financing for efficient, climate-friendly cooling is available from national and international sources, including MLF, GEF, and GCF. New private sector financing models have been successfully introduced into the market.
- HFC phase-down under the Kigali Amendment is on track. Given technological progress, parties to the Montreal Protocol have agreed to accelerate the HFC phase-down schedule.
- The cooling industry offers energy-efficient, smart AC equipment, with natural refrigerants, sensors, data connectivity, and load-following and renewable energy (solar photovoltaic) options. Technologies that meet the specifications of the Global Cooling Prize are available to consumers. Domestic AC units and whole-building chillers that consume more energy than 50 percent of average new equipment in 2020 are no longer being sold. Domestic manufacturers of cooling equipment have access to knowledge and support to participate in a race to the top.
- Demand has shifted to cleaner, more efficient AC equipment, driven by policies, financial incentives, new financing and business models, “green” procurement, and higher energy and carbon prices. CaaS-type businesses have taken off and are supporting the cooling transition in dozens of countries. Skilled technicians are readily available to service this new market.
- Some new buildings, new urban development, vehicles, and transport systems meet strict cooling and energy efficiency standards. Passive cooling in building design and construction is increasingly common as part of a trend toward net-zero-energy buildings.
- Cooling hubs have been successfully piloted in rural areas. Cold chain mobile data platforms (Uber of cold chain) have been market tested and are poised to change how small farmers connect with urban customers. Some villages have learned how to use cooling for value-added food production, health, and comfort.
- A vaccination campaign in the wake of the COVID-19 pandemic has driven the medical cold chain into remote and rural areas, which makes the case for synergies with rural cooling hubs and shelters more obvious.

READINESS ACTIONS

Readiness and capacity-building actions must continue during Phase 2. As much better understanding of cooling needs, technologies, and market trends develops, governments should update their NCAPs and HFC phase-down plans and continue to support global coordination by updating their NDCs and cooling road-maps. An international network of organizations and experts, working effectively in a coordinated manner, should continue to support governments as they seek to implement policies and finance cooling actions. Governments must update and strengthen policies and regulations, building codes, equipment standards, and incentive instruments regularly to maintain momentum toward sustainable cooling by, among other efforts, supporting emerging cooling technologies, removing obstacles to new business models, and creating an environment that supports the cooling transition.

Accelerating market transformation will require additional significant financial resources because of the sheer size of the cooling market and the higher-cost technologies that must be deployed. Traditional sources of climate and development finance (e.g., GCF, GEF, DFIs) must provide some of the financing to support developing countries. New sustainable cooling funds and facilities must be replenished and expanded to support the cooling access agenda, although most new financing for expansion must come from end users and the financial sector, who would benefit from substantially expanded use of blended finance and much greater leverage generated by concessional sources.[22] As climate heat intensifies, and urbanization and incomes grow, willingness to pay for comfort and healthy and productive living will also increase. The energy- and cost-savings potential available in new cooling equipment and the new business models developed in the previous roadmap decade must now be deployed to convert end-user willingness to pay into ability to pay through, for example, smart financing and pay-for-service arrangements.

Actions to prepare for the net-zero, post-2050 cooling economy, which the third roadmap decade will help build, are also needed. The cooling industries and all relevant sectors, encouraged by competition, innovation prizes, advance purchase commitments, and other rewards, must continue to innovate and develop the technologies that will facilitate using a much broader spectrum of low-GWP energy sources and energy-saving opportunities. Deployment of new cooling technologies in the transport sector, with low energy use and low or zero GHG emissions, may be a challenge, because they must be integrated into electric vehicles and other new vehicle technologies. Governments and public authorities must prepare to systematically deploy and support existing and new technical solutions with much closer integration of energy and cooling systems. It will be essential to develop an understanding that, in a hotter world, cooling must become an essential part of productive public infrastructure in all relevant sectors.

EXPANDING SUSTAINABLE COOLING IN BUILDINGS AND CITIES

Because climate protection and sustainable development are problems of scale, it is essential to realize sustainable cooling at scale. Governments cannot do this alone; it requires the force of markets, although governments can set objectives and influence market conditions to promote sustainable cooling. This market growth will ideally accelerate replacement of the existing stock of less-efficient cooling equipment and make efficient equipment widely available to first-time buyers. In support, the low-cost actions under Phase 1 must be continued and enhanced in Phase 2.

22 • Additional sources of finance may come from an increase in social impact investing and successful demonstration of commercial sustainability from publicly supported projects in Phase 1.

Early replacement of (inefficient) cooling equipment has been a staple of demand-side management programs for residential and industrial users.[23] These programs often operate with **financial incentives**—to make end users aware of the inefficiencies of their older equipment and overcome habits, financial constraints, and procrastination or to buy out the remaining economic value of younger equipment. Instruments such as property-assessed clean energy financing can help building owners justify and finance energy-efficiency upgrades. Other instruments that authorities can employ include inspections, maintenance, and operating requirements in combination with minimum technical and safety standards. Such measures may lead to repairs or retirement, as is typical for aging vehicles.

Governments and standardization bodies can influence the market for new equipment through **technical requirements**—at a minimum for energy and refrigerants used, but also for other features such as safety requirements and possibly sensors and data connectivity. Such requirements can be formulated for each piece of equipment or averaged over a supplier's equipment sold each year (fleet concept). Applying the latter option to energy efficiency, GHG emissions, or refrigerants makes it easier to steadily tighten standards, which drives product innovation while offering manufacturers some flexibility.

Although stricter requirements often come with initially higher costs, actions to lower costs will increase market uptake. There are multiple ways to influence equipment cost; experience has shown that, over time and with mass production, the market price of energy-efficient appliances tends to decrease. Actions to focus demand on more-efficient products can therefore lower prices, as India has experienced through its bulk procurement program. Fostering competition between global manufacturers can also drive down costs. Supporting smaller domestic manufacturers in acquiring the skills, knowledge, technical capacity, and access to critical parts to innovate on their own in a race to meet stricter equipment standards and face global competitors can be an effective and relatively low-cost strategy to expand market access and gain domestic support for higher standards.

Unfair (and illegal) competition by domestic companies and imports of substandard new and used equipment can undercut policies and regulations that direct market participants to sell cooling equipment with higher standards at potentially higher costs. Enhanced testing and **enforcement** capabilities will therefore be necessary. Although this can be a burden on developing countries, the burden can be eased and regulation made more effective through international agreement and cooperation. The enforcement mechanisms for controlled substances under the Montreal Protocol can stand as a model for this.

First-time buyers, who may need inexpensive cooling, may find themselves priced out of a market of high-end, standard-compliant equipment. Governments can meet the needs of this group by helping them finance and purchase compliant equipment, thereby increasing demand, and by promoting access to alternative solutions such as fans, building insulation, cool roof programs, and community cooling centers.

In the second roadmap decade, cities must continue to limit the urban heat island effect by, among other efforts, using reflective surfaces and green spaces, limiting waste heat, and applying the cooling-informed **urban design** principles and plans developed in the first phase of the roadmap. Cities should no longer approve urban developments that do not address urban heat concerns or construction of new buildings that do not meet passive cooling standards. Municipalities should require communal cooling solutions for large residential and commercial properties, from chillers for new high-rise buildings to district cooling solutions.

23 • See for example, the Mexico appliance replacement program (Davis, Fuchs, and Gertler 2013) and the Thailand chiller replacement program (UNEP 2017).

Utilities should work with developers to enable and encourage load-following interconnections to manage cooling and energy supply peaks jointly, including by cycling AC equipment in buildings and cold storage facilities, providing off-peak storage of cold, and using alternative and renewable energy sources and heat sinks. In addition, investment in district cooling in new residential, commercial, and industrial areas must become the norm where natural heat sinks (e.g., lakes, sea water), waste heat and cold (liquefied natural gas), or other forms of cost-effective renewable energy can be used.

BRINGING COOLING TO RURAL POPULATIONS

As heat risks increase, the second roadmap period must emphasize access to cooling for at-risk communities and individuals while helping build resilience, adapt to climate heat, and protect and enhance their economic activities. Based on NCAPs and the pilots and test runs of cold chains and rural cooling hubs in the first roadmap period, governments should increase systematic investment in the living conditions and productivity of rural communities rather than generating additional migration pressures and contributing to the trend of ever-larger urban populations. Although it may be too early to bring rural cooling access to full scale, actions that can be taken in the second roadmap decade can begin to transform life in rural areas, particularly those close to urban centers. Rural access to electricity will contribute to this objective, which the recent success of the off-grid solar industry will facilitate (Box 13).

BOX 13: OFF-GRID ENERGY SECTOR

The off-grid solar industry is only 10 years old, yet even at this early stage, it has delivered quality energy services to hundreds of millions of people—something traditional electric utilities had been unable or unwilling to do.

- In 2009, off-grid solar was almost completely unknown as Lighting Africa kicked off in Kenya. Today, the industry is thriving across Sub-Saharan Africa, Asia, and beyond.
- In 2010, only six products met Lighting Global Quality Standards; today nearly 40 million units of more than 150 quality-verified products have been sold.
- The off-grid energy sector has been succeeding primarily on commercial terms, with more than USD500 million in investment pouring into the sector in the past two years.
- Electrification in Sub-Saharan Africa is out-pacing population growth, which is largely attributed to off-grid solar expansion (Rysankova and Sturm 2019).

The strategy to bring cooling services to rural populations will rest on three pillars:

- Continuation of R&D, piloting, training, evaluating, and raising awareness to increase knowledge about heat impacts and evidence-based rural cooling solutions, including through technologies and systems for livestock and produce cooling that work even without reliable access to grid-connected electricity.
- Promotion of business models and support of commercial operations that foster and monetize productivity gains that farmers and rural communities can benefit from through access to cold chains and cooling in its various applications.
- Government programs and funding to support community cooling, such as medical services, schools, and heat shelters, that increase rural resilience and improve living conditions.

In the second roadmap decade, cooling should be formalized as a critical objective of public health and agriculture programs. Governments should continue agricultural extension and awareness-raising activities on the benefits of cooling for food safety, health, and productivity and increase their investment in cold chain infrastructure (e.g., cold storage facilities). This should lead to further efficiency upgrades and close gaps in cold supply chains, for example, with refrigerated trucks and ice-making facilities for fisheries. These improvements will, however, remain ineffective without an integrated tool to organize the operation and growth of rural cold chains as an organic business challenge. This is critically important because any investments that farmers make in heat-sensitive higher-value agricultural products depend on timely, reliable, low-risk access to cooling.

It is possible that the idea of organizing rural **cold chain corridors** through online and mobile data platforms will become commercially attractive enough for Uber-like mobility companies to invest in developing this idea as a new business line.[24] If this happens, governments should set the conditions under which businesses operate, particularly with respect to environmental and food quality standards. At a minimum, operators admitted to the platform, as well as the platform itself, should adhere to stringent sustainable cooling and quality standards to ensure that no overall increase in GHG emissions is generated from inefficient refrigeration services. This assessment should take avoided emissions from reduced food loss into account. In an alternative scenario, national governments or local authorities could partner with, or support, producer organizations, cold chain service suppliers, urban customers, and others to establish regional cold chain digital platforms as cooperative businesses that adhere to strict sustainable cooling and produce standards.

24 • An example is the e-commerce platform PinDuoDuo, which connects Chinese farmers with urban consumers (www.pinduoduo.com).

It is likely that providing broad-based rural access to cooling will remain a public responsibility and will present complex challenges for many developing countries. **Rural cooling** can be provided more efficiently and sustainably as a shared community service, although organizing this service may be more difficult if cold chain users and villagers use the same facilities (e.g., a cold storage facility or pack house) for different cooling services (e.g., for agricultural production and processing, veterinary and medical services, schools and community shelters, and household refrigeration). Providing access to energy for cooling is an additional challenge.

If cold hub pilots and similar programs in the first roadmap period have confirmed that these challenges can be overcome, governments, in collaboration with multilateral development banks and other organizations, should invest in a range of broad-based rural cooling programs in the second roadmap period. Alternatively, if by 2030, off-grid cooling technologies, businesses, and programs such as Rwanda's "Coolease" program have made substantial progress in bringing medicinal cooling and household refrigeration services to villages, governments should help expand these services to large swathes of the rural population. The success of each approach may be country and sector specific—and will depend critically on the outcome of the first roadmap period.

EIGHT

Amadej Tauses / Unsplash

ROADMAP PHASE 3 (2040–2050)

The third and final decade of the roadmap will see the **emergence of the sustainable cooling economy**.[25] Box 14 shows indicative targets that could be pursued during this decade. In Phase 3, smart urban design, zero-energy buildings, new technologies, and principles of systems thinking must come to the fore; electric and thermal energy symbiosis must deliver advanced efficiencies; and renewables and waste thermal resources must be fully used to achieve net-zero GHG emissions by 2050—all while expanding to full urban and rural access to cooling in a warming world. Achieving both the access and emissions goals will be difficult and uncertain, not least because important aspects are not under the global cooling community's control (e.g., development of grid-connected renewable energy generation, decarbonization of electricity grids, rural electricity access, and technical progress in transport systems and other uses of cooling). Phase 3 is therefore necessarily visionary but no less so than the Paris climate goals, which are both visionary and necessary. This section of the report outlines the challenges of the third decade.

BOX 14: INDICATIVE TARGETS FOR 2050

- Consumption of hydrofluorocarbon refrigerants has ended; remaining supplies are safely destroyed.
- Greenhouse gas emissions from cooling are net zero (including offsets).
- Newly installed cooling systems use only 20 percent of electricity per unit of cooling as in 2020.
- Many cities have thermal networks to harness waste and free thermal resources integrated with electricity supply; trading of energy in thermal networks is routine.
- Mobile cooling in new passenger vehicles and refrigerated transport units is free of greenhouse gas emissions.
- Thermal comfort and medical cold chain services, including protection from more frequent heat extremes, are available to all people at risk.
- Agricultural and food cold chains are widely available, benefitting small farmers.
- Food loss in cold chains is less than 10 percent.

25 · We define the cooling economy as an economy in which human activities critically depend on access to reliable, sustainable forms of cooling for enhanced productivity, health, safety, and comfort, as is, for example, already the case for cities in southern regions of the United States and in the Middle East, where cities face many days with temperatures higher than 35°C and would not be prosperous without cooling—a situation that climate change will make more common.

It is unknown which development goals world leaders will set when the current SDGs expire after 2030, but keeping people safe from ever-more severe heat waves in the second half of the century while increasing productivity and protecting the volume and quality of food to feed billions more people can be expected to be among the new goals to be set. This will be possible only with radical innovations in widely deployed cooling solutions. Seen from a vantage point of what must be achieved by 2050, the expectations placed on the cooling industry are broad and comprehensive, and the responsibility of industry and political leaders to anticipate needed steps, prepare, and implement is daunting.

Development of a cooling infrastructure based on the following priorities will thus characterize plans for Phase 3.

- **Install energy-symbiotic cooling systems:** Actions needed to dramatically reduce GHG emissions by further reducing cooling needs, incorporating cooling into efficient energy systems (including thermal networks and storage), and expanding use of renewable energy for cooling.
- **Make mobile cooling emissions free:** Actions needed to decrease cooling demand while raising mobile cooling efficiency, integrate transport cooling into renewable energy systems, and eliminate fossil fuels from vehicles and cooling transport units.
- **Achieve full access to cooling:** Actions needed to develop a rural cooling infrastructure, based on lessons learned from the previous decade, to enable rural populations to lead healthy, productive lives supplying growing cities with food and resources while protecting the rural environment.

Actions to be implemented during Phase 3 must build on the technologies, lessons, and readiness created by 2040 while considering needs and limitations in 2060, given the long lifetimes of cooling systems. By 2040, a partnership must be developed between population-rich developing countries, developed countries, and the global cooling industry, with a shared understanding that the world needs a smart, climate-friendly cooling infrastructure to address the climate and development challenges of the second half of the century.

If Phase 2 of the roadmap is implemented, the following achievements, on which Phase 3 will build, may describe the situation at the beginning of the third roadmap decade.

- GHG emissions from cooling (direct and indirect) decline to 50 percent of 2030 peak emissions and continue to fall by 5 percent per year while demand for cooling keeps increasing by 10 percent per year. The existing stock of cooling equipment is being replaced at a rate of 10 percent per year. Almost all obsolete ODS refrigerants are being collected and destroyed.
- Access to affordable cooling is still not achieved for hundreds of millions of people, who remain at risk. Heat waves will be more frequent and more intense in various regions, affecting about 2 billion people already living in climates with episodes too hot to handle without some form of cooling. Needs have been assessed, and there is a clear understanding of the remaining gap and necessary remedies.
- The cooling industry offers cooling solutions that consume only 20 percent of the electricity per unit of cooling used by efficient cooling equipment in 2020, with safe non-HFC-based refrigerants, at an average inflation-adjusted first cost not higher than 130 percent of the cost of 2020 equipment.

- Integration of cooling into thermal and electric energy systems, including storage of thermal energy, is well understood and tested. Use of waste heat, free cooling, and waste cold has become more common. Electricity grids in most parts of the world carry about 60 percent of power from renewable sources. That said, integrating cooling systems thinking into investments in energy systems, buildings, cities, industrial complexes, transport, and rural applications while using all available forms of energy is still a challenge in developed and, even more so, developing country contexts with less capacity.
- Training of technicians, engineers, architects, and business managers in sustainable cooling principles continues at pace. There is no shortage of skilled labor for installation and maintenance of cooling equipment. A new generation is planning and ready to invest in the sustainable cooling economy of the future.
- Governments have put in place and are prepared to enforce policies, regulations, and much more demanding efficiency standards and are encouraging the demand that will be needed to create a net-zero-GHG-emissions cooling economy from 2050 onward.
- New large buildings and urban developments are routinely being planned and built to meet strict cooling standards, including passive cooling and zero-energy house principles, with changes in behavior to match. Buildings and cities reflect more and more incoming solar radiation or convert it to electricity, although funding to cool existing towns and cities and build new cooling-informed urban spaces remains limited.
- The vehicle industry has aggressively innovated and invested in e-mobility with efficient mobile cooling. Buses and trains use thermal energy storage for cooling to reduce electrical demand. But for electric passenger vehicles, it is still costly to deliver the on-board power needed for AC in hot climates, as well for long-range battery life and fast charging (which requires cooling). For these reasons, replacing outdated vehicle stocks in hot developing countries with zero-GHG-emission vehicles will remain difficult.
- Good progress has been made on sustainable agricultural cold chains and postharvest, farm-to-fork food management. Several cold chain e-commerce platforms and business models connect smallholder farmers and fisherfolk directly with customers in cities and international markets, which in some cases also serve as medical and veterinary cold chain and rural cooling hubs.
- Bringing cooling to more remote rural areas that lack grid access and have poor road connections remains a challenge. The medical cold chain has reached remote locations but remains difficult to maintain, because these locations may have neither the capacity nor the markets to sustain a cooling economy and will continue to depend on government support.

READINESS ACTIONS

During Phase 3, capacity-building and readiness actions must continue to support expansion and adaptation to changing circumstances. Efforts must be made to integrate these actions with other areas of climate policy and technological development and to prepare for an even hotter world if climate targets (including in the cooling sectors) cannot be reached. Governments and the cooling industry should prepare to participate in carbon markets to offset GHG emissions from cooling to reach emission limits in line with the Paris Agreement goals (assumed to be net zero by 2050). But even if the climate goal is met, some locations may experience repeated heat and humidity extremes approaching or exceeding human tolerance.

Governments must continue to fund cooling R&D, and the cooling industry must continue to innovate to accommodate economic growth and meet growing demand for cooling sustainably. This may require radically different technologies, such as including a carbon-removal function in AC equipment to produce hydrogen as the basis for liquid fuels (Coniff 2019). If these systems are powered using renewable energy, they could become part of the answer to climate change and future energy needs and offer offsetting opportunities to other sectors. Just as solar energy R&D in the 1970s and 1980s established the basis for technologies that are commercial today, research on cooling strategies can make solutions possible that may be needed in the future. Hence, R&D of cooling solutions must not be myopic, favoring incremental changes; instead, innovations with long lead times must be aligned with long-term carbon neutrality goals.

Readiness actions should also address some of the unintended consequences of a fast-growing cooling economy, such as changes in demand for products and services (e.g., fewer outdoor markets, changes in social interactions and activities when people prefer the cooled indoors, more plastic use in cold chains). Such concerns should not stop us from cooling people, cities, and the planet, but they may modify the context and ways in which cooling is delivered and may call for supplemental actions to counter unintended consequences.

Finally, governments must prepare for the requirements of a sustainable cooling economy from 2050 onward—a time when cooling must be delivered in an environmentally, socially, and financially sustainable way, featuring some or all of the following characteristics: full access to cooling for the health and comfort of people at risk; emission-free cooling for productive purposes; operating within the limits of available renewable energy sources; CaaS delivered by service companies, utilities, and others; cooling fully interconnected with energy supply systems; zero-energy buildings; livable, productive, cool cities in hot locations; zero-carbon mobile cooling; compliance with long-term, globally agreed-upon GHG emission limits; and if emission limits are not met, mandatory offsetting of GHG emissions from cooling.

INSTALL ENERGY-SYMBIOTIC COOLING SYSTEMS

Design of cooling systems, integrated with the wider energy and environmental system, requires consideration of all cost-effective technologies, energy inputs (and outputs), markets, and organizational forms. Such designs should meet all cooling needs and maximize SDG co-benefits at affordable costs while allowing for adaptive management of the combined cooling-energy system and saving resources. Systems approaches and CaaS pose complex challenges because they involve trade-offs in terms of costs, risks, timing, ownership, regulations, and system management responsibilities. These challenges can be difficult to overcome in the absence of a central authority unless system infrastructure, technology-enabled and regulated markets, and economic incentives are available that allow and encourage cooling stakeholders to enter into enforceable contracts on sharing cooling and thermal energy between them at low transaction costs.

Based on the description of the principles of systems approaches to cooling (as described in Section 3), it is possible to anticipate certain actions that will be needed to make integrated cooling systems a basis for the cooling economy of the future. For local and city administrations, these include:

- Further reducing cooling needs, discouraging wasteful use of cooling and energy, and encouraging secondary use of waste heat and cold and direct use of renewables and natural heat sinks (water bodies) for cooling purposes.
- Making available the right of way and physical infrastructure for thermal networks (hot and cold) and thermal storage solutions to develop and operate within and between city districts and industrial complexes. Such networks will enable the thermal symbiosis that allows for use of waste and free energy.
- Entering into public-private partnerships to use public buildings and facilities as pilots and anchors for district cooling and heating and thermal networks, including access to free city-owned thermal resources.
- Issuing rules and regulations for, and promoting development of, data systems, smart contracts, and trading platforms to facilitate trading energy in thermal networks; and actively encouraging participation in such trades with city-owned assets.
- Working with local and regional electric utilities and utility regulators to connect thermal and electric networks and enable and encourage load management.

MAKE MOBILE COOLING EMISSIONS FREE

GHG emission-free mobility is a technical challenge for several segments of the mobile cooling market. Although new battery-operated passenger vehicles in moderate-climate developed countries can be expected to be largely GHG-free by 2040, this will not be the case in hot climates and developing countries. Using non-HFC-based refrigerants can be less energy efficient in hot climates, and cooling of vehicles and batteries (to avoid thermal failure, including during fast charging) puts a much heavier cooling load on batteries (up to 50 percent of capacity) than in cold climates, which conflicts with long-range battery requirements. Solutions that deliver more on-board power, thermal storage, or technologies that reduce and manage cooling demand are technically challenging and costly and may be difficult to deploy in developing countries without technological breakthroughs.

Decarbonizing cooling in cars and trucks will remain difficult without radical, affordable mobile cooling innovations and interventions (including in vehicle design and insulation, personal cooling devices). Replacing the fast-growing but outdated vehicle stock in hot developing countries with zero-GHG electric vehicles with cooling included would put additional strains on often weak power systems, making it even more difficult to deploy enough renewable energy to decarbonize these grids. Continuing to service AC units in aging vehicle stocks will involve continued emissions of high-GWP refrigerants, on top of continued fossil fuel use in vehicles.

Relief may come from prioritizing and expanding public transportation systems. Large buses and trains can more easily be equipped with efficient AC units, temperature management, and thermal storage solutions than automobiles. Providing thermal comfort in public transport systems can attract new customers. Shifting mobility to public transport modes will not only reduce energy use but can also help decarbonize mobile cooling. Such solutions require foresight, planning, and long-range political decisions on the balancing of investment in public and individual transport systems. By 2040, sustainable cooling can boost support for public transport and therefore should be integrated early into cooling-informed urban design and planning.

Avoiding or reducing physical mobility through electronic and data connectivity (through the Internet) and autonomous transport and delivery systems is another way to reduce mobile cooling demand. Information-based human connectivity systems (e.g., Zoom)—stress-tested globally during the COVID-19 pandemic—can be expected to handle much (business related) transportation demand. Autonomous vehicles and drones may deliver goods more quickly and with less cooling. Drones can already deliver vaccines quickly in some locations, reducing the energy needed to keep them cold in transit.

Although developed countries will have mostly eliminated diesel-based mobile refrigeration in new transport vehicles through technologies such as better insulation and temperature management, vehicle engine integration, and thermal and electric batteries, developing countries must follow suit by setting similar fuel and emission standards and using these technologies in refrigerated trucks and transport containers with high cooling demand. In addition, more-challenging solutions, such as liquid nitrogen and phase-change materials, must be deployed to decarbonize transport refrigeration fully, including on fishing vessels. Using cold chain services to reach increasing numbers of rural areas will exacerbate this challenge.

ACHIEVE FULL ACCESS TO COOLING

Despite a projected steep increase in cooling services by 2040, access to cooling for all who need it will not yet be a reality in remote rural locations and some poor urban areas. Whereas authorities can provide relief to the urban poor using emergency measures during heat waves, such relief will not be available to rural populations in remote areas without some form of a rural cooling or thermal comfort infrastructure—a service that market forces are unlikely to provide.

Where possible, rural cold chain services may continue to be introduced with government financial support and in combination with provision of agricultural and community cooling services. Where this is not feasible because of remoteness, poor road conditions, long supply chains, or lack of commercially relevant products, government authorities and development organizations must provide minimal cooling facilities. A plan to do this must also work for locations without access to the power grid and without regular (road) transport connectivity and must include the following elements:

- Existing technologies such as passive cooling, water evaporation, wind flow, and shelter construction using local knowledge and materials.
- Mechanical cooling devices such as fans, community refrigerators, and cold storage boxes for vaccines and emergency supplies (brought in occasionally by road or aerial drones). These technologies exist but depend on some form of electric power supply, typically by off-grid generators or photovoltaic or other renewable sources for at least hours per day with good cold retention.
- A plan to finance, deliver, and maintain such rural cooling facilities.

THE NET-ZERO CHALLENGE

After 2050, challenges will remain in fully decarbonizing the growing demand for cooling and further developing the sustainable cooling economy. Developing countries will continue to lag and remain in need of technology, capacity support, and financial assistance. The global community must therefore be prepared to offset remaining emissions from cooling through carbon absorption (including reforestation) in other sectors to meet the Paris Agreement climate goals. But this is not a reliable strategy considering the technical and economic difficulties, the enormous scale that may be needed, and potentially high costs of carbon removal technologies (Dyke, Watson, and Knorr 2021).

Cooling stakeholders around the world, from governments to cooling industries to development organizations, can seize the opportunity to eliminate GHG emissions from cooling gradually using cleaner, more-efficient technologies and systems. Alternatively, cooling demand and supply could remain a persistent, growing problem and present a real obstacle to achieving the Paris goals, climate resilience, and the SDGs. As this roadmap shows, the global cooling community must make this choice today.

NINE

World Bank Group

FINANCE

A range of financial products, instruments, and approaches is needed to deliver specific solutions and address the diversity of cooling access needs and the equally diverse range of financial needs.[26] Decisions on how to address specific cooling needs are often a relatively minor part of a much larger project or objective (e.g., the design of a building). For instance, temperature control is a major challenge for effective delivery of vaccines but is only one of many challenges that public health officials face. The result is that finance for cooling often must be addressed as a secondary consideration or a subproject within a broader context.

COSTS AND BENEFITS

Assessment of finance begins with an appreciation of the magnitude of costs and benefits associated with alternative cooling solutions. Some measures with the greatest potential benefits also require substantial up-front investment and incentives to overcome higher first costs. For example, the IEA (2018) Efficient Cooling Scenario, based on commercial adoption of more-efficient AC equipment—at least initially higher first cost—produces net savings of almost USD3 trillion from 2017 to 2050. The same example illustrates a further economic reality of cooling solutions that who pays is not always who gains. The bulk of the savings from more-efficient AC comes in the form of lower power demand and lower electricity prices, a widely shared benefit. Another version of the same problem exists when owners of rental properties do not pay energy costs and tenants are unable to choose the AC equipment or have short time horizons.

Analysis of the costs and benefits of many cooling options has been relatively limited until recently, and many of the examples available are from the United States and other developed nations.[27] The needs, challenges, and constraints that developing countries face may be very different, especially the poorest and most vulnerable countries. In the near term, it is possible to categorize options based on their initial cost and complexity. Table 5 provides an overview of financial needs according to sector, with likely initial capital requirements for a range of potential measures and sources of investment, but much more work remains to be done in terms of a detailed cost–benefit analysis of roadmap actions. Uncertainties regarding the private sector response to policy measures on the supply (e.g., equipment manufacturers) and demand (buyers and users of cooling) sides, as well as the impacts and valuation difficulties of climate and SDG benefits and any indirect (unintended) consequences complicate this analysis.

26 • Financial challenges and opportunities for sustainable cooling have recently been reviewed in several sources, most recently in SEForAll (2020). A series of reports that UNEP has prepared since 2014 assesses the costs of meeting adaptation needs and the adequacy of funds available from donor sources. The most recent focuses on health-related needs (UNEP 2018a).

27 • Analysis and documentation of cooling measures are becoming increasingly available (e.g., ESMAP (2020a; 2020b; 2020c), with many examples).

TABLE 5: Financial Needs According to Sector, Likely Funding Requirements, and Potential Sources

SECTOR OR APPLICATION	NO REGRETS OR LOW COST	MEDIUM COST	HIGH COST	POTENTIAL FUNDING SOURCE
Food and meal cold chains	• Monitor and collect data on losses • Assess policy measures and guidance packages • Encourage use of cold boxes for food handling • Raise awareness of added value of processing • Provide skills training for processing plant, food, and meal supply cold chains	• Encourage research, development, and demonstration • Create return-on-investment incentives to encourage private sector investment • Develop and implement enabling regulatory environment • Provide technical assistance to farmers in cold chains and postharvest management	• Develop funding infrastructure for food and meal supply cold chains • Invest in aggregation, postharvest management hubs, and cold chains • Develop cold chain logistics that do not rely on diesel	• Public funds from agriculture budgets • Development finance institutions • Philanthropies
Domestic refrigeration	• Increase awareness of importance of domestic and retail refrigeration for food safety, quality, and nutrition	• Encourage research, development, and demonstration, especially thermal energy storage for time-of-use management (peak shaving) and resilience	• Fund grants for rural households and communities to purchase domestic refrigeration • Manage unintended consequences for food markets	• Commercial stakeholders related to domestic refrigeration (e.g., manufacturers, distributors, retailers, industry associations) • Public funding from energy budgets

SECTOR OR APPLICATION	NO REGRETS OR LOW COST	MEDIUM COST	HIGH COST	POTENTIAL FUNDING SOURCE
Buildings	• Increase awareness of passive cooling methods • Benchmark energy use of buildings, passive cooling, and natural ventilation • Leverage various approaches (e.g., property-assessed clean energy) to lower first costs of energy efficient construction	• Develop and enforce building codes to accelerate use of passive cooling strategies • Enhance thermal insulation of buildings • Use appliance labeling to indicate energy efficiency • Create financial incentives for space cooling	• Provide incentives for good design • Provide debt subsidies for space cooling • Develop, strengthen, and enforce minimum energy performance standards for cooling equipment	• Private sector investments in buildings • Public support from energy and utility budgets • Development finance institutions • Kigali Cooling Efficiency Program and other philanthropies
Medical supply chains and role of cooling in responding to COVID-19	• Raise awareness of importance of temperature control for medical product integrity generally and specifically for COVID-19 • Provide skills training for medical cold chains • Promote greater use of low-cost insulating and cooling devices	• Encourage research, development, and demonstration • Encourage private sector financing through return-on-investment incentives • Develop and enforce enabling regulatory environment	• Invest in processing hubs and medical cold chains	• Public funds from health budgets • Development finance institutions • Health-focused international organizations, philanthropies, partnerships and financing initiatives

SECTOR OR APPLICATION	NO REGRETS OR LOW COST	MEDIUM COST	HIGH COST	POTENTIAL FUNDING SOURCE
Retail cooling	• Provide skills training for retail display	• Encourage research, development, and demonstration • Encourage private sector financing through return-on-investment incentives	• Fund rural retailers to purchase sustainable retail cooling equipment	• Commercial stakeholders related to retail cooling (e.g., manufacturers, distributors, retailers)
Animal management	• Raise awareness of animal heat stress • Provide skills training for cooling of livestock • Develop cell phone apps to inform pastoral herders about land areas with drought and heat stress risks	• Encourage research and development • Encourage private sector financing through return-on-investment incentives • Develop and enforce enabling regulatory environment	• Give grants to farmers for animal heat stress mitigation equipment and technology • Fund demonstration of and investment in sustainable, zero-energy cooling approaches, technologies, and equipment for livestock cooling • Invest in commercial and mobile semen stations and associated cold chains	• Public funds from agriculture budgets • Development finance institutions • Nongovernmental organizations and philanthropies with a focus on rural agriculture and development

SECTOR OR APPLICATION	NO REGRETS OR LOW COST	MEDIUM COST	HIGH COST	POTENTIAL FUNDING SOURCE
Thermal comfort	• Develop tools to calculate potential risk and cost of heat stress in most-vulnerable urban and rural areas • Provide skills training for sustainable thermal comfort equipment	• Encourage research, development, and demonstration • Create return-on-investment incentives for private sector financing • Develop and implement measures to improve enabling regulatory environment	• Create return-on-investment incentives for private sector financing • Expand access to financing for space cooling • Fund installation of sustainable cooling equipment approaches in clinics, hospitals, schools, and workplaces	• Commercial stakeholders with interest in thermal comfort (e.g., manufacturers, distributors, retailers) • Funding sources with interest in health promotion
Transport standards and modal shifts	• Develop guidelines for modal shifts • Develop technology options list • Convene governments, international organizations, manufacturers, and other stakeholders on transparency and policies relating to vehicle fuel consumption and emissions • Expand skills training related to mobile air conditioning maintenance	• Develop, implement, and enforce standards	• Demonstrate and pilot new technology for low-emission mobile air conditioning	• Broad range of public and private stakeholders involved in transport • Development finance institutions • Nongovernmental organizations

SECTOR OR APPLICATION	NO REGRETS OR LOW COST	MEDIUM COST	HIGH COST	POTENTIAL FUNDING SOURCE
Urban planning	• Identify energy-efficiency options and existing mitigation opportunities • Create heat data maps of cities • Expand urban forestry efforts	• Establish requirements for energy efficiency, solar-reflective roofs, and walls in building codes • Increase reflective infrastructure in urban settings • Build thermal networks	• Launch demonstrations and pilots of urban cooling solutions • Build thermal networks	• Collaborative initiatives focused on climate change and cities (e.g., C40; Development finance institutions with sustainable city programs) • New financial products (e.g., resilience bonds)

Note: Cost categories (low, medium, high) were assigned to groups of actions taking an economy-wide perspective. Costs include all strategy- and program-related costs that all stakeholders and participants (public, private, individuals) incur (Fakhri et al. 2017). The relatively high economic cost of policies and regulations includes public and private costs throughout the implementation timeframe of the regulation, whereas the lower costs of financial incentives do not include transfer payment components (which are not counted as economic costs). Costs were estimated based on historic technical and cost characteristics of similar programs (Mislick and Nussbaum 2015; ReSpa 2018).

ACCESSING CAPITAL

At a commercial level, large air conditioner manufacturers are well resourced and have good access to private capital, but there are concerns that these companies remain wedded to the established vapor compression cycle and have been slow to risk large investments in R&D and make the even larger investments required to develop and commercialize innovative alternatives. Thus, the Global Cooling Prize was designed to attract interest in radical innovation in AC equipment.[28] The challenge is market acceptance of typically higher first costs for more-efficient products, which can be addressed through MEPS, consumer subsidies (e.g., utility rebate programs), and innovative approaches such as bulk procurement.[29] Some mix of public and private support may be needed to promote greater risk taking and investment in R&D and innovation.

Although there is tracking and reporting of donor funding for resilience (Buchner et al. 2019) and some funding from public budgets, data on private sector financing for adaptation have been difficult to obtain because definitions of financing categories are inconsistent. Also, such investments "are often integrated into business activities and are therefore rarely stand-alone activities or among those called 'adaptation', making

28 • Three of the eight finalists and the two winners of the prize are established AC equipment manufacturers (Kalanki, Winslow, and Campbell 2021; www.globalcoolingprize.org).

29 • There are many small regional air conditioning companies that may not be as well-resourced as their large multinational competitors but have significant market share in their country or region. These companies may need help obtaining financing on commercial terms.

them hard to track or monitor. Similarly, investment databases lack the contextual information needed to identify whether an investment has any relevance to adaptation or may be too sensitive to release" (UNEP 2018a, 25). The amounts reported have tended to be modest; for example, the Global Landscape of Climate Finance 2019 report (Buchner et al. 2019) found that adaptation flows were USD30 billion (almost all bi- and multilateral climate finance formally labeled for "adaptation"), versus USD537 billion for mitigation for 2017/18, with another USD12 billion for cross-sectoral allocation.

FINANCING ACCESS TO COOLING—AN ADDED CHALLENGE

Some access to cooling will be difficult to provide without some combination of new business models and public support. This includes small farmers and fisherfolk without access to cold chains to preserve their products, health providers that depend on cooling for delivery of vaccines to rural areas, and slum dwellers exposed to extreme heat. Meeting these needs involves several challenges, including high transaction costs associated with serving many "uncreditworthy" small customers. Several innovative business models have shown promise for meeting these needs, including farmer producer organizations, pay-as-you-go, CaaS, and public bulk procurements (Dreyfuss et al. 2020; SEforAll 2019a; 2020). Cooling for delivery of public health and protection of slum dwellers from heat extremes is likely to remain dependent on public budgets and donor support.

Tracking financing for access to cooling is another urgent need.[30] As a recent SEForAll Knowledge Brief indicated, "a formal tracking effort to understand access to cooling finance remains a key need for the community in order to establish a comprehensive baseline for investment, understand the trends and gaps, and to redirect efforts where further effort is required." Meeting this need will not be easy because "a substantive methodology to track access to cooling finance would therefore recognize that cooling finance exists as a subset of finance for access to energy, renewable energy, energy efficiency, and non-energy investment across the spectrum of cooling needs" (SEForAll 2020, 11).

FINANCING CHALLENGES FOR CITIES

Financing for city planning and heat action plans is another category of need. This challenge was addressed in a GCF–European Bank for Reconstruction and Development project for a green cities facility to support climate mitigation and adaptation initiatives in 10 cities that includes among its objectives "concessional financial instruments that will allow ambitious investments in climate-resilient urban infrastructure such as district heating/cooling, low-carbon buildings, and solid waste management" (GCF 2018, ESMP 2020c).

Much of the financing needed for cities and providing access to cooling must be some combination of grants and highly concessional loans. "Such funds are critical for multiple purposes, including technical assistance for country climate programs or NDCs and enabling policies at the national and local level, e.g., appliance efficiency regulation, building code development, and implementation of cooler cities programs; support for research and development of innovative technologies; capital for small businesses offering cooling services; and financing for low-income consumers. Donor support for such activities is therefore crucial" (SEforAll 2018, 56).[31]

30 • The absence of consistent definitions, tracking, and reporting for climate adaptation investments, including many measures relevant to sustainable cooling, was the focus of a recent report from the Climate Policy Institute (Richmond and Hallmeyer 2019). SEforAll (2021) has recently proposed a framework for tracking cooling investments.

31 • Financial flows for all forms of energy access have been limited. A review undertaken for SEforAll (2017, 11) found that "finance commitments for decentralized energy solutions are miniscule, accounting for roughly US$200 million per year, or only one percent of total trackable finance for electricity committed in 2013/14 across the [20] high-impact countries."

Some cooling challenges have been underappreciated and thus also underfinanced. One is support for training to install and maintain AC equipment properly; when equipment is poorly installed or maintained, energy consumption can be 50 percent greater or more.

SOME PROMISING SIGNS OF ADDITIONAL DONOR FUNDING

There are signs that multilateral development banks and other sources of climate finance are beginning to recognize the importance of sustainable cooling and the need to provide developing countries with the resources to promote it (Orozco, Hawkins, and Sharma 2020). The GCF (2016) and GEF (2016) have for many years approved projects to help finance more-efficient buildings and appliances. The GCF Green Cities Facility and two winners of the GEF Challenge Program for Adaptation Innovation have potential to address heat extremes and promote sustainable cooling, although not as a primary objective.[32] Donor support also helped create and expand the IFC EDGE program, a source of technical assistance for design, certification, and financing of green commercial and residential buildings.[33] Passive cooling measures are a significant element of the program. As the largest dedicated sources of funding for climate change in developing countries, the GCF and GEF must play more active roles in promoting sustainable cooling solutions. These funds have not specifically identified cooling as a priority or addressed the need to coordinate refrigerant replacement with energy efficiency. By working with the World Bank and other DFIs, these funders may be able to support the institutional reforms needed and incorporate cooling as a secondary element (or subproject) within climate finance and larger sector-focused programs (IFC 2013).[34]

One short-term need is to coordinate refrigerant replacement projects that the MLF supports with increases in the energy efficiency of appliances (Eil et al. 2019). There is a risk that refrigerant replacement could otherwise increase net energy consumption and GHG emissions. Both should be encouraged to promote innovative business models with the potential to attract more private investment and to assume risks beyond those acceptable to DFIs and commercial sources of finance. Since the World Bank became an implementing agency in 1991 and began helping developing countries comply with the Montreal Protocol, its focus has been on replacing ODSs (World Bank 2015), but with the creation of K-CEP, it has been able to expand its focus to sustainable cooling solutions (Orozco, Hawkins, and Sharma 2020).

K-CEP and other sources of philanthropic support, although also limited, have been increasing their contributions to sustainable cooling solutions. With initial financing of USD51 million, in 3 years, K-CEP has supported work in 52 countries; facilitated the proposal, adoption, or implementation of 15 new national policies; enabled 71 new cooling efficiency proposals; engaged in 45 business partnerships; and identified 35 potential investments (K-CEP n.d.3). K-CEP has also made a significant contribution to the World Bank's involvement in sustainable cooling in the form of a USD3 million grant to the Energy Sector Management Assistance Program, supporting technical assistance to ensure that efficient cooling is included in new WBG investment projects and mobilize further financing (World Bank 2019a). With K-CEP support, the WBG has been exploring possible cooling components in a wide range of projects, including health, agriculture, urban development, and green buildings. The commitment of philanthropies to climate change generally has grown

32 • The winners of the GEF competition included a climate technology center and network to help mid-sized cities access financing for climate adaptation technologies and a Conservation International fund that will provide training, investment, and market access to adaptation-focused small and medium enterprises in Madagascar and Liberia (GEF 2019).

33 • The U.K. government funds EDGE, which Switzerland's State Secretariat for Economic Affairs originally funded. Austria, Canada, Denmark, the Energy Sector Management Assistance Program, the European Union, Finland, GEF, Hungary, and Japan have provided additional support (www.edgebuildings.com/).

34 • A World Bank project along these lines proposing a sustainable cooling facility for GCF funding is in preparation.

as well. In September 2018, 29 philanthropies pledged USD4 billion over the following 5 years to combat climate change—the largest-ever philanthropic investment focused on climate change mitigation (Philanthropy New York 2018). In 2020, Amazon founder and CEO Jeff Bezos announced an even larger commitment to create the Bezos Earth Fund with USD10 billion to address the climate crisis (Schleifer 2021).

The strategy underlying the climate funds increasingly aims to mobilize private capital. One example is the Climate Investment Platform (CIP n.d.), an initiative of the GCF, United Nations Development Programme, SEForAll, and International Renewable Energy Agency. The goal is to mobilize USD1 trillion in clean energy investment in 20 least developed countries—countries particularly dependent on external support—by 2025. In support of its ambitious goals, the Platform has four tracks, all potentially relevant to sustainable cooling: ambitious clean energy goals in NDCs, policies and regulations for clean energy investments, financially de-risking clean energy investments, and access to capital markets to connect clean energy investors with projects (IISD 2019).

EARLY-STAGE FINANCING FOR INNOVATIVE MEASURES

Financing for early-stage innovative technologies and business models is usually difficult to obtain from commercial sources. For example, successful commercialization of solar and wind technologies, now both highly competitive clean energy sources, with many billions of dollars in investment, initially depended greatly on public subsidies. Box 15 presents examples of successful public support for early-stage R&D.

The Global Lab for Innovative Climate Finance, created in 2014, is an innovative approach to developing proposals for climate-related investment concepts with the potential for commercial sustainability (Climate Finance Lab n.d.). Public and private funders periodically call for ideas and select those that are most promising for analysis, stress testing, and guidance from experts and investors. Lab members vote to support the ideas that appear most promising, an endorsement that is often the basis for substantial additional commercial investment. One recently endorsed Lab concept is CaaS, which the Basel Agency for Sustainable Energy and K-CEP developed. In March 2020, the Basel Agency for Sustainable Energy in turn supported five pilot proposals providing free technical, legal, and financial assistance, including contractual arrangements, pricing strategy, financial structuring, and risk-mitigation mechanisms. At the end of the incubator program, the aim is to have CaaS providers fully equipped to launch their first demonstration projects. The five winners came from different parts of the world (Nigeria, India, Argentina, Costa Rica, Grenada) and proposed a range of approaches and business models (Climate Finance Lab 2020).

The IFC TechEmerge program connects high-impact technology solutions from around the world with clients and technology users in emerging markets to increase awareness, test and validate new solutions, and de-risk technology adoption. TechEmerge recently launched a program to support sustainable cooling innovation and, in a recent review of innovative cooling technologies, concluded that the program can help surface new technologies, match local technology users with international innovators, and increase the visibility of innovators and their technologies.

BOX 15: IMPORTANCE OF PUBLIC SUPPORT FOR EARLY-STAGE RESEARCH AND DEVELOPMENT (R&D)

Innovative technologies are required to meet many cooling needs and achieve climate and development goals but attracting early-stage finance can be difficult. Although there are many promising ideas for radical improvements in cooling methods and technologies, attracting the necessary capital for early-stage R&D is almost always challenging because of the high risk of failure and the lengthy commitment typically required to achieve profitability. If the product is designed to provide a public good such as health care for the poor, attracting finance will be even more difficult. This rationale was recently evident in a proposal for funding of technology for direct air capture of carbon dioxide by an influential group, the Bipartisan Policy Center. While noting that the "barriers and unknowns aren't trivial," the report concluded, "By supporting vigorous R&D efforts and by creating policy incentives for early commercial deployment, the U.S. government can help ensure that DAC [direct air capture] costs come down and that U.S. companies have the intellectual property advantages and implementation experience to compete successfully in future global markets for this and other CDR (Carbon Dioxide Removal) technologies" (Bipartisan Policy Center 2020, 15).

The role of government support for photovoltaic modules illustrates the potential payoff from public funding of early-stage clean energy. The cost of this technology has declined by 99 percent over four decades and is now increasingly competitive with large-scale power applications in many parts of the world (Morton 2020). A detailed analysis by researchers at the Massachusetts Institute of Technology explored the factors responsible for reducing costs over time. The authors concluded that "increased module efficiency was the leading low-level cause of cost reduction in 1980–2012, contributing almost 25 percent of the decline. Government-funded and private R&D was the most important high-level mechanism over this period" (Kaviak, McNerney, and Trancik 2018, 1; see also Chandler 2018; Pew Charitable Trusts 2015). After 2001, policies to promote market growth helped overcome higher first costs, and as scale increased, costs steadily declined.[a]

a • Another study compared early support for renewable energy with that given to nuclear and fossil fuels and concluded that support for nuclear energy was five times as great, and that for fossil fuels was 10 times as great, at least in part because of opposition from entrenched industries (Johnson 2011).

Several financing challenges, beyond the need to make much more money available for cooling efforts, appear to be most pressing: support of early-stage R&D on innovative technologies, funding for innovative business models, greater incentives for design changes and passive cooling measures, and exploring de-risking instruments with the potential to attract much greater private investment. Development of financial initiatives and new instruments to mobilize public and private sector finance for sustainable cooling is another area that needs urgent attention but will require time to implement, evaluate, and expand—a sequence addressed in the preceding sections.

“SOME ACCESS TO COOLING WILL BE DIFFICULT TO PROVIDE WITHOUT SOME COMBINATION OF NEW BUSINESS MODELS AND PUBLIC SUPPORT.”

TEN

World Bank Group

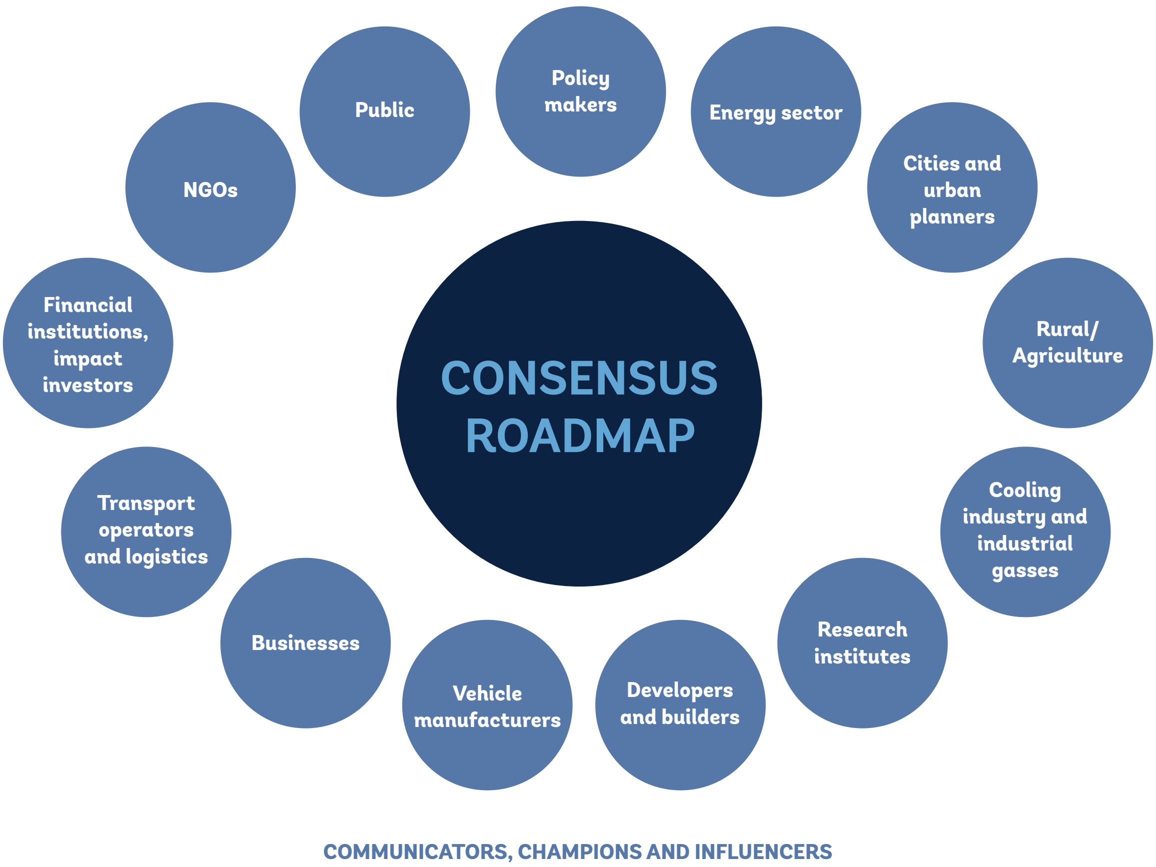
ROADMAP IMPLEMENTATION

A roadmap for sustainable cooling will necessarily evolve in stages, with increasing awareness, knowledge, support, and policy interventions driving technology research, new business models, capacity building, and better integration of thermal demands within energy strategies. It will further require an ongoing flexible process to accommodate lessons learned and changing conditions. Recognizing the need to engage a wide-ranging cooling community is the starting point for implementation.

ROADMAP DELIVERY PARTNERS

A successful roadmap must bring global expertise from multiple sectors together to bring near-term solutions to market and to define and implement the step-change pathways that will eventually lead to sustainable cooling (Figure 9). The capacity of actors and supporters to implement roadmap actions is therefore an important factor in making realistic plans and producing the intended outputs and outcomes.

FIGURE 9: Key Intervention Delivery Partners



The roadmap identifies the types of stakeholders and actors that must come together to implement proposed actions. Assessing their willingness and capacity to act will require systematic, extensive engagement with the global cooling community and individual stakeholders—a time-consuming process. The proposed sustainable cooling roadmap is a preliminary version that will accommodate changes that emerge when negotiating broad stakeholder support for its implementation. A final revised roadmap should drive government and industry cooperation, align policy with finance, shape academic research agendas, and accelerate transition of innovations to market and widespread adoption at scale.

The sustainable cooling agenda has many stakeholders (e.g., manufacturers, retailers, service providers, cooling user groups, governments, city planners, financing institutions, academia). Manufacturers and governments, in addition to enabling and development partners where needed, will play an important role in bringing this diverse community together. Growth in demand for cooling equipment and services will mean substantial business opportunities, but these opportunities can be realized only if this growth aligns with sustainability goals. The successful creation of a community of shared interests in response to the Montreal Protocol provides reason to believe that this collaboration of sustainable cooling stakeholders is achievable.

BOX 16: ACTIONS REQUIRED TO DELIVER THE ROADMAP

- Bring key intervention delivery partners to a common viewpoint to enable a consensus around implementing a shared strategy
- Understand the size of the challenge by conducting a comprehensive needs assessment that recognizes the important role of cooling in adapting to climate change and achieving the SDGs
- Plan for future global warming and cooling needs, taking into account that mitigation pathway outcomes are uncertain and consequently mapping multiple parallel scenarios
- Engage the range of actors necessary to bring together technology and system innovations into a cross-sector integrated systems-of-systems approach
- Support countries in formulating plans to accelerate supportive policy and financing environments
- Identify the need for new manufacturing capability and supply chain innovation and develop interventions to drive them
- Recognize the skilled workforce needed to meet the growing cooling demand with efficient and sustainable products and design, install, and maintain them
- Demonstrate impact of new solutions to accelerate transition of innovation to market and widespread adoption
- Identify, plan for, and mitigate unintended consequences from introduction of sustainable cooling solutions

IMPLEMENTATION PROCESS

Five broadly defined activities are needed to deliver the roadmap and begin to implement it: reaching agreement on the roadmap and its goals, targets, and priority interventions; creating specific, detailed action plans; deciding who will do what and within what timeframe; creating a tracking system for monitoring, evaluating, and reporting on progress and challenges; and assigning responsibility and establishing a timeframe for updating the roadmap and action plans. In addition, Box 16 suggests some specific actions that may be required to build a consensus roadmap.

1. REACHING AGREEMENT ON THE ROADMAP

This roadmap offers a platform for discussion and a starting point to build agreement with partners on a more-elaborate strategy and global roadmap action plan. The diverse range of cross-cutting operations covering sectors and regions complicates leadership and direction. In some areas, the Word Bank has expertise and an established leadership role (e.g., in energy efficiency), whereas in others it may wish to play a more limited role in support of established networks or other more appropriate organizations.

- Given its operational priorities and the large community of actors, the World Bank has a choice. One option is to rely on other organizations to organize the engagement process and coordinate the global cooling community around a cooling roadmap. Another option is to create a more formal engagement process around roadmap actions that it may wish to undertake or lead. The Energy Storage Partnership that the WBG and 29 organizations initiated to develop energy storage solutions tailored to the needs of developing countries is an example of the latter, more-formal engagement option (World Bank 2019b).
- The Global Roadmap of Action Toward Sustainable Mobility (World Bank 2019c) is another example of what is needed to build consensus around a global roadmap. A broad coalition of stakeholders developed it over several years, with technical expertise and coordinating leadership from the World Bank. The Global Roadmap on sustainable mobility provides a detailed analysis and implementation tool for countries to achieve the four distinct elements of sustainable transport: universal access, efficiency, safety, and green mobility. As with cooling, innovative technologies will be required, as well as government leadership. The Global Roadmap on sustainable mobility outlines a process for countries to decide on an appropriate path, recognizing that there is no "one size fits all" solution and that some actions will require considerable time to achieve.
- Implementation challenges for a roadmap on sustainable cooling are even greater, because the global cooling community is very diverse, covering multiple sectors, and because the current level of engagement is very uneven, lacking effective coordination. A strategy to promote roadmap implementation must therefore be foremost an effort in facilitating agreement among this diverse community.
- As part of this consensus process, the present approach to a roadmap on sustainable cooling will inevitably be scrutinized and revised. Specific stakeholder interests will influence the process to modify its overall direction, targets, and modalities in line with business or political interests and guided by their constituents. It can be expected that much more work on future technology pathways, GHG mitigation potential, and costs will be requested—and needed to foster agreement. An effort to define a pathway and action plan to zero-GHG emissions from cooling is already underway under the umbrella of the Cool Coalition (Cool Coalition et al. 2020; 2021), contributing to the Climate Action Pathways under the Marrakesh Partnership for Global Climate Action (UNFCCC 2019).

2. CREATING DETAILED ACTION PLANS

Forming effective agreement around a consensus roadmap must include commitments from actors who are able and willing to take on specific challenges (e.g., technology development, standard setting), participate in agreed-upon activities in a coordinated manner, and achieve results. This requires a level of specificity that only detailed timebound action plans can provide; these action plans are specific to sectors, challenges, targets, and actors but must still be created—by or in cooperation with actors willing to engage—and must be in line with the global roadmap and joined with other planning processes, such as NCAPs. Managing this process and meeting commitments will be challenging but is essential to ensure that the outputs of the various roadmap activities, often performed by different actors, come together at the right time to produce the desired results. For instance, setting demanding efficiency standards (a politically sensitive process) must be aligned with the time-consuming introduction and commercialization of compliant products.

3. DECIDING WHO WILL DO WHAT AND WITHIN WHAT TIMEFRAME

There is no specific plan for how to make independent actors commit to specific roadmap actions and no formal way to enforce them.[35] In this regard, the roadmap is not dissimilar to international agreements between countries, but for a subset of important actors (e.g., governments, cooling industry), there is a history of cooperation that successful implementation of the Montreal Protocol established and continues, and there is the potential for benefits for all groups involved. Obtaining implementable commitments will involve reaching shared understanding of goals and benefits and fostering an atmosphere of successful repeated cooperation over time. Competent institutions with expertise must support both in an impartial manner.

4. CREATING A MONITORING SYSTEM

Tracking progress made toward specific targets, uncovering failures, and analyzing challenges will be essential for effective implementation of the action plans, to assess the roadmap's success and revise it as needed. The IEA already tracks progress in the AC sector and has good data on AC installations and associated energy use (IEA 2018). In contrast, data on unmet cooling needs (including for agriculture, medicine, and comfort) are partial and irregular, yet SEforAll (2019a) plans to quantify these needs annually and assess progress toward reaching the most vulnerable populations. There are similar tracking programs in other specialized organizations. Recent analyses have indicated a lack of consistent definitions to track adaption-related investments and the impact metrics needed to value resilience benefits (UNEP 2018a; CPI 2020). It is likely that measuring progress in providing sustainable cooling will encounter the same challenges; that is, it may be difficult to isolate the incremental cost of changes in building design following a reduced need for mechanical cooling. Creating a coherent data and results framework, bringing existing monitoring programs together, and filling remaining gaps, must be a part of the roadmap implementation process. This requires technical expertise and organizational leadership, which effective implementation of the roadmap program will have to provide.

35 • The limited exception is the reduction in use of HFCs as refrigerants mandated for parties that have ratified the Kigali Amendment.

5. UPDATING THE ROADMAP

Roadmaps become obsolete as landscapes change. There are also persistent uncertainties about technologies, costs, policies, financing, and shifting national and international priorities, as well as inevitable delays and failures. It will therefore be necessary to update, refine, and revise the roadmap and any associated action plans regularly to ensure continued consensus and effectiveness. These updates must be linked to other international processes, such as the NDC process under the Paris Agreement, increasing levels of climate ambitions, adjustments to the Kigali Amendment, and possibly revision to the SDGs after 2030.

STRUCTURE OF COOPERATION

The roadmap can succeed only if key groups with potentially conflicting interests cooperate. These groups include at a minimum the global cooling industry, national governments, and networking and development organizations. The long-term benefits of sustainable cooling are clear, but barriers to progress remain in the form of short-term commercial interests and governments maximizing political support by sidestepping burdensome policies, which together can result in suboptimal, noncooperative outcomes (e.g., market failure, unsustainable development).

Notionally, a coalition that builds on these key groups could overcome this deadlock by providing a series of repeated, and therefore long-term, benefits to each group.[36] These long-term benefits include business growth and access to new markets for the cooling industries and economic and sustainable development for developing countries, both supported by capacity building and financial flows from networking and development organizations. The Montreal Protocol works similarly: governments collectively regulate consumption of harmful ODSs, the cooling industry benefits by developing substitutes and supplying markets with new equipment, and financial flows and implementing agencies (United Nations organizations, World Bank) support developing countries. All three groups are bound together in a career-spanning global community of practice with its own benefits.

36 · In game theory, this structure could be analyzed as an interdependent repeated game.

Making a global sustainable cooling coalition work requires conditions under which partners cooperate with each other repeatedly. The repetitive structure can turn short-term uncooperative considerations into long-term mutually beneficial interests because repetition makes it possible to retaliate if noncooperative behavior occurs, which can lead to the breakdown of cooperation and the loss of future benefits. The three principal groups of a global coalition may have the following choices and benefits.

- Development organizations (and their donors) may commit to assisting developing countries with capacity and financial flows to access cooling—for improved health, living conditions, and productivity—and help domestic cooling manufacturers stay technologically competitive, thereby advancing their mission and objectives. The Montreal Protocol has shown how to do this.
- Governments would commit to regulating inefficient, harmful cooling technology, thus making foreign assistance effective, and to investing in access to sustainable cooling, thereby enhancing resilience to climate change and generating socioeconomic progress while expanding markets and commercial opportunities for the cooling industry.
- The cooling industry would commit to investing in R&D and bringing needed technology and business innovations to market to meet increasingly stringent sustainability requirements, reassuring governments of successful policy outcomes, and possibly energy and financial savings, while gaining new customers and markets from expanded access to cooling.

This is a simplistic, high-level view of the much more granular and complex dynamics that play out in situations with hundreds of partners and interests, yet it is not unrealistic, especially when dominant partners are involved who can make and maintain credible commitments (e.g., by linking follow-through on commitments to other issues of consequence). For example, government partners can link promised actions and policies on cooling to international agreements (e.g., Montreal Protocol) or include them in NDCs under the Paris Agreement; some partners can create and fund multilateral financial vehicles (e.g., a sustainable cooling window under the GCF); or they can set up and fund large commercial R&D facilities and programs.

An impartial coordinating body, a type of secretariat, not unlike bodies that support international agreements but without executive power, must be established to support an effective, global sustainable cooling coalition. This body would carry out the coordinating functions outlined above and use the roadmap and the associated processes as catalytic instruments to help build and sustain the coalition.

“THESE LONG-TERM BENEFITS INCLUDE BUSINESS GROWTH AND ACCESS TO NEW MARKETS FOR THE COOLING INDUSTRIES.”

ELEVEN

Roxanne Desgagnes / Unsplash

CONCLUSIONS AND RECOMMENDATIONS

This roadmap leads to a number of conclusions and recommendations, many of which are not only relevant in the context of this roadmap. These conclusions are:

1. **Action to promote sustainable cooling is urgently needed** to address climate change and achieve the SDGs.
   - Conventional cooling technologies, such as refrigeration, AC, and fans, account for more than 10 percent of fossil CO_2 emissions. Demand for cooling will grow as the world becomes hotter, resulting in more GHG emissions and leading to a vicious cycle.
   - More than 1 billion people face risks from lack of access to cooling, which threatens SDGs for health, food security, clean energy, labor productivity, sustainable cities, and gender.
   - Current cooling trends are not sustainable. More than 13 cooling devices are being purchased per second, much of it inefficient, often not properly maintained, and frequently operated during periods of peak demand. This trend will require enormous, costly additions to generating capacity and increase GHG emissions.
   - Urgent action is needed to avoid as much as 1°C in warming this century from GHGs used as refrigerants; power consumed by inefficient refrigerators and AC units; and future emissions from long-lived inefficient equipment, buildings, and mobile cooling.

2. **A global roadmap can coordinate global actions toward sustainable cooling.** The roadmap must provide a description of a long-ter m vision for a path toward sustainable cooling by 2050 and help coordinate the actions of the global cooling community over the next three decades. The roadmap must address the many challenges and opportunities involved, describe the diverse community of actors and institutions to be engaged, define goals and targets along the way, outline actions to be taken now and in coming decades, and indicate steps needed to build consensus among stakeholders willing to implement the roadmap actions.

3. **The global cooling community is as diverse as the range of cooling needs and solutions.** The resulting diversity of stakeholders, interests, and constituencies presents a challenge and an opportunity—a challenge insofar as ways must be found to bring together these many different parties and interests and an opportunity insofar as there are many potential sources of technical assistance, innovation, resources, finance, and political support. The cooling community is mostly organized around specific sectors and applications (e.g., AC equipment manufacturers, urban planners, building design and regulation, food and medical cold chains), but there are also gaps in sectors where no effective organizations represent cooling needs and can build knowledge and skills (e.g., smallholder farmers and rural communities).

4. **Several networking organizations and initiatives are working on cooling.** Since the 2016 adoption of the Kigali Amendment, a number of networking organizations have become active in cooling-related areas, including SEforAll and the Cool Coalition in the area of research and advocacy, K-CEP in supporting cooling initiatives, the Global Cooling Prize (Rocky Mountain Institute) in accelerating technical innovation, the Basel Agency for Sustainable Energy in business models, and the Collaborative Labeling and Appliance Standards Program (CLASP) on policy support, but consensus and coordination is still insufficient among the wider cooling community, including governments and the cooling industry, on taking and financing long-term actions that will be needed to realize sustainability goals by 2050.

5. **The goals of simultaneously promoting sustainable development and stopping climate change must guide the roadmap's vision, targets, and actions.** In planning for 2050, the vision and goal should be a sustainable cooling economy based on net-zero GHG emissions and near-universal access to cooling for all countries and development needs. Notional landmarks and intermediate targets must be defined to focus actions, facilitate coordination, and allow for tracking of results and adjustment of plans.

6. **Roadmap actions must address many barriers** that are characteristic of the diversity of cooling markets and applications, including the higher first cost of more-efficient equipment; lack of consumer awareness of cooling challenges; lack of skilled technicians for operation and maintenance; behavioral concerns, such as the "rebound" effect; a weak policy and regulatory environment with inadequate codes and standards; domination of large market segments by a small number of insufficiently dynamic global companies with limited incentives for innovation; insufficiently understood and managed linkages between the many needs for cooling, cooling demand, and resulting energy consumption; and unique challenges in some sectors, such as MAC.

7. **A diverse range of actions that has been proposed to overcome these barriers must be sequenced appropriately to be effective.** Many future solutions, including innovative technologies and business models, are designed to meet roadmap targets; may take decades to fully develop and scale; and depend on near-term efforts by a range of actors to create knowledge, build capacity, develop plans and policies, innovate, and generally prepare. The proposed roadmap actions fall into the following categories of interventions:
    - **Dramatic improvement in technology and innovation** to achieve climate and universal access goals and to identify solutions that do not depend on electricity
    - **Business models** that help overcome the higher initial cost of more efficient equipment, enable proper maintenance, and facilitate access by the rural poor
    - **Policy reforms** to encourage accelerated innovation and market transformation, such as predictably accelerating performance standards
    - **Public and private finance** to support new technologies, expand successful business models, and support urban development and cooling action plans
    - **Capacity building** to make governments, businesses, and consumers more aware of cooling challenges, encourage solutions, identify priority needs, define action plans, and develop the skilled workforce necessary to install and maintain the growing number of cooling devices so that they operate efficiently and safely.

8. **It will be necessary to "think thermally" about cooling, as well as in terms of integrated systems.** Future solutions will require far more than efficient electrically driven appliances. A sustainable cooling economy will be possible only if much greater efforts are made to develop and invest in holistic solutions and aggregate cooling services to facilitate commercial scale. This requires developing systemic approaches, such as buildings that incorporate passive cooling and cool roofs; district cooling using lakes, ocean water, and other free heat sinks; use of waste and free thermal and renewable energy for cooling purposes; and thermal symbiosis in the form of, for example, tri-generation and other multiple uses of thermal energy. Integration of cooling into energy supply networks, with load-following capacity and thermal storage, will equally be needed.

9. **Government leadership is needed to encourage the cooling transformation.** Because the cooling industry is local and global, many solutions must be country specific but also coordinated internationally, which requires government leadership. Governments can promote efficient products through policy reforms on labeling and MEPS, bulk procurement of efficient equipment to lower prices, and training programs for skilled technicians. NCAPs and consideration of cooling in NDCs merit greater support as well as leading actions by sub-national governments. India, for instance, developed one of the first NCAPs and buys AC equipment in bulk to push energy efficiency boundaries and lower costs. Cities in India and elsewhere are working with heat action plans; and a county in Florida (Miami-Dade 2021) has appointed the first "Chief Heat Officer".

10. **The roadmap identifies short-term actions and a long-term vision.** The approach is framed in terms of the next three decades, each with a leading theme:
    - Phase 1 (2020-2030) is the **decade of readiness and quick results** and thus emphasizes low-cost and high-impact opportunities, as well as measures to promote preparedness and avoid lock-in.
    - Phase 2 (2030-2040) is the decade of **market transformation and expansion** and, in addition to further measures to promote preparedness, emphasizes access to cooling and expanding clean space cooling.
    - Phase 3 (2040-2050) will see the **emergence of the sustainable cooling economy,** when systems integration will help meet the net-zero GHG target in line with the Paris climate goals while approaching universal access to cooling.

11. **Financing is a critical need across the spectrum of cooling sectors and markets.** Financing is particularly needed to overcome first-cost barriers, encourage R&D and early-stage innovation, and support business models that work toward universal access to affordable cooling. The potential economic gains are large. For instance, the IEA's Efficient Cooling Scenario produces net savings of almost USD3 trillion from 2017 to 2050. Public (and private) financing of early-stage technologies has been successful in the case of solar and wind technologies, yet only an estimated 0.04 percent of total official development assistance is currently directed at cooling solutions.

12. **DFIs such as GCF and the World Bank are showing interest in sustainable cooling,** following the lead of philanthropic organizations (through K-CEP). Financing sustainable cooling investments and interventions from climate finance and other development finance sources should be feasible given the many possible co-benefits of such investments, yet a decision is still needed on how to finance energy-efficiency improvements in cooling equipment alongside MLF grants to phase down HFCs—a matter that should be resolved quickly.

13. **Implementation of the roadmap depends on consensus among key stakeholders**—chiefly governments, the cooling industry, and enabling and financing institutions—with other organizations at the global and local level (e.g., agricultural cooperatives) making significant contributions. Fostering the needed consensus requires further analysis, engagement, and the following steps:
    - Reaching agreement on a roadmap and its objectives, goals, targets, and priority interventions
    - Developing specific, detailed action plans (e.g., for countries and sectors)
    - Assigning roles to stakeholder actors and institutions and defining the timeframe
    - Developing a tracking system for monitoring, assessing, and reporting on progress and challenges
    - Assigning responsibility and a timeframe for revising the roadmap and consequent action plans

14. **A global coalition of actors and stakeholders can implement the roadmap.** National governments, the cooling industry, and enabling organizations, among other stakeholders, can reap long-term benefits from cooperating to implement the roadmap. These benefits are interdependent and include, for the cooling industry, growth and access to new customers and markets from "cooling for all" programs; for developing countries, enhanced resilience to climate change, as well as economic and social development and co-benefits; and for enabling and development institutions (and their donors), increasing investments in poverty alleviation, socioeconomic development, GHG mitigation, and climate adaptation in their client countries.

RECOMMENDATIONS AND NEXT STEPS

The cooling community may want to consider following a number of recommendations and taking urgent next steps independently of the specific roadmap context, including:

1. **Engaging the global cooling community to win support for a roadmap process.** As a first approach, this roadmap can engage cooling stakeholders in discussions on goals, pathways, and actions toward a sustainable cooling economy by 2050 and begin to build the coalition of actors and commitments that will be needed to implement a roadmap. Organizations with the networks and interest to take on this challenge already exist within the global cooling community.

2. **Improving the availability and quality of data on cooling** to support more accurate analysis of sustainable cooling strategies and solutions. A major challenge that must be addressed quickly is limited data on the range and volume of cooling needs. In addition, terms and goals for measuring progress must be clearly defined. Basic data are available on AC installations, associated energy use, and resultant GHG emissions (IEA 2018), but data for tracking and reporting on lack of access to cooling (including agricultural and medical cold chains) and its energy implications are largely based on data sources developed for other purposes and are partial or irregular (SEforAll 2019a).

3. **Quantifying the sustainable cooling challenge** in terms of potential cooling volumes and associated energy demands and environmental impacts, as well as costs not only of delivering more efficient cooling, but also of meeting the requirements of the SDGs and access to cooling for all while returning GHG emissions from cooling to net zero.[37]

37 • See the conversion modeling work undertaken at the University of Birmingham (2018a).

4. **Creating a reporting system on progress** toward sustainable cooling, possibly including the roadmap goals, targets, and actions. A monitoring and reporting system must reflect numerous linked target dates and objectives, foremost the SDGs. Other drivers include the Paris Agreement, planned review of NDCs, and the timetable to phase down the use of HFCs under the Kigali Amendment.

5. **Raising funding for sustainable cooling action.** Large public and private financial flows will be needed to implement a work program as challenging as this roadmap. Existing financing instruments ranging from climate finance (e.g., GCF) to environmental and sustainable development funds (e.g., GEF) should integrate sustainable cooling into their strategies and work programs. Engagement with social impact funds and private funds and foundations with commitments to blended finance can help leverage private investments.

6. **Supporting cooling R&D and innovation.** Technological innovation is essential for meeting many of the medium- and long-term objectives of sustainable cooling but is among the most difficult activities to finance. Building on experiences with the Global Cooling Prize and past successes in financing renewable energy R&D, governments, in partnership with the cooling industry, should invest more to create, demonstrate and rapidly expand acceptance of transformative cooling technologies, as well as the innovative business models that will be needed to address the sustainable cooling challenge.

7. **Sharing knowledge on sustainable cooling, including with businesses and underserved communities.** Dissemination of knowledge among cooling stakeholders is crucial, particularly in rural communities, where awareness and education can lead to greater access to cooling, improved cold chains, better, locally adapted cooling techniques, and greater efficiency.

8. **Training cooling technicians to meet rising demand.** Training of a large skilled workforce on safe, effective installation and maintenance to ensure efficient operation of cooling equipment is a much-ignored challenge. Developing this workforce will take time and must be accelerated to keep pace with the extraordinary growth in the market for new AC units.

9. **Supporting city administrations in applying sustainable cooling principles.** Cooling-informed urban design and infrastructure, such as streets, buildings, and reflective surfaces, can reduce heat build-up and future cooling demand. Avoiding this lock-in is a low-cost, near-term measure that the cooling community should support (e.g., by creating an expert center for cooling-informed urban design to encourage planners and city administrations of fast-growing urban areas to consider sustainable cooling when making infrastructure decisions).

APPENDIX A: ROADMAP TECHNOLOGY MATRIX

NOW	2020-2030	2030-2040	2040-2050
MAKING COLD			
SOURCES OF COLD Better use of available low-temperature sources, including geother-mal-sourced cooling, river and sea water, adiabatic and evaporative cooling, nighttime stored energy, locating large consum-ers of cold and cooling (e.g., data centers) near waste cold centers (e.g., liquefied natural gas), evaporative cooling	**SOURCES OF COLD** Sources of cooling in ear-ly stages of deployment or development: integra-tion of geothermal heat with cooling capability, waste cold from liquefied natural gas capture, better use of ambient air temperature as part of cooling system	**SOURCES OF COLD** Key development: small-scale liquefaction for wide-scale deployment of liquid nitrogen	**SOURCES OF COLD AND FAR FUTURE TECHNOLOGIES** Developments likely to be of great importance in the longer term: wind-powered liquid air production, direct-drive liquefaction, optical cooling, baro-caloric refrigeration, ice nucle-ation proteins, ultra-sound-assisted freezing, hydraulic refrigeration
EFFICIENCY AND INTEGRATION Significant energy sav-ings from enhancements in current technologies and how they are used: increasing efficiency or coefficient of perfor-mance, use and sharing of heat and cold between applications, optimized deployment of heat pipes and targeted cooling (e.g., district cooling), booster heat pumps for district heating and cooling	**EFFICIENCY AND INTEGRATION** Next-step opportunities for enhanced efficiency and systems integra-tion: gas-electric hybrid heat pumps integrated into cooling systems to reduce electricity peak usage, development of combustion engine-pow-ered heat pumps that use waste heat from the engine to generate heat and cold	**EFFICIENCY AND INTEGRATION** Potential for develop-ment of new solid-state refrigerants with high cooling power	

NOW	2020-2030	2030-2040	2040-2050
MAKING COLD			
REFRIGERANTS Deployment of existing high-efficiency, low-environmental-impact refrigerants: investment in research into lower-GWP refrigerants, particularly azeotropes; replacement of R134a with near drop-in replacement HFO-1234yf; conversion of R22 systems to R290 (propane); conversion of R410a systems to R290 (propane); development of techniques to reduce refrigerant leakage	**REFRIGERANTS** Developments in new refrigerants and associated adoption: increased use of hydrocarbons in household refrigerators and freezers and food retail refrigeration; carbon dioxide for supermarket applications, industrial refrigeration relying on ammonia, rapid development of standards to support introduction of flammable refrigerants, improvement in safety technologies for use of flammable refrigerants, reduction in costs of production of some low-GWP refrigerants (e.g., hydrofluoro-olefins)	**REFRIGERANTS** Novel technologies with potential to deliver cooling at scale: electro-caloric, magneto-caloric, air cycle refrigeration, pressure-shift freezing, thermionic refrigeration, thermoelectric generation, vortex tube cooling, commercialization of gas-electric hybrid heat pumps to reduce electricity peak usage, thermoelectric cooling used in automotive (converting some of the waste heat of an internal combustion engine), active solar thermal used to drive refrigeration cycles (supply and demand of energy well synchronized), improvement of sorption cooling from renewable energy sources, optimization and integration of renewable energy sources into district heating and cooling networks	**REFRIGERANTS** Phase-out of hydrofluorocarbons in all refrigeration applications

NOW	2020-2030	2030-2040	2040-2050
MAKING COLD			
DEVELOPING TECHNOLOGIES Emerging technologies are available that can be deployed on a small scale but require further R&D for scale up: thermoelectric coolers used in consumer goods (portable coolers, replace heat sinks for microprocessors) and electronic and scientific equipment, small-scale magnetic cooling-based technology	**DEVELOPING TECHNOLOGIES** Technology developments with potential for near-term (some with longer term) impact: sorption cooling systems driven by hot water at moderate temperature, high-capacity heat pump for simultaneous production of hot and cold water, optimization of thermally driven heat pumps, thermoelectric, perfusion, use of nanoparticles in cooling systems, vortex tube cooling, ejector or jet pump, Stirling cycle for cooling, electronic expansion valves, borehole condensing, magnetic cooling in domestic cooling appliances, proof of concept for electro-caloric cooling unit, eutectic packaging of cold and cooling	**DEVELOPING TECHNOLOGIES** Novel technologies with potential to deliver cooling at scale: electro-caloric, magneto-caloric, air cycle refrigeration, pressure-shift freezing, thermionic refrigeration, thermoelectric generation, vortex tube cooling, commercialization of gas-electric hybrid heat pumps to reduce electricity peak usage, thermoelectric cooling used in automotive (converting some waste heat from an internal combustion engine), active solar thermal used to drive refrigeration cycles (supply and demand of energy well synchronized), improvement of sorption cooling from renewable energy sources, optimization of renewable energy sources and integration into district heating and cooling networks	

NOW	2020-2030	2030-2040	2040-2050
STORING COLD			
CURRENT TECHNOLOGIES Media deployed for storing cold: cryogens, ice, water, glycol, water–ethylene glycol mixtures, propylene glycol, propylene glycol–water, paraffin wax-based storage materials, eutectic salt-based solutions, fatty acid-based formulations, other phase-change materials, gravel bed, aquifer thermal energy storage, underground thermal energy storage, thermal piles, large natural energy stores	**DEVELOPING TECHNOLOGIES** Opportunities for cold as an energy storage medium: composite cold storage materials, cold storage components and devices, heat transfer intensified storage components and devices, novel building fabrics, development of new installation technologies for retrofitting district cold with minimal disruption, cold storage heat exchangers	**NEXT GENERATION** Cold energy storage possibilities: inter-seasonal cold storage, high-power-density high-grade cold storage materials, high-power-density cold storage components and devices, combined cold storage and power devices, low-cost and economical solutions for low-usage cold storage devices, compact domestic and district-scale storage devices, zero-boil-off cryogenic systems	**DISRUPTIVE COLD STORAGE OPPORTUNITIES** Thermochemical storage for cold and power, development of bespoke phase-change materials for very-low-temperature applications, composite cold storage materials with tunable boiling point through microstructures and surface forces, smart cold storage components and devices
MOVING COLD			
CURRENT TECHNOLOGIES for moving cold (e.g., in district cooling networks and cooling applications): cryogens, ice, water, glycol, water–ethylene glycol mixtures, propylene glycol, propylene glycol–water, phase-change materials	**DEVELOPING TECHNOLOGIES** Opportunities for cold as an energy vector: containerized liquefied natural gas	**NEXT-GENERATION** cold energy transportation possibilities: harnessing waste cold from cryogenic fuels	**DISRUPTIVE COLD MOBILITY OPPORTUNITIES** Novel materials with high energy density and low production cost that are readily transportable, district cryogen networks

NOW	2020-2030	2030-2040	2040-2050
USING COLD			
IMMEDIATE ACTIONS to improve use of cold and cooling: maintenance and repair of existing equipment to ensure optimum performance, better exploitation of natural opportunities (e.g., ice, reducing loads, vacuum insulation, use of light-emitting diodes), cryogen evaporation systems, eutectic plates, further development of air conditioning and refrigeration technologies, better development of food cold chain, exploitation of heat pumps, doors on cabinets in supermarkets, occupancy sensors for retail cabinet lighting	**OPPORTUNITIES** for widening use of cold: cryogenic 'cold and power' engines, need for better cryogenic ancillaries—transition from cottage industry to manufacture at scale, low-cost systems for low-use systems, integrated plan for recycling end-of-use of cooling with embodied energy and carbon costing, super chilling, tri-generation	**NEXT-GENERATION** exploitation opportunities for using cold: cold and power systems, systems integration in automotive (e.g., air conditioning and auxiliary power), passive air conditioning, passive systems employing eutectic plates, development and introduction of white goods suitable for integration into district heating and cooling scheme	**HORIZON** for exploitation of cold: harnessing waste cold from liquid hydrogen infrastructure, full integration of advanced cold technologies (magnetic, Peltier), electro-caloric, acoustics, thermoelectric devices that can generate electricity directly from waste cold
MANAGING COLD			
IMMEDIATE OPPORTUNITIES AND REQUIREMENTS for better management of cold and cooling: data capture on cold usage, big data processing and interpretation, intelligent control, variable-speed compressor drives, thermal management in vehicles, thermal management of power electronics, "smart" loads that are responsive to grid frequency variations to improve grid stability by acting as a flexible load, development of systems to monitor and maintain temperature accurately across large supermarket chiller volumes	**EMERGING OPPORTUNITIES** for better management of cold: new devices for cold production, smart refrigerators—grid sensing—linked to Internet of things, cold chain optimization, climate-robust cooling, weather prediction linked to cold production and utilization, de-superheating and heat recovery	**LONGER-TERM MANAGEMENT OF COLD** Fully integrated cold chain with energy vectors and optimization of all system components	

NOW	2020-2030	2030-2040	2040-2050
TECHNOLOGY DEMONSTRATION			
AD-HOC TECH DEMONSTRATION driven by commercial firms that can raise capital, large-scale demonstration of thermal (heating and cooling) grids	**DEMONSTRATION AND PROOF OF CONCEPTS** of elements of integrated schemes, demonstration systems capable of providing validation data, essential for commercialization	**DISTRICT SCHEMES** with integrated demonstration of technologies	**WHOLE-CITY-SCALE** integrated cold demonstrator
MANUFACTURING AND EXPORT			
IMMEDIATE ACTIONS required to build manufacturing capability: opportunities exist from manufacture to export, may also be capability to export and franchise manufacturing, need for better cryogenic ancillaries—transition from cottage industry to manufacture at scale, mapping capabilities throughout supply chain	**DEVELOPMENT OF MANUFACTURING CAPABILITY** linked to thermal energy technologies to solve some common manufacturing challenges, development of appropriate scale of skills to take advantage of growing market	**DEVELOPMENT OF MANUFACTURING FRANCHISE** (factory in a box) model to create manufacturing capability in emerging markets, implementation of best manufacturing practice (e.g., industry 4.0) in thermal energy technologies, embedded intelligence in manufacturing and products to create service market	**FULLY INTEGRATED COLD AND REFRIGERATION** manufacturing process with supply chain and skills and servicing underpinning growing export market

Source: University of Birmingham 2015, 60.

APPENDIX B: SUMMARY OF ACTIONS PROPOSED IN BACKGROUND REPORTS

COOLING IN BUILDINGS (ESMAP 2020A; 2020B)

- Conduct country-specific assessment of cooling landscape to build a case for sustainable space cooling and assess need to elevate it as a government priority
- Develop nationwide cooling action plan or road map with meaningful targets and expected impacts
- Enhance "cooling awareness" (awareness of importance and benefits of sustainable space cooling practices) to encourage individual actions and behavior changes
- Leverage labeling as an effective, low-cost way to steer consumers toward sustainable purchasing decisions
- Establish minimum energy performance standards of cooling equipment and a mechanism to increase them
- Catalyze the market by leading by example through government budgeting and procurement strategies for energy-efficient buildings and sustainable cooling equipment
- Build capacity in critical institutions, among trade professionals, and in the building and heating, ventilation, and air conditioning service sectors
- Leverage ongoing refrigerant technology transition activity (as required under the Kigali Amendment) to integrate energy efficiency into cooling equipment and maximize benefits
- Support and leverage a research and development and innovation ecosystem that enables technology advancement
- Incorporate strategies to enable access to cooling in off-grid or weak-grid locations
- Cultivate market demand for energy-efficient buildings by increasing visibility of building energy performance
- Accelerate adoption of passive cooling strategies through national building energy codes with a robust enforcement mechanism
- Create incentive mechanisms to shift market demand toward sustainable space cooling
- Aggregate demand to decrease acquisition cost of sustainable cooling equipment, build market confidence, and spur greater adoption
- Reduce first cost of sustainable space cooling using debt subsidy and risk mitigation instruments
- Implement cooling as a service, including district cooling and beyond
- Catalyze investment in sustainable space cooling by developing energy service company capability
- Expand access to financing for sustainable space cooling by developing energy service agreements and managed energy service agreements, and other derivatives of the energy service company model
- Leverage property-assessed clean energy and environmental upgrade financing approaches to lower the first cost of energy-efficient construction
- Manage peak cooling loads using utility-led demand-side management and financial measures

URBAN COOLING (ESMAP 2020C)

- Develop a cooling action plan: Having an overarching cooling action plan (or urban heat mitigation plan) to articulate the rationale for urban cooling, set targets and goals, and establish a means to measure progress can be a helpful way to organize strategies and actions toward cooler cities
- Identify heat-vulnerable areas and populations
- Demonstrate urban cooling strategies with pilot projects
- Engage the public: Creating an environment in which the public plays a meaningful role in the policy development process is essential, especially for poor or marginalized communities where the need for urban cooling is greatest but trust in government may be low
- Lead by example: Municipal procurement that benefits urban cooling, efficiency, and broader increases in resiliency will help create local markets for these solutions, provide test cases for the general public and the private sector, and build capacity for implementing and evaluating the measures
- Make urban cooling measures the standard: Establish passive design principles (e.g., solar-reflective surfaces, vegetated surfaces, natural ventilation, shade) and energy efficiency in buildings and building energy codes
- Consider incentives: Properly designed, well-targeted incentives can encourage adoption of urban cooling measures, passive design, and energy efficiency in the public and private sectors
- Expand urban forestry efforts
- Work with other cities and city networks

INDUSTRIAL AND COMMERCIAL COOLING (IFC 2019)

- Design a calculator that helps industrial and commercial end users measure the business cost of heat stress
- Provide technical guidance on project evaluation and return-on-investment time frames for sustainable cooling equipment
- Provide technical guidance and criteria for sustainable cooling procurement practices
- Train contractors on appropriate sizing for cooling equipment
- Align incentives between decisions makers and bill payers
- Integrate business models that share incentives
- Mobilize commercial financing from local financial institutions to expand energy efficiency credit lines to include clean cooling solutions
- Expand traditional lending instruments and green bonds to build more green buildings, including clean cooling

MOBILE COOLING (AYRES, STANKEVICH AND DIEHL 2020)

- Further develop and revise the standards contained in the Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be used for Such Carriage.
- Develop standards for new and used cars (differentiate between groups of countries)
- Initiate discussion about increasing funding applied under the Montreal Protocol Multilateral Fund to expand skills development, particularly in relation to proper maintenance and installation practices of mobile air conditioning and transport refrigeration equipment
- Improve equipment stock assessments
- Encourage greater emission reductions from refrigerated trucks and containers (reefers) using the Ship Energy Efficiency Management Plan
- Develop a technology option list
- Conduct research on fishing vessels—impact on climate change
- Develop guidelines for policy makers (on climate change resilience and emissions)
- Assess policy measures and guidance packages (to clarify which approaches are most effective)
- Develop a needs-driven toolkit to help policy makers identify their own mobile and stationary cold chain (and investment) requirements within their economies

COLD CHAINS (PETERS 2019B)

- Develop clear consensus roadmaps for sustainable refrigeration
- Develop a detailed technology options list to include cost and emission impacts for cooling solutions that can facilitate cost–benefit analysis by operators and policy makers of options while they develop their own cold chain plans
- Create novel business models such as cooling as a service for food producer organizations or other service providers
- Drive collaboration between all actors within the cold chain, including flow of information (demand forecasts) from retailers or processors to farms and digital supply chain tools to make transactions in the supply chain more efficient and seamless and enable tracking of loss and waste
- Provide incentives and financing structures to support end users in leapfrogging to low-climate-impact solutions
- Adopt protocols to stop developing markets from being dumping grounds for high-polluting, low-efficiency, and end-of-life equipment
- Create centers of excellence and model cold chains (living labs) to demonstrate end-to-end systems
- Undertake comprehensive needs assessments
- Build supportive policy and regulatory environments
- Develop financing instruments from development banks aligned with life-cycle value creation and performance risk mitigation
- Facilitate low–greenhouse gas technology procurement
- Transfer knowledge, develop skills, and build capacity

RURAL COOLING (PETERS 2019C)

- Provide guarantees for investment loans to early adopters and cooperatives for cooling and cold chain equipment and technology
- Provide public grants to farmers purchasing animal heat stress–mitigation equipment and technology
- Award publicly funded grants to rural households, communities, and retailers to purchase refrigeration and cooling equipment
- Create and enforce regulatory environment, industry standards, guidance and protocols for thermal comfort and cold chains based on sustainable cooling equipment and technology deployment, operation, and approaches
- Encourage equitable, fair private sector financing of efficient, sustainable domestic refrigeration, including community food lockers within a community cooling hub
- Form public-private partnerships for investment in sustainable cold chains, natural cooling, and cooling equipment and approaches in clinics and hospitals
- Foster private sector financing for sustainable cooling equipment, digital technologies, and approaches through return-on-investment incentives such as tax breaks and credits for investors and owner-operators
- Publicly fund extension services to raise awareness in rural communities of critical importance of cold chain and cooling for health, productivity, comfort, agriculture, and processing, as well as transfer of technical and business knowledge to cold chain and cooling equipment owners and operators
- Encourage manufacturers to research, develop, and supply affordable, robust, easily maintained, sustainable on- and off-grid cooling equipment through tax breaks and credits and product-related subsidies
- Invest in infrastructure for affordable, accessible sustainable energy provision for rural communities
- Offer public funding and attractive terms on investment loans to demonstrate sustainable cooling and cold chain equipment, technology, and approaches
- Offer public funding for installation of natural cooling and sustainable cooling equipment and approaches in rural settings (domestic, commercial, public)
- Offer publicly funded subsidies to farmers participating in artificial insemination programs
- Publicly fund affordable, accessible insurance services for early adopters, cooperatives, and farmer producer organizations
- Publicly fund affordable, accessible insurance services for workplace owner-operators and workers
- Support public funding and public-private partnership investment in skills training for building, operating, and maintaining cold chains and thermal comfort based on sustainable cooling equipment and approaches

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