ESMAP

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PRIMER FOR SPACE COOLING

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TABLE OF CONTENTS

List of Figures

List of Tables

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FOREWORD

This publication is intended as a primer on space cooling. It was developed in the context of the rapidly growing demand for space cooling and the critical need for access to affordable but sustainable space cooling solutions. This context includes solutions that can respond to the need for greater access to cooling, especially in large parts of the developing world facing increasingly high temperatures, while avoiding the considerable and disruptive impacts on energy systems and the accompanying greenhouse gas emissions that would result from business-as-usual growth.

The objectives of the Primer are to introduce a broad audience, including practitioners in different fields, to the broad topic of space cooling and its key considerations, and to help initiate and advance sustainable space cooling into policy discussions and investment considerations in developing countries. It aims to enhance the reader's understanding of the applicability of different space cooling options and key factors enabling their implementation, along with potential trade-offs to consider. The Primer brings together key findings from many relevant studies and publications, makes a convincing case for sustainable space cooling, provides an overview of available strategies and technologies to meet space cooling needs, and shares examples of effective regulatory, financial, and enabling mechanisms.

This publication is structured in five sections and also contains a compendium with supplementary information. The first section explains the context for space cooling as a critical development need tied to several Sustainable Development Goals and covers the foundational aspects of space cooling. The second section discusses the impacts of cooling demand growth, making the argument that sustainable space cooling achieved through low-energy and low-climate-impact pathways is a critical priority. The third section—underscoring an integrative approach—dives into how cooling needs can be optimally met, discussing passive cooling strategies, space cooling technologies, and strategies for optimization and control. Section 4 gives an overview of the barriers to implementing sustainable space cooling and presents the various demonstrated space cooling intervention strategies that can help overcome these barriers. For those interested in learning more about the interventions that could accelerate the pace of sustainable space cooling, the Compendium contains detailed information covering 20 such interventions, with over 100 real-world examples of space cooling–related practices that have been implemented. The final section provides an illustrative road map for advancing sustainable space cooling, based on a country's hierarchy of needs and informed by its assessed readiness and capacity.

Note that cooling-specific examples have been presented (mostly within the detailed interventions in the Compendium) when available and demonstrated at sufficient scale to enable relative success to be assessed, but when these are unavailable, examples from adjacent sectors have been included, with an explanation of how the lessons from those interventions could be applied to advancing sustainable space cooling. The Compendium also provides practitioners additional resources and details on space cooling interventions.

This publication has been developed under the Energy Sector Management Assistance Program (ESMAP) Efficient, Clean Cooling Program, jointly managed by ESMAP and the World Bank Climate Change group, and was initiated with the support of a grant from the Kigali Cooling Efficiency Program (K-CEP). Other publications tackling different aspects of sustainable cooling are under development. These knowledge products complement the technical assistance provided by ESMAP to inform country dialogues, as well as the design and development of a pipeline of projects with sustainable cooling features or components that could be supported by the World Bank Group and other sources of financing.

A NOTE ON THE NOVEL CORONAVIRUS (COVID-19) PANDEMIC

The Primer and accompanying compendium were published during the global outbreak of COVID-19, which has taken the world in uncharted territory and disturbed billions of lives, posing unprecedented threats to human health, economic activity, and fiscal resources, and impacting nearly every aspect of life. The pandemic has significantly changed our utilization of the built environment as we spend more time indoors, conducting work and study from our homes. While the pandemic will surely recede, it would have acted as an accelerator to many emerging trends—this includes rapid growth in demand for cooling in the building sector, especially our homes.

While governments will, rightly, be focusing on the immediate health impacts of the pandemic and may not have the capacity and bandwidth to address cooling in the very short term, this unique situation presents the need to identify options and solutions for access to affordable thermal comfort that can support the health, well-being, and productivity of their populaces as we emerge from the immediate risks of COVID-19 and are able to intensify our focus on the long-term risks of exposure to extreme heat. The sustainable cooling solutions outlined in this primer have been developed with reference to the increasing need for access to affordable cooling that can deliver multiple benefits, including health, well-being, and productivity—while reducing the burden on energy systems and the environment—for the billions of people that live, work, and conduct so many aspects of their lives within the built environment.

Air conditioners on the wall on the back street. Urban design solutions.
Credit: Katharina13/istock.

EXECUTIVE SUMMARY

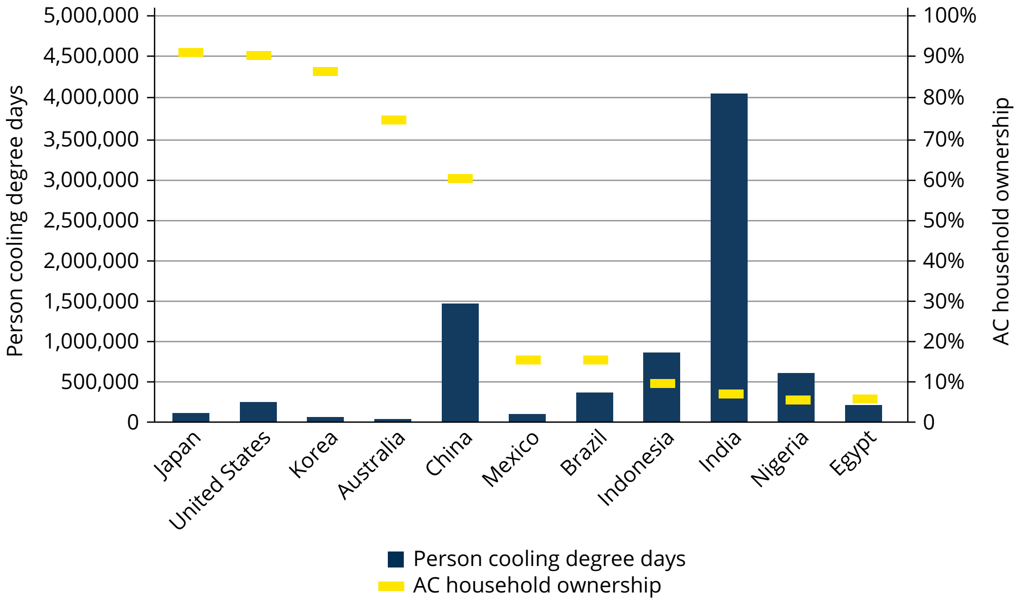
- *Developed in the context of the rapidly growing demand for space cooling and the critical need for access to affordable space cooling solutions, this primer aims to introduce a broad audience to the topic of space cooling and its key considerations, and to help initiate and advance sustainable space cooling into policy discussions and investment considerations in developing countries.*
- *Space cooling, also referred to as "comfort cooling," refers to the means by which people are provided thermal comfort from heat by maintaining the optimum temperature, humidity, and ventilation within the built environment.*
- *The global energy use for space cooling is projected to grow three-fold between 2016 and 2050, with a majority of this growth occurring in developing countries. While the growing need for space cooling is in alignment with the developmental needs of countries, this growth must be addressed with carefully designed strategies and solutions to avoid severe economic, power system, and environmental impacts.*
- *Technologies and strategies exist that can deliver today's space cooling needs with less than half the energy use, while delivering a lower life cycle cost to users and consumers—however, these remain largely unexploited. While it is not possible to recover this opportunity cost of the past, there is an opportunity to avoid increasing the opportunity cost in the future, by acting now to make the shift to sustainable space cooling practices.*
- *Underscoring an integrative approach to space cooling, the Primer provides the reader with an overview of strategies that reduce the cooling loads of buildings by applying building efficiency measures that enhance thermal performance, serve the cooling load as efficiently as possible through appropriate choice of cooling solution and utilization of most efficient cooling equipment available, and optimize the performance of cooling through their operation. Discussing the barriers to implementing sustainable space cooling, the Primer also presents demonstrated space cooling intervention strategies that can help overcome these barriers, with over 100 real-world examples and implementation considerations included in the Compendium.*

ACCESS TO SPACE COOLING IS A CRITICAL DEVELOPMENT NEED

Space cooling is increasingly recognized as a development priority and an issue of equity in a warming world. It directly supports three of the Sustainable Development Goals (SDGs)—ensure healthy living and promote well-being for all at all ages, decent work and economic growth, and sustainable cities and communities[i]—and contributes to multiple other SDGs. There is increasing evidence that the rise in temperatures and lack of access to cooling, that is most prominent in developing countries in the tropics, will impact the health, education, productivity, and economic development of nations. In 2019, the Intergovernmental Panel on Climate Change (IPCC) reported that at 1.5ºC of warming, 2.3 billion people

i Sustainable Energy for All's 2018 *Chilling Prospects* report links space cooling to SDG 3, SDG 8, and SDG 11.

FIGURE ES.1: COOLING DEMAND VERSUS CURRENT AIR CONDITIONER (AC) OWNERSHIP IN DIFFERENT PARTS OF THE WORLD



Source: RMI 2020 © Rocky Mountain Institute.
Note: The cooling demand, represented by person cooling degree days, is a function of a country's average annual cooling degree days multiplied by the respective population.

could be both exposed and vulnerable to heat wave events—a threshold that could be reached as early as 2030. Effective, affordable, and accessible space cooling is a key component of the solution to this development challenge.

Currently, 40 percent of the world's population resides within the tropics, with dramatically lower access to space cooling in relation to their need—and this figure is predicted to grow to 50 percent by 2050. One indicator used to show this unmet need for cooling is the air conditioner (AC) ownership in different parts of the world today versus the requirement for cooling (using person cooling degree days as a proxy, represented in figure ES.1). As figure ES.1 indicates, the unmet need for space cooling is the highest in populous and developing countries within the tropical climate zone, such as India, Indonesia and Nigeria.

SIGNIFICANT GROWTH IN DEMAND FOR SPACE COOLING IS INEVITABLE BUT CAN LEAD TO SEVERE ENERGY AND CLIMATE IMPACTS

In addition to today's unmet needs, multiple accelerators are acting concurrently to contribute to the escalating demand for space cooling: population growth, particularly in the hottest parts of the world; urbanization; a warming planet; and growing incomes that facilitate access to cooling. The global energy use for space cooling is projected to jump from 2,020 terawatt-hours (TWh) in 2016 to 6,200 TWh in 2050—an astounding 300 percent increase. Most notably, developing countries such as Indonesia, India, Mexico, Brazil, and many African countries will see a sharp increase in their cooling energy demand. If not proactively and responsibly managed, this growth can erode some of the benefits of space cooling through high operating costs for users, the cost of massive additions to grid infrastructure, and increased greenhouse gas (GHG) emissions that perpetuate a cycle where more cooling begets more warming.

Globally, the escalating space cooling demand will necessitate a capacity increase of 395 percent, from 850 gigawatts (GW) in 2016 to 3,350 GW in 2050. This increase of 2,500 GW is equal to the total generating capacity of the United States, Europe, and India combined today. This substantial capacity increase would not even be enough to expand access to space cooling to all, and would still leave many poor and vulnerable urban and rural households with unmet space cooling needs.

The projected surge in energy demand for cooling could put significant pressure on the already strained energy systems in many developing countries with hot climates. It is estimated that by 2050, space cooling will account for 30–50 percent of peak electricity load—typically the most expensive load to serve—in many countries, with the biggest increase occurring in India.

Greenhouse gas emissions from electricity use for space cooling (indirect emissions) are set to double by 2050, even as the grids get cleaner, reflecting that the transition to renewable generation will not proportionally keep pace with the projected growth of cooling. Add to this the direct emissions originating from the high global warming potential (GWP) refrigerants used by most of today's air conditioners, and the overall emissions impact becomes even greater. Section 2 of the Primer discusses the future impacts of cooling demand growth under a business-as-usual scenario in more detail.

IT IS CRITICAL TO MAKE THE SHIFT TO SUSTAINABLE SPACE COOLING

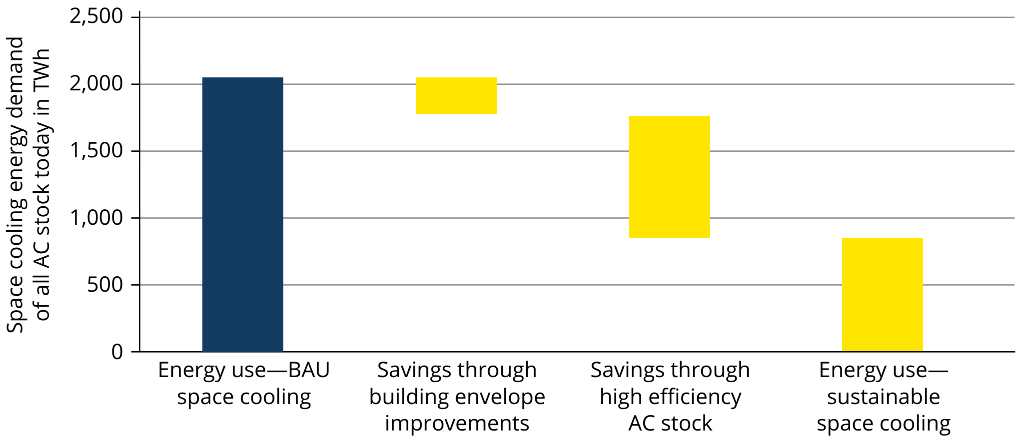
While the growing need for space cooling is in alignment with the development needs of countries, this growth must be addressed with responsibly designed strategies and solutions to avoid severe economic, power system, and environmental impacts. The good news is that **technologies and strategies exist that can deliver today's space cooling needs with less than half of the energy use** while delivering a lower life cycle cost to users and consumers.

However, the potential benefits of these technologies and strategies remain largely unexploited. For instance, the average efficiency of room air conditioners (RACs) sold today is less than half that of the commercially available best-in-class (that is, the most energy-efficient units); in most developing countries, the potential benefits and cooling load reduction opportunities of thermally efficient buildings remain largely untapped.

The Opportunity Cost of Today's Space Cooling Practices

In producing this primer we undertook a high-level analysis to get a view into the opportunity cost to society of not adopting best-in-class existing technologies and strategies that have demonstrated a lower life cycle cost for users and consumers. This analysis takes into account the impact of switching today's space cooling equipment stock (1.6 billion residential and commercial air-conditioning units) from a business-as-usual technology efficiency level to a higher efficiency level that is already commercially

FIGURE ES.2: OPPORTUNITY COST TO SOCIETY OF NOT ADOPTING BEST-IN-CLASS EXISTING TECHNOLOGIES AND STRATEGIES THAT HAVE DEMONSTRATED A LOWER LIFE CYCLE COST FOR CONSUMERS



Source: RMI analysis based on RMI, *Solving the Global Cooling Challenge* (2019) and IEA, *Future of Cooling* (2018).
Note: The assumptions behind the analysis are explained in section 1 of the Primer.

available (in alignment with the International Energy Agency (IEA) Efficient Cooling Scenario), and the impact of improvement in building envelopes (figure ES.2).

- **Impact on energy use.** The energy required to provide space cooling could have been **reduced by about 58 percent (or 1,177 terawatt-hours**) by switching to commercially available high-efficiency technology in conjunction with building envelope improvements achievable today that have demonstrated a lower life cycle cost.

- **Impact on power systems. Nearly 500 GW of power generation capacity** to meet space cooling needs could have been avoided, translating to around US$345 billion in capital investment (not including the associated transmission and distribution costs) that could have been directed to address other priorities.

- **Impact on GHG emissions.** The current total indirect emissions (1,135 million tons CO_2) from space cooling operation would have been **less than half (540 million tons CO_2).** In addition, the avoided space cooling capacity would have resulted in lower use of refrigerants and associated direct emissions.

- **Impact on consumers.** Meeting cooling needs with efficient cooling equipment could have cost consumers dramatically less over the equipment's lifetime. For instance, in the Indian market, an average entry-level room air conditioner can **cost the consumer almost two times more** over its lifetime (typically 10–12 years), compared with commercially available high-efficiency RAC units (even more where electricity is not/less subsidized).

It is important to note the above analysis does not take into account the positive impacts of systemwide solutions (such as district cooling), innovative early stage technologies yet to be fully commercialized, or any emerging radical technology solutions.

The opportunity costs of today's cooling practices are too high to ignore and the impact will only be further compounded through the projected growth in space cooling demand if countries continue on the business-as-usual pathway. While it is not possible to recover the opportunity cost of the past, there is an opportunity to avoid increasing the opportunity cost in the future by shifting to sustainable space cooling practices.

About half of the building stock that will exist in 2050 is yet to be built, and most of it will occur in developing countries. In this context, as we consider future cooling needs, there is an opportunity now for cost-effectively incorporating deep building envelope and energy efficiency improvements which will further increase the potential energy savings.

What Is Sustainable Space Cooling?

Sustainable space cooling, in the context of this report, refers to the achievement of human thermal comfort within buildings through a combination of energy-efficient building design and practices, efficient cooling technologies and practices, and more climate-friendly refrigerants (in line with or exceeding obligations under the Montreal Protocol on Substances That Deplete the Ozone Layer and its Kigali Amendment) that collectively have a lower environmental impact than do current practices, and are in line with or exceeding a country's internationally agreed-to GHG mitigation objectives. Other publications may use different terms to convey the same or similar definitions, such as "efficient and clean cooling."

Space cooling is an integral part of energy efficiency in buildings—particularly in hot climates. For example, in some climates, such as Singapore, cooling represents up to 70 percent of the total energy load in buildings. Therefore, the interventions to promote building-specific sustainable space cooling may not be so different from those that would be considered for enhancing overall building energy efficiency, where common barriers prevail and similar solutions are applicable. However, space cooling does have some unique factors and attributes, including the impact on energy systems in terms of driving peak load, the role of refrigerants and their impact on emissions, and the ability to design cooling solutions at an urban or community level (where cooling can be provided more efficiently and with a lower GHG footprint over multiple buildings).

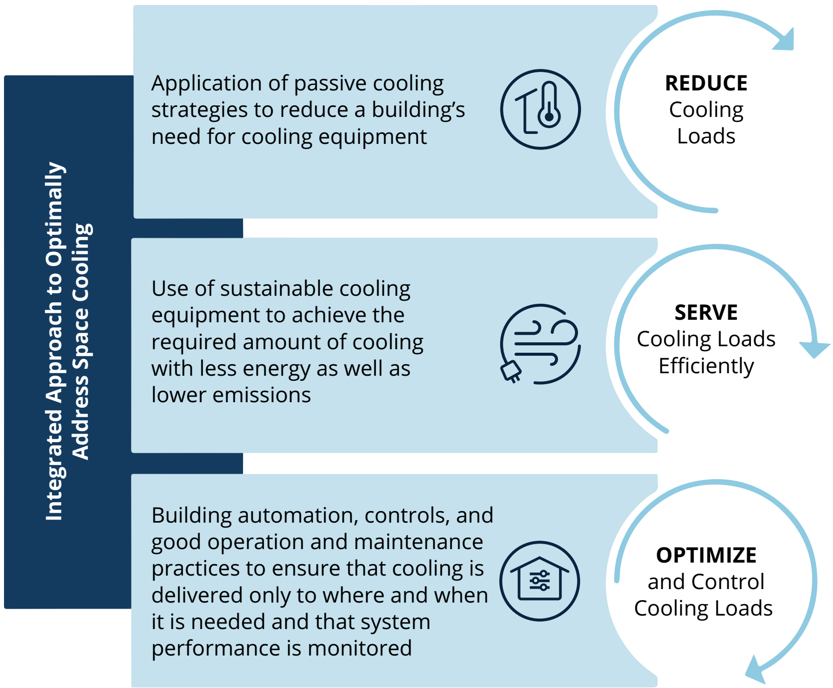
AN INTEGRATED APPROACH TO SPACE COOLING SHOULD BE THE NORM

An integrated approach to space cooling—one that reduces cooling loads through building energy efficiency, radically improves the efficiency of the cooling equipment serving those loads, and optimizes the performance of cooling through its operation—is foundational to sustainable space cooling and should be pursued to the fullest extent possible (figure ES.3).

- **Reduce cooling loads: Passive cooling strategies**

  Passive cooling refers to energy-efficient building design strategies—such as building orientation, thermal insulation, and ventilation—that prevent heat from entering a building and facilitate natural

FIGURE ES.3: INTEGRATED APPROACH TO OPTIMALLY ADDRESS SPACE COOLING



Source: RMI Infographic based on RMI, *Integrative Design*.

cooling. Passive cooling strategies, typically driven through building energy codes as well as voluntary building energy-efficiency measures, can reduce a building's cooling load by more than 25 percent, even in hot climates. Building energy codes are common in developed countries, but their adoption remains low in developing countries largely because of challenges with implementation and enforcement.

Passive cooling measures apply to both new building construction as well as existing building retrofits and should be the first line of opportunity toward sustainable space cooling by enhancing thermal performance and thereby reducing the cooling needs of buildings. Due to the relative ease of integration into new construction, passive cooling is especially relevant in developing countries that are experiencing substantial new construction.

- **Serve cooling loads efficiently: Energy-efficient and low-climate-impact technologies**

Multiple cooling equipment options are prevalent to actively cool buildings, such as vapor compression systems, fans, and air coolers. Vapor compression systems—which rely on refrigerants' phase-change properties to provide cooling—are the dominant choice today because they are effective in all climate conditions, can be scaled up or down, and can address both air temperature and humidity. However, vapor compression systems are energy intensive and contribute to both indirect and direct (through refrigerant use) greenhouse gas emissions. Vapor compression systems are a broad category in themselves, including several technologies of varying complexity and considerations for application, such as room air conditioners, central AC systems, variable refrigerant flow systems, and chillers.

Fans and air coolers—the non-refrigerant-based cooling technologies—are lower in cost and in energy consumption. Even though operation of these technologies has practical limitations—they are not very effective in extreme heat and humid conditions—fans and air coolers will continue to be pervasive in developing countries, and particularly among low-income populations, as the first step toward accessing thermal comfort. Fans in particular, are a unique segment of space cooling due to their link to energy access: as many countries in Asia and Africa work on electrification programs for rural households, this is expected to generate a greater demand for fans as the first point of access to cooling. While the dialogue on equipment efficiency generally tends to focus on the air-conditioning systems, due to the sheer (and likely underestimated) volume of their market stock, it is important to advance the energy efficiency of these appliances also.

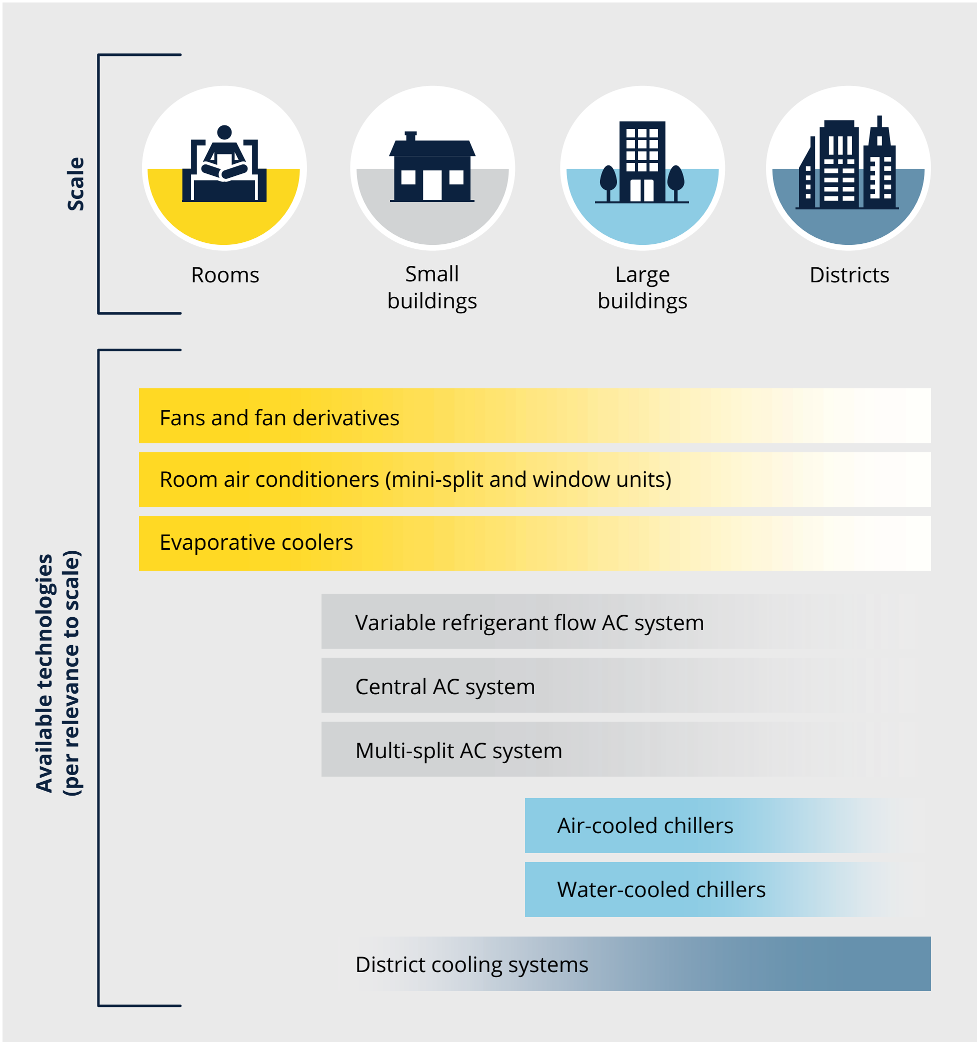
The Primer also gives a brief overview of some available or evolving alternate cooling technologies that either break away from traditional air-conditioning systems' reliance on a vapor compression cycle using a gaseous refrigerant, or may be integrated with vapor compression or evaporative cooling systems as a hybrid solution. These technologies are mostly either limited in application to specific sectors or are in the early stages of technical demonstration. However, these new and alternate cooling solutions are likely to play an increasing role in the future of cooling that is climate friendly and free of hydrofluorocarbons (HFCs), starting in the sectors that align best to the specific attributes of these technologies.

The Primer discusses the characteristics, enabling conditions, and considerations for the above-mentioned space cooling technologies. With a wide range of cooling technologies available, the choice of the most suitable solution will depend on several factors. These include building scale, type of construction (new or existing building), building ownership profile, climate zone, immediate environmental attributes, and country-specific factors (such as labor costs, utility rates, and grid factor). These factors come together to determine the optimal economics and the choice of space cooling solution, and are discussed in detail in the Primer. While the factors apply in combination, a dominant determinant of the optimal space cooling technology is the scale of the built environment being addressed—that is, whether cooling is to be provided, for example, for a room, a single building, or a campus (as presented in figure ES.4).

- **Optimize and control cooling loads: Ensure that cooling is delivered only when and where it is needed**

Behaviors and usage patterns of the building occupants can be important variables in the overall energy utilization for space cooling. Several strategies can be applied to ensure that cooling is delivered only where and when it is needed and that system performance is monitored and maintained, thus avoiding any wasteful cooling. Broadly, these strategies include automated building controls and sensors to ensure that cooling is delivered only to where and when it is needed (essentially enabling part-time and part-space operation), load shifting strategies, user adaptations and behavior change,

FIGURE ES.4: TECHNOLOGIES TO SERVE COOLING LOADS



Source: Authors, composed by Rocky Mountain Institute.
Note: Shading represents each cooling equipment's applicability at the corresponding building scale.

good operation and maintenance practices, and capacity building in the service sector. Collectively, such strategies control and optimize cooling utilization.

While space cooling can be addressed in many different ways, an integrated approach to cooling will maximize the potential benefits through integrative effects and should be pursued to the extent possible. Accompanying measures to ensure that an increasing proportion of power comes from grid- or building-integrated renewables will be important to further lower the greenhouse gas impact of meeting the need for space cooling.

UNDERLYING MARKET BARRIERS TO SUSTAINABLE SPACE COOLING

The challenges of scaling up or investing in sustainable space cooling practices can be fundamentally attributed to a lack of market demand for sustainable space cooling. This lack of market demand results from a number of underlying market barriers, which together are the core reason why market solutions and enablers (such as financial instruments and policy measures) are necessary.[ii] These underlying market barriers, which are also interrelated and reinforcing, are:

- **Lack of awareness** (about the broad benefits of sustainable space cooling)
- **Lack of transparency** (about the cost savings of energy-efficient buildings and sustainable cooling equipment)
- **First-cost bias**
- **Split incentives**
- **Lack of valuation of efficiency**
- **Complexity of choice** (due to multiple technology choices and trade-offs between refrigerant options)
- **Misaligned policies**

More often than not, a combination of barriers is at play in any country, with interrelated effects. Thus, addressing space cooling challenges effectively requires multipronged efforts and a comprehensive approach tailored to a country's specific market conditions.

ii Commonly, a discussion of barriers to sustainable cooling or energy efficiency at large includes lack of policy and financial instruments, but we posit that policies, regulations, institutional capacities, and financial instruments serve as solutions to the problem. Their lack is not the underlying reason for the problem itself, that is, why the market demand for sustainable cooling practices does not exist in the first place. Similarly, lack of capacities could be a barrier to adequately serving the demand for space cooling, but not a reason why the market demand for space cooling does not exist. The discussion of barriers above focuses on the underlying barriers for a lack of market demand for sustainable space cooling.

INTERVENTIONS TO ADDRESS MARKET BARRIERS AND PROMOTE SUSTAINABLE SPACE COOLING EFFECTIVELY

Broadly, opportunities to address market barriers and advance sustainable space cooling practices can be grouped into three overarching strategies that together can overcome the underlying barriers that appear in multiple segments of the market. These strategies are:

- **Establish a supportive policy and regulatory environment.** A supportive policy and regulatory environment, including government leadership by example, is a critical enabler of the right ecosystem to scale up access to sustainable space cooling practices. Active government intervention to enable markets to operate logically toward the lowest life cycle and system cost solutions will send the necessary signals to industry, driving and accelerating the adoption of best practices and innovation in sustainable space cooling.
- **Create sustainable financing and enabling mechanisms.** Most markets, in particular in developing economies, see a lack of fit-for-purpose financing that can allow facility owners and consumers to procure the usually higher first-cost sustainable cooling equipment or energy-efficient buildings. This lack of fit-for-purpose financing is closely tied to the market barriers. As several of those barriers—such as awareness, transparency, and valuation of efficiency—are effectively addressed by policy and regulatory systems, the risks associated with financing sustainable cooling begin to lessen, creating an environment where financing and enabling mechanisms can be more effectively deployed. With fit-for-purpose financing, the market demand for sustainable space cooling solutions can be enabled, in turn leading to innovation and faster adoption of sustainable space cooling solutions.
- **Enhance consumer and stakeholder awareness, strengthen institutional and professional capacities, and promote technology advancement.** Collectively referred to as "supporting instruments" in this publication, these enabling factors—when applied in parallel with policy measures, and financing and enabling mechanisms—can maximize impact and potential benefits.

Within each of the overarching strategies, the Primer discusses specific interventions that are meant to be options to inform strategies, plans, and road maps for countries that are seeking to increase sustainable space cooling through a combination of reducing cooling loads, serving cooling needs efficiently, and optimizing and controlling cooling loads. There is not one "right" solution, as each country's context and need will vary. For instance, many developing countries may face greater barriers from institutional capacities, regulatory frameworks, and enabling financial mechanisms, and some of the interventions may not immediately apply without first addressing the factors that can build initial demand. Each country, thus, will need to develop its own path according to its priorities, opportunities and constraints.

The sustainable space cooling interventions discussed in the Primer are listed in table ES.1, grouped within the three overarching categories. The sequencing within each category is not meant to be prescriptive, but is simply based on an assessment of the relative ease of implementation, required resources, and critical interdependencies. However, depending on the context and priorities, a different sequence or grouping of interventions may serve a country's needs better. A detailed description of each of the interventions can be found in the Compendium of this report, including examples from across the world—both in developed and developing countries—with an aim to highlight real-life implementation and the respective key insights learned. The Compendium also seeks to serve as a reference for readers seeking more detailed information on sustainable space cooling.

While there is no single strategy or road map for pursuing the interventions that will work equally well for every country, the Primer—as a broad, guiding framework—suggests establishing and strengthening the policy and regulatory enablers as the primary underpinning for scaling up sustainable space cooling. In parallel with policy interventions, the framework suggests applying appropriate financial interventions and supporting instruments based on the respective country's context and readiness. Using complementary interventions in parallel can amplify their impact and maximize potential benefits. While navigating a pathway to sustainable space cooling, it is also good practice for countries to plan for periodic assessment of interventions to make sure that they are still effective and serve their purpose, and to continuously explore areas for improvement or additional interventions.

ACCESS TO COOLING IS REQUIRED FOR DEVELOPMENT, YET THE SOLUTIONS MUST BE SUSTAINABLE TO AVOID ADVERSE EFFECTS

Space cooling is an important determinant of human comfort, well-being, and productivity within the built environment—and, increasingly, a development priority. Yet, without an accompanying focus on the sustainable aspect of space cooling, some of these benefits get eroded through high operating costs for users, the cost of massive additions to grid infrastructure, and increased greenhouse gas emissions that perpetuate a vicious spiral where more cooling begets more warming.

While each country will chart its own pathway toward sustainable space cooling, the need for a comprehensive and multipronged approach consistently applies. The best outcomes will emerge from a multipronged approach that incorporates information, clear leadership, policy and regulatory measures, financing and enabling mechanisms, training, and research and development (R&D). It is critical to act now to make the shift to sustainable space cooling practices and lock in a low-energy and low-climate-impact pathway toward access to space cooling for all.

TABLE ES.1: INTERVENTIONS TO ADDRESS MARKET BARRIERS AND PROMOTE SUSTAINABLE SPACE COOLING EFFECTIVELY

POLICY INTERVENTIONS

P1. Conduct a country-specific assessment of the cooling landscape to build a case for sustainable space cooling and assess the need to elevate it as a government priority
P2. Leverage labeling as an effective, low-cost way to orient consumers toward sustainable purchasing decisions
P3. Establish minimum energy performance standards of cooling equipment and a mechanism to ratchet them up
P4. Catalyze the market by leading by example through government budgeting and procurement strategies for energy-efficient buildings and sustainable cooling equipment
P5. Develop a nationwide cooling action plan or road map with meaningful targets and expected impacts
P6. Cultivate market demand for energy-efficient buildings by increasing visibility of building energy performance
P7. Accelerate the adoption of passive cooling strategies through national building energy codes with a robust enforcement mechanism

FINANCING INTERVENTIONS

F1. Create incentive mechanisms to shift the market toward sustainable space cooling
F2. Aggregate demand to drive down the acquisition cost of sustainable cooling equipment, build market confidence, and spur greater adoption
F3. Reduce the first cost of sustainable space cooling through debt subsidy and risk mitigation instruments
F4. Implement Cooling as a Service, including district cooling and beyond
F5. Catalyze investment in sustainable space cooling through the development of an energy service company capability
F6. Expand access to financing for sustainable space cooling through the development of energy service agreements and managed energy service agreements, derivatives of the energy service company model
F7. Leverage property assessed clean energy or environmental upgrade financing approaches to lower the first cost of energy-efficient construction
F8. Manage peak cooling loads and cooling energy demand through utility-led demand-side management measures

SUPPORTING INSTRUMENTS

S1. Enhance “cooling awareness,” or awareness of the importance and benefits of sustainable space cooling practices, to encourage individual actions and behavior changes
S2. Build capacity in critical institutions, as well as among trade professionals and the buildings and heating, ventilation, and air-conditioning service sector
S3. Leverage ongoing refrigerant technology transition activity (as required under the Kigali Amendment) to integrate energy efficiency in cooling equipment and maximize benefits
S4. Support and leverage a research and development, and innovation ecosystem that enables technology advancement
S5. Incorporate strategies to enable access to cooling in off-grid or weak-grid locations

DEFINITIONS

Energy-Efficient Buildings (or building energy efficiency), in this publication, refer to buildings designed and constructed (or renovated) to be efficient in their use of energy and having reduced thermal loads through better site planning, building design and construction, integrated building system design, and systems and processes that support longer-term efficient operation and maintenance.

Fit-for-Purpose Financing refers to financing structured to meet the specific market needs for affordable financing of energy efficiency in buildings and sustainable space cooling. These market needs can include a need to enhance credit risk, address performance risk in relation to the realization of savings, provide appropriate accounting characterization of the financing, and mitigate split incentives by matching the flow of future energy savings with the obligation of loan repayment. The combination of financing and enabling mechanisms can deliver fit-for-purpose financing. While applicable to new construction, fit-for-purpose financing is more typically needed to support the retrofit and renovation of existing buildings where the market barriers are greater.

Mechanical Cooling refers to the meeting of cooling loads through a mechanical system, such as vapor compression.

Room Air Conditioners are the smallest of all the vapor compression–based air-conditioning systems and typically have up to 15 kilowatts or 4.5 tons of refrigeration of cooling capacity. They are usually used to cool a single room in a home, an apartment, or a small office.

Space Cooling, also referred to as "comfort cooling," refers to the means by which people are provided thermal comfort from heat by maintaining the optimum temperature, humidity, and ventilation within the built environment.

Sustainable Cooling Equipment, in this publication, refers to cooling equipment that has a lower environmental impact than current practices. This lowered impact is attained through a combination of reduced energy use and more climate-friendly refrigerants (in line with or exceeding obligations under the Montreal Protocol on Substances That Deplete the Ozone Layer and its various annexes, including the Kigali Amendment) that collectively have a lower environmental impact than do current practices and are in line with or exceed a country's internationally agreed-to greenhouse gas mitigation objectives. Cooling equipment includes all technologies that alter temperature, humidity, or air movement to create a cooling effect, for example, fans, air coolers, air conditioners, and chillers. Other publications may use different terms to convey the same or similar definitions, such as "efficient and clean cooling equipment."

Sustainable Space Cooling, in this publication, refers to achieving human thermal comfort within buildings through a combination of energy-efficient building design and practices (that enhance thermal performance of the building thereby reducing the need for mechanical cooling), efficient cooling technologies and practices, and more climate-friendly refrigerants (in line with or exceeding obligations under the Montreal Protocol on Substances That Deplete the Ozone Layer and its various annexes, including the Kigali Amendment) that collectively have a lower environmental impact than do current practices and are in line with or exceed a country's internationally agreed-to greenhouse gas mitigation objectives. Other publications may use different terms to convey the same or similar definitions, such as "efficient and clean cooling."

Sustainable Space Cooling Interventions are actions that a country or region could undertake to promote, support, incent, or regulate sustainable space cooling. This publication presents many sustainable space cooling interventions that may be considered by developing countries.

Thermal Comfort is defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as the "condition of mind which expresses satisfaction with the surrounding thermal environment."[1] While the commonly used indicator of thermal comfort is air temperature, a combination of both environmental and personal factors affects human thermal comfort.

Vapor Compression–Based Air Conditioners, also called simply "air conditioners" in this publication, refer to a type of cooling equipment that uses the vapor compression cycle principle to cool and dehumidify the air. A vapor compression cycle operates on four primary components: an evaporator, compressor, condenser, and expansion valve. Refrigerants, with the ability to undergo phase changes by absorbing and releasing the latent heat at relatively lower temperatures, operate in a closed-loop cycle and transfer heat from one space to another, thus producing a cooling effect. Most air-conditioning equipment available today is based on the vapor compression cycle, including room air conditioners, central air-conditioning systems, variable refrigerant flow systems, and chillers.

ACRONYMS

AC	Air conditioner
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEE	Bureau of Energy Efficiency (India)
CaaS	Cooling as a Service
CFC	Chlorofluorocarbon
CHP	Combined heat and power
CLASP	Formerly the Collaborative Labeling and Appliance Standards Program
CO_2	Carbon dioxide
COP	Coefficient of performance
DSM	Demand-side management
DX	Direct expansion
ECBC	Energy Conservation Building Code (India)
EDGE	Excellence in Design for Greater Efficiencies
EER	Energy efficiency ratio
ESA	Energy service agreement
ESCO	Energy service company
ESMAP	Energy Sector Management Assistance Program
EU	European Union
EUF	Environmental upgrade financing
GDP	Gross domestic product
GHG	Greenhouse gas
GW	Gigawatts
GWP	Global warming potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbons
HFO	Hydrofluoroolefin
HVAC	Heating, ventilation, and air-conditioning
ICAP	India Cooling Action Plan
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IECC	International Energy Conservation Code
IFC	International Finance Corporation
IPCC	Intergovernmental Panel on Climate Change
ISEER	Indian Seasonal Energy Efficiency Ratio
ISO	International Organization for Standardization
K-CEP	Kigali Cooling Efficiency Program
kW	kilowatt
kWh	kilowatt-hour
LED	light-emitting diode
LiBr	Lithium bromide
MEPS	Minimum energy performance standards
MESA	Managed energy service agreement
MMT	Million metric tons
MT	Million tons
MW	Megawatt
O&M	Operation and maintenance
ODP	Ozone depletion potential

PACE	Property assessed clean energy
PV	Photovoltaic
R&D	Research and development
RAC	Room air conditioner
RISE	Regulatory Indicators for Sustainable Energy
RMI	Rocky Mountain Institute
ROIC	Return on invested capital
RTU	Rooftop unit
SDGs	Sustainable Development Goals
SEforALL	Sustainable Energy for All
TEAP	Technology and Economic Assessment Panel
TR	Tons of refrigeration
TWh	Terawatt-hours
US	United States
VRF	Variable refrigerant flow
W/W	Watt/Watt

Thermometer in green pharmacy screen sign displays extremely hot temperature of 44 degrees Celsius during heatwave in summer in Belguim.
Credit: Philippe Clement/istock.

1. THE COOLING CONTEXT

INTRODUCTION

The Important Role of Cooling in Modern Society

Cooling has become vitally important to many aspects of modern life. It affects the thermal comfort in our homes, offices, and transportation; the preservation of our food, medicines, and data; and the provision of suitable conditions for learning in schools. Thus, the demand for cooling in all its forms is rapidly growing. The term "cooling" is broadly defined as the process through which heat is removed from a substance (solid or fluid), resulting in a lower temperature or phase change of that substance. The application of cooling covers many different sectors (such as buildings, transportation, industrial process cooling, and cold chains) and serves different functions (such as ventilation, air-conditioning, and refrigeration).

This publication is focused specifically on space cooling, which is defined as keeping the temperature of the air in a confined space at a given set point for a given heat load to be extracted.[2, iii] In simpler terms, space cooling, also referred to as "comfort cooling," refers to the means through which people are provided thermal comfort from heat by maintaining the optimal temperature, humidity, and ventilation within the built environment.

Space Cooling: A Critical Societal and Development Need

Space cooling is fast gaining global attention as an increasingly vital enabler of health, well-being, and productivity. Although in many developed countries in temperate climate zones space cooling is often perceived as a luxury, in the hottest climate zones within and close to the tropics, it is increasingly viewed as an important determinant of human health and well-being within the built environment, and increasingly seen as a development priority. For example, when speaking about Singapore's 100-fold increase in per capita gross domestic product (GDP) between 1960 and 2011, Prime Minister Lee Kuan Yew attributed space cooling through air-conditioning as a key factor in Singapore's success: "Air conditioning . . . changed the nature of civilization by making development possible in the tropics. . . . The first thing I did upon becoming prime minister was to install air conditioners in buildings where the civil service worked. This was key to public efficiency."[3]

Currently, 40 percent of the world's population—50 percent by 2050, according to predictions—resides in the tropics and has dramatically lower access to cooling in relation to their need.[4] In 2019, the Intergovernmental Panel on Climate Change (IPCC) reported that at 1.5°C of warming, 2.3 billion people could be both exposed and vulnerable to heat wave events—a threshold that could be reached as early as 2030. There is increasing evidence that this huge unmet need for cooling—dominant in developing countries in the tropics—impacts the health, education, productivity, and economic development of a nation, thus underscoring that cooling is essential to achieving many of the United Nations' Sustainable Development Goals (SDGs).[iv]

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iii The Energy Sector Management Assistance Program is developing a primer focused on cities and the mitigation of the urban heat island effect (*A Primer on Cool Cities—Responding to Excess Heat,* 2020).

iv Sustainable Energy for All's 2018 *Chilling Prospects* report links space cooling to the following Sustainable Development Goals (SDGs): Ensure healthy living and promote well-being for all at all ages (SDG 3), decent work and economic growth (SDG 8), and sustainable cities and communities (SDG 11).

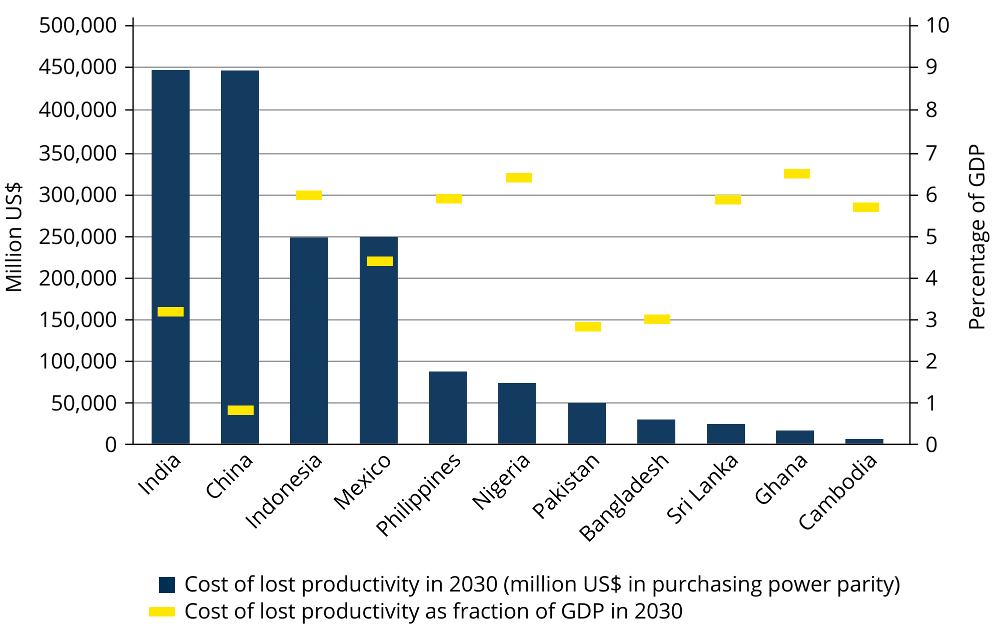
Health. Extreme heat events lead to health risks, particularly for the most vulnerable, including elderly adults, infants, low-income populations, and those who are chronically ill. But access to cooling minimizes these health impacts and decreases mortality. For instance, when air conditioners (ACs) became a commonly used appliance in the United States, the number of heat-related deaths fell significantly.[5, v]

Education. Negative impacts of excessive heat are also observed in the learning environment. A study of schoolchildren in Cameroon associated high indoor temperatures with fatigue, headaches, and slow writing speeds.[6] US-based research shows that without air-conditioning, each 1°F (approximately 0.55°C) increase in the average school year temperature is associated with a 1 percent decline in the amount learned during the school year.[7]

Productivity and economic development. The *Asia Pacific Journal of Public Health* estimates that the cost of lost productivity due to heat stress in developing countries ranges from 1 percent to 6 percent of GDP, amounting to billions of dollars (figure 1.1).[8] The International Labor Organization finds that the increase in heat stress resulting from global warming is projected to lead to global productivity losses equivalent to 80 million full-time jobs in the year 2030.[9]

The Sustainable Energy for All (SEforALL) *Chilling Prospects: Providing Sustainable Cooling for All* report estimates that work-hour productivity losses due to heat are expected to be more than 2 percent globally by 2050, and up to 12 percent in the worst-affected regions of South Asia and West Africa.[10]

FIGURE 1.1: ECONOMIC LOSS FROM EXPOSURE TO HEAT IN DEVELOPING COUNTRIES



Source: Kjellstrom 2016.[11]

v Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S. Shapiro, 2016, "Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the Twentieth Century," *Journal of Political Economy* 124 (1): 105–59, https://www.journals.uchicago.edu/doi/10.1086/684582?mobileUi=0. This paper reports that the mortality impact of days with a mean temperature exceeding 26°C (80°F) declined in the United States by 75 percent and that the diffusion of residential air-conditioning explains essentially the entire decline in hot-day-related fatalities.

A growing body of evidence underscores that greater and rapid access to affordable cooling is a development necessity. As countries strive to meet this need, the resulting spike in cooling demand comes with consequent social, economic, and environmental impacts (discussed in more detail in section 2). And therein lies the cooling challenge: how to enable thermal comfort for all while minimizing the emissions and environmental impacts of increased access to cooling.

UNDERSTANDING SPACE COOLING

Determinants of Human Thermal Comfort

Since the function of space cooling is to achieve human thermal comfort, it is important to understand the key concepts behind thermal comfort. “Thermal comfort” is defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as the “condition of mind which expresses satisfaction with the surrounding thermal environment.”[12] While the commonly used indicator of thermal comfort is air temperature, a combination of both environmental and personal factors affects human thermal comfort, as summarized in figure 1.2.

FIGURE 1.2: DETERMINANTS OF HUMAN THERMAL COMFORT

Environmental Factors for Thermal Comfort

Radiant temperature: the heat that radiates from a warm object. Typical examples of radiant heat sources include the sun, fire, ovens, hot surfaces, and machinery.

Air temperature: temperature of the air surrounding the body.

Air speed: the speed of air movement. Moving air in warm or humid conditions can increase heat loss from the human body through convection without any change in temperature, thus aiding in cooling.

Humidity: water vapor in the air. The ability of air to hold water vapor directly relates to its temperature. The warmer the air is, the more humidity or water vapor it can hold.

Personal Factors for Thermal Comfort

Clothing: appropriate clothing for climatic conditions.

Metabolic rate: inherent and affected by a person’s activity level.

Source: Authors, composed by Rocky Mountain Institute.

Of the list of determinants identified above, the two most important factors affecting thermal comfort are air temperature and humidity—both of which are affected by the following forms of heat energy:

- **Sensible heat** is commonly understood as heat energy that can be sensed by touch and that results in a change in the temperature of a substance (which can be measured directly with the help of a thermometer). It is essentially this heat that causes a change in air temperature. Sensible heat is usually considered a proxy for comfort. To maintain the desired temperature in a space, sensible heat may have to be added or removed from it.

- **Latent heat**—commonly understood as humidity (figure 1.2)—is the thermal energy released or absorbed by an object undergoing a phase change at constant temperature and constant pressure. For example, liquid water at 100°C and 1 atmosphere of pressure will convert to water vapor by absorbing the latent heat at a constant temperature and constant pressure. The process is reversed when the latent heat is removed. Because air contains water vapor (which is a measure of humidity), latent heat may need to be added or removed to maintain the desired humidity level in a space.

What Is the Relationship between Sustainable Space Cooling and Building Energy Efficiency?

Delivery of thermal comfort to building occupants is the primary driver of the energy load in most buildings. As such, cooling in buildings is an integral part of energy efficiency in buildings—particularly in hot climates. For example, in some climates, such as Singapore, cooling represents up to 70 percent of the total energy load in buildings.[13] Thus, the interventions to promote building-specific sustainable space cooling are not so different from those that would be considered for enhancing overall building energy efficiency, where common barriers prevail and similar solutions are applicable.

However, while cooling is a part of building energy efficiency, it does have some unique factors and attributes, including the impact on energy systems in terms of driving peak load, the role of refrigerants and their impact of emissions, and the ability to design cooling at an urban or community level (where cooling can be provided more efficiently and with a lower greenhouse gas [GHG] footprint over multiple buildings). When looking through the wider lens of sustainable space cooling, as opposed to building-specific energy efficiency, we see more clearly the impact of cooling on energy systems, economies, and climate.

Given the significant growth in global cooling demand in buildings (particularly in developing countries), and the consequent impacts on energy systems and climate, the critical need of the hour is to meet space cooling demand as sustainably as possible to reduce associated impacts on energy systems and climate, building on general demand-side energy-efficiency experience to date and integrating cooling-focused approaches.

WAYS TO ACHIEVE SPACE COOLING

Broadly, the strategies to address space cooling and achieve thermal comfort can be grouped into two general categories: passive and active cooling.

Passive Cooling

“Passive cooling” refers to a building design approach that reduces, avoids, or eliminates the need for mechanical cooling and relies on making the built environment intrinsically thermally efficient and comfortable. This is achieved primarily through design strategies that prevent heat from entering the building's interior (heat gain prevention) and remove heat from the building through natural cooling. Leveraging the principle that heat naturally flows from warmer to cooler areas, the building design uses the site's natural resources (such as the night sky, outdoor air and wind, and earth and soil) as heat sinks to transfer the heat passively from a higher-temperature to a lower-temperature medium. Passive cooling strategies are typically cost-effective—particularly when integrated during new construction—but are less effective when temperature and humidity remain consistently high throughout a 24-hour period.

A diversity of building design strategies can help achieve passive cooling, such as building orientation, thermal insulation and massing, reflective roofs, and ventilation. These are discussed in greater detail in section 3 of this publication. The choice of which passive cooling strategies to employ is largely determined by the local climate as well as the environmental attributes of the site (such as shading, vegetation, orientation, prevalent wind direction, and soil conductivity).

Commonly covered within the purview of energy-efficient building design, the use of passive cooling approaches is typically driven by a country's national building energy codes.[vi] A high-level analysis by Rocky Mountain Institute (RMI) suggests that building envelope improvements—a key passive cooling approach driven by building codes—have the potential to achieve a 15 percent reduction in space cooling demand in 2050 in developing countries. Regarding developed countries, the analysis suggests a reduction potential of 7.5 percent in cooling demand in 2050 (lower in comparison, due to existing code implementation).[14] This reduction in space cooling demand allows for downsized active cooling equipment to be installed, resulting in reduced capital cost and energy use.

Greater adoption of passive cooling strategies—that enhance the thermal performance of buildings thereby reducing the requirement for mechanical cooling—presents meaningful potential for reducing the cooling energy demand of the building sector and the associated climate impacts. However, this potential remains largely untapped in developing countries (this is discussed in greater detail in section 3).

While passive cooling strategies are the logical foundational step when addressing the cooling needs of the building sector, it is important to recognize that in hot climate zones, passive strategies alone will typically not be enough to meet thermal comfort needs and will most often have to be complemented with active cooling.

Active Cooling

Active cooling involves the use of mechanical means and energy to remove or transfer the heat from an indoor space, thereby making it thermally comfortable. With active cooling, the design also leverages the principle of heat sinks for the active rejection of heat. There are several technology options—of varying complexity and effectiveness—that can help achieve the thermal comfort needs of a particular space. These are discussed in greater detail in section 3.

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vi For a more complete discussion on building energy codes, please see intervention P7, *Accelerate the adoption of passive cooling strategies through national building energy codes with a robust enforcement mechanism* in the Compendium. Prescriptive national building energy codes set minimum requirements for energy-efficient design and construction and generally cover thermal envelope and heating, ventilating, and air-conditioning systems and performance. However, they may not cover all passive cooling approaches, such as cool roofs. For example, India's prescriptive path in its Energy Conservation Building Code does not cover cool roofs, whereas, in the United States, the prescriptive building energy codes do include cool roofs for warm climate zones. Where national prescriptive building energy codes do not include all passive cooling measures, regional and municipal passive cooling programs can be implemented, such as those that leverage benefits from cool roofs.

Vapor compression–based air-conditioning systems are the dominant space cooling technology today—and are expected to remain an important choice for space cooling in the foreseeable future—because they are easy to use, scalable, reliable, and effective in all climate conditions and applications. They cool the air to the desired temperature and, in the process, can also reduce the humidity of the air by condensing the water vapor, depending on the humidity content of the air. That said, air-conditioning is energy intensive; largely depends on grid electricity predominantly fueled by fossil fuels in the majority of countries, driving indirect GHG emissions; and further, is associated with refrigerants (that overwhelmingly have high global warming potential [GWP]) responsible for direct GHG emissions.

Today's most prevalent air-conditioning system, room air conditioners (RACs)—which constitute about 75 percent of the total number of installed AC units today,[vii] and are on a growth curve—are fraught with market failures resulting from first-cost bias. Thus, the industry has largely focused on first-cost optimization and less on lowering the life cycle costs. As a result, the average efficiency of RACs sold today is less than half that of the commercially available best-in-class (that is, the most energy-efficient units).[15]

Fans and air coolers are the other commonly used space cooling technologies, particularly prevalent in developing countries—in the residential sector as well as in small to medium-sized commercial applications—owing to their affordability. Fans and air coolers have relatively lower energy use (compared to ACs) and do not utilize refrigerants. However, the operation of these technologies has practical limitations in achieving satisfactory thermal comfort in regions with soaring temperatures, especially when coupled with high humidity. That said, fans—due to their affordability—can play an important role in enabling access to cooling for poor households, and depending on the climate and building design, they could continue to meet a meaningful share of growing residential space cooling needs.

An optimal combination of passive and active cooling strategies should be considered for addressing space cooling to achieve thermal comfort. In addition, operational practices—in terms of user operations, and maintenance and servicing of cooling equipment—constitute an important variable in space cooling energy use. Often overlooked, collectively, operational practices can influence the demand for and the efficacy of space cooling, and should be carefully managed. This is discussed in more detail in section 3.

MULTIPLE FACTORS INFLUENCE THE CHOICE OF SPACE COOLING SOLUTIONS

Choosing the appropriate space cooling solutions involves many factors, including building scale, type of construction (new or existing building), building ownership profile, climate zone, immediate environmental attributes, and country-specific factors (such as labor costs, utility rates, and grid factor). These factors come together to determine the optimal economics and the choice of space cooling solution, and are described in detail in section 3 (figure 3.15). While these factors apply in combination, a dominant determinant of the optimal space cooling technology is the scale of the built environment being addressed—that is, whether cooling is to be provided, for example, for a room, a single building, or a campus. This is also discussed in greater detail in section 3 (and figure 3.6).

In addition to being dependent on the abovementioned factors, the cooling solutions must align with the ability and willingness of the population being served to pay the first costs and the operational costs. Such solutions also are contingent on the cost and availability of financing. This is especially relevant in emerging markets, where price-sensitive new adopters have a tendency to purchase entry-level

vii While predominantly used in residential buildings, RACs are in use in a small portion of the commercial sector as well.

solutions—that is, low-first-cost and low-efficiency ACs—resulting in a high overall economic burden for the user, increased strain on energy systems, and high environmental impacts.

KEY TAKEAWAYS

- Space cooling is increasingly recognized as a critical enabler of health, well-being, and productivity. Greater and rapid access to affordable cooling is becoming a development necessity.
- While space cooling is an integral part of building energy efficiency—particularly in hot climates where it is a key driver of building energy demand—and some of the same barriers and solutions (as applicable to building energy efficiency) apply, it does have unique attributes that impact energy systems (particularly driving peak loads), economies, and climate.
- An optimal combination of passive and active cooling elements should be considered for addressing space cooling to achieve thermal comfort.

Air conditioners on building wall.
Credit: baona/istock.

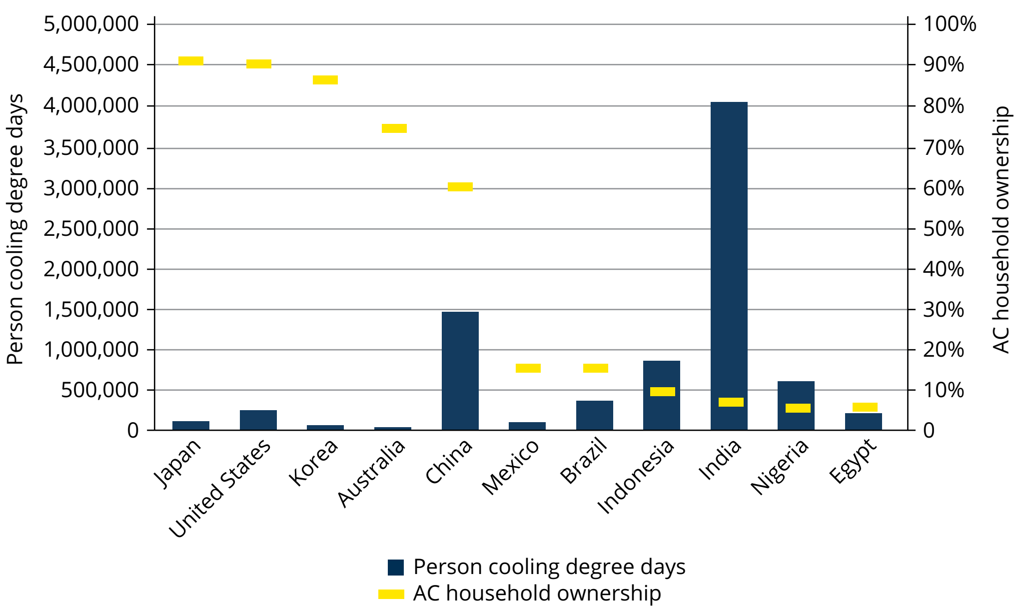
2. WHY ADDRESSING SPACE COOLING SUSTAINABLY IS A PRIORITY

COOLING DEMAND GROWTH IS INEVITABLE AND SIGNIFICANT

In response to the unmet, and growing, need for thermal comfort in the hot regions of the world, it is predicted that 10 air conditioners (ACs) will be sold every second over the next 30 years.[16]

Air conditioner ownership in different parts of the world today in relation to the demand for cooling (represented in figure 2.1) is a good representation of the unmet need for thermal comfort. A recent study quantifies this unmet need: between 1.8 and 4.1 billion people—mostly located in India, Southeast Asia, and Sub-Saharan Africa—require access to cooling.[17]

FIGURE 2.1: COOLING DEMAND VERSUS CURRENT AIR CONDITIONER OWNERSHIP IN DIFFERENT PARTS OF THE WORLD



Source: Based on RMI analysis.[18]

Note: The cooling demand, represented by "person cooling degree days," is a function of a country's average annual cooling degree days multiplied by the respective population.

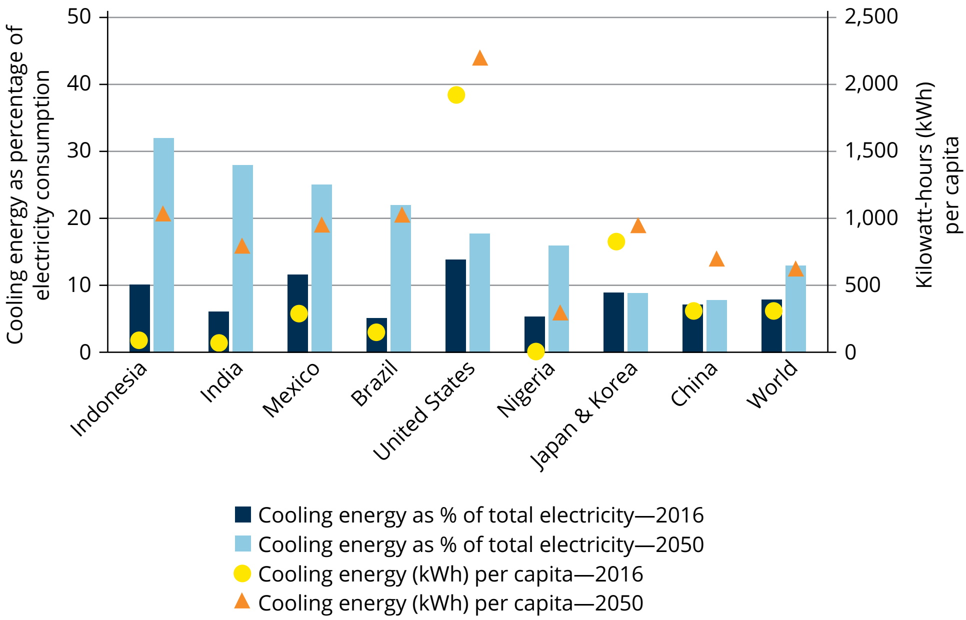
In addition to today's unmet cooling needs, multiple accelerators are acting concurrently to contribute to the escalating need for space cooling (figure 2.2). With warming global temperatures, and some of the most populous and hottest parts of the world seeing large increases in population and urbanization, the demand for cooling will grow. With increased purchasing power, so too will the ability of households to satisfy this need. It is expected that rising incomes will enable many low- and middle-income families around the world to purchase their first air conditioner. Such purchases will have significant implications for growing energy demand and associated greenhouse gas (GHG) emissions.

Based on this expected growth, the global energy use for space cooling is projected to jump from 2,020 terawatt-hours (TWh) in 2016 to 6,200 TWh in 2050—an astounding threefold increase. World-wide, cooling is expected to account for 21 percent of the total increase in final electricity consumption between 2016 and 2050. Most notably, developing countries such as Indonesia, India, Mexico, and Brazil will see a sharp increase in cooling energy demand, accounting for 25–35 percent of their

FIGURE 2.2: ACCELERATORS OF DEMAND FOR SPACE COOLING

Source: RMI infographic based on RMI, *Solving the Global Cooling Challenge,* with data from the United Nations Department of Economic and Social Affairs, Population Division, Organisation for Economic Co-operation and Development, State of the Tropics (2017), and the International Energy Agency.[19]

FIGURE 2.3: SHARE OF SPACE COOLING ENERGY IN TOTAL ELECTRICITY DEMAND AND PER CAPITA COOLING ENERGY CONSUMPTION BY COUNTRY



Source: RMI analysis with data from the International Energy Agency's *Future of Cooling* and *Africa Energy Outlook* reports and the United Nations Department of Economic and Social Affairs, Population Division.[20]

respective final electricity consumption in 2050 (figure 2.3). Many African countries also show a similar growth trend, constituting a huge jump in their per capita energy use for space cooling over the same period.

While this growth in space cooling is in alignment with development needs across the globe, it comes with significant impacts to energy systems, the environment, and society at large, given that today's cooling practices are generally very energy intensive and rely predominantly on fossil-fuel-generated electricity and refrigerants harmful to the climate (with high global warming potential [GWP]).

IMPACTS OF COOLING DEMAND GROWTH UNDER A BUSINESS-AS-USUAL SCENARIO

Impact on Power Systems

The projected exponential increase in space cooling demand will put pressure on already strained electricity systems in many countries, most notably in the form of peak loads, which in turn will require a significant increase in grid capacity.

Peak load is the most expensive load to serve due to the need to bring online the most inefficient plants, which may operate for only a few hours on the hottest days of the year. Increasing peak loads necessitates capacity additions and, in turn, leads to either increased operating subsidies or increased electricity costs for consumers.

The daily and seasonal profiles of projected cooling demand are expected to accentuate peak loads significantly. It is estimated that by 2050, space cooling will account for 30–50 percent of peak electricity load in many countries, with the biggest increase occurring in India.[21]

- India is expected to have a total peak power demand of around 1,300 gigawatts (GW) by 2050,[viii] compared to around 160 GW in 2016, and the expected growth in ACs will contribute about 45 percent to this peak alone.[22]
- Similar trends are observed in China, where, by 2050, it is anticipated that in some of the state and local grids, the cooling load could contribute up to 50 percent of the total peak demand.[23]
- In Indonesia, total electricity peak demand is expected to reach 260 GW by 2050, compared to 45 GW today, of which about 40 percent will be attributable to ACs.[24]
- A study of four countries in the Maghreb region of North Africa (Algeria, Libya, Morocco, and Tunisia) shows that the growing use of air-conditioning is already contributing to 30–70 percent of the peak load, depending on the country.[25]

Globally, the total capacity needed to meet the escalating space cooling demand jumps 395 percent, from 850 GW in 2016 to 3,350 GW in 2050. This increase of 2,500 GW is equal to the current total generating capacity of the United States, Europe, and India combined,[26] and it amounts to an investment of US$1.7 trillion in power generation capacity alone (excluding associated fuel costs and transmission and distribution infrastructure costs).[ix] Just four countries—India, China, Brazil, and Indonesia—account for 60 percent of the total capacity additions and 75 percent of the total investments required globally to meet the 2050 cooling demand under a business-as-usual scenario (figure 2.4).

Impact on Consumers' Pockets

Expenditures to achieve space cooling already account for 5–15 percent of the median household income in many parts of the world. With rising temperatures and increased demand for comfort, the operation of air-conditioning units to provide cooling will only increase.

In the residential sector, the projected adoption of entry-level cooling equipment—that is, the most commonly sold room air conditioners (RACs) on the market today, which are typically less-energy-efficient and low-first-cost units—will lock in high operational costs for customers, resulting in a higher fraction of disposable income allocated to electricity bills. A less efficient entry-level RAC can cost one-and-a-half to two times more over its lifetime (typically 10–12 years), compared with commercially available high-efficiency RAC units (figure 2.5).[27, x] An energy-efficient air conditioner can significantly reduce energy

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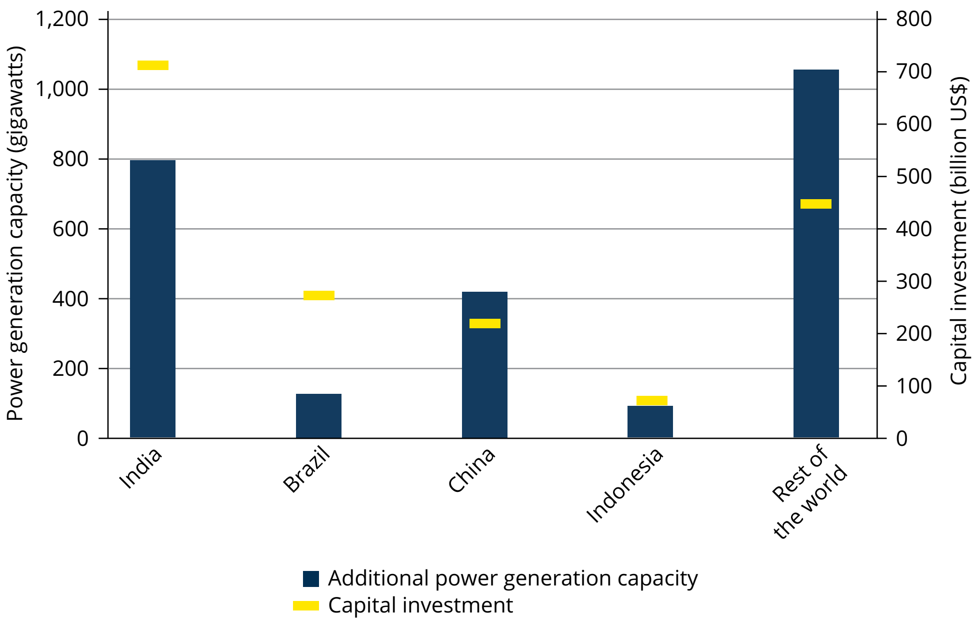
viii The 2050 peak power demand is estimated based on the following inputs and assumptions: total capacity required to meet India's cooling demand in 2050 is around 850 GW; peak coincidence factor is 0.7; space cooling contributes 45 percent to India's total peak demand. Based on these inputs, it is assumed that 70 percent of total capacity required for space cooling in 2050 will coincide and contribute to the overall peak demand on the grid, therefore suggesting a total peak demand of around 1,300 GW.

ix To determine the investment required, the average cost of construction of natural gas power generators in the United States (US$696 per kilowatt) was used as a proxy for the most common power generator.

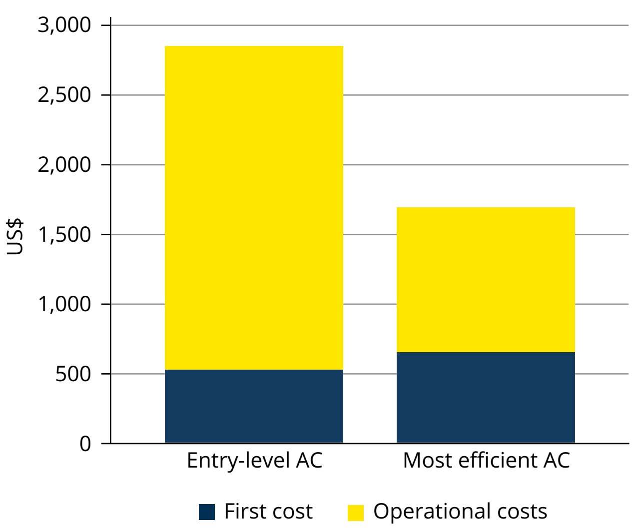
x The energy cost savings are determined by comparing the first installed cost and operational cost of a 1.5 tons of refrigeration (TR) fixed-speed room air conditioner (RAC) with an energy efficiency ratio (EER) of 3.5 Watt/Watt that is most commonly sold on the Indian market today with one of the most efficient 1.5 TR inverter RACs (Indian Seasonal Energy Efficiency Ratio, or ISEER, 5.2) available on the Indian market. The annual energy consumption of the entry-level fixed-speed RAC is determined from the energy model by simulating a typical residential apartment home in New Delhi, India, over a full year's temperature and humidity profile. The annual energy consumption of the most efficient unit is determined based on research. It is assumed that both the ACs have a lifetime of 10 years and an annual operation of 1,600 hours. The electricity price is considered to be 6.5 rupees (Rs.) per kilowatt-hour and to increase at 4 percent per year for the next 10 years. The discount rate is assumed to be 7 percent.

FIGURE 2.4: POWER GENERATION CAPACITY ADDITIONS AND ASSOCIATED INVESTMENT REQUIRED TO MEET THE COOLING DEMAND IN 2050



Source: RMI analysis with data from IEA, *The Future of Cooling*.[28]

FIGURE 2.5: LIFE CYCLE COST COMPARISON OF A TYPICAL ENTRY-LEVEL ROOM AIR CONDITIONER AND THE MOST EFFICIENT RAC SOLD IN INDIA



Source: RMI analysis with data from RMI, *Solving the Global Cooling Challenge*.[29]

costs, typically repaying the incremental cost of a higher-efficiency model in less than three years through accrued energy savings. These cost savings don't impact only the residential sector. While the above statistics are for RACs, life cycle cost savings from more energy-efficient cooling equipment exist for all sizes and types of equipment, meaning the commercial and public sectors also stand to achieve significant savings from the adoption of efficient cooling practices.

Overall, all consumers will also face increased electricity costs, including those who do not use air-conditioning, as the utilities and power companies invest in capacity additions and grid improvements to address the rising demand for electricity at peak load.

Impact on Emissions and Climate

GHG emissions associated with operating typical cooling equipment can be categorized as indirect emissions (resulting from the production of electricity used for operation) and direct emissions (resulting from the leakage and release of high-GWP refrigerants). While some cooling equipment types, such as fans and air coolers, do not use refrigerants and therefore do not have any direct emissions, all air conditioners commercially available today use refrigerants.[xi] Most fluorinated refrigerants—chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and many hydrofluorocarbons (HFCs)—are powerful climate pollutants with high GWP. Whereas direct emissions occur mostly as a result of inadvertent leaks during operation and maintenance (O&M) and disposal of the system, indirect emissions (which depend on the energy efficiency of the equipment and the source of electricity generation) drive overall emissions, globally constituting about 80 percent of the total annual emissions associated with cooling equipment.[30]

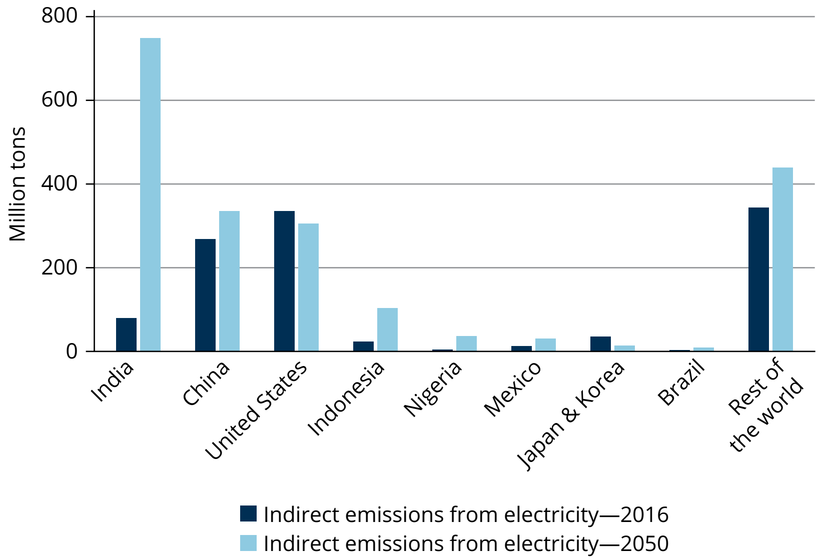
Given that today's cooling equipment depends largely on power grids that are fueled predominantly by fossil fuels, the projected increase in global electricity consumption for space cooling will result in 18 percent of the total increase in global carbon dioxide (CO_2) emissions between 2016 and 2050.[31] This growth in consumption will also make it much harder for many developing countries to meet their goals to invest in decarbonizing and reducing the emissions intensity of their electricity systems.

Despite the grid's declining emissions intensity due to ongoing clean energy efforts, International Energy Agency (IEA) analysis shows that the global annual indirect emissions associated with space cooling almost doubles, from 1,135 million tons (MT) in 2016 to 2,070 MT in 2050 (figure 2.6).

Add to this the direct emissions originating from many common refrigerants used in air conditioners, and this number would further expand. The cumulative emissions over the intervening years would amount to significant climate impacts. Cumulative emissions for air-conditioning in the residential sector alone could result in up to 0.5°C of global warming by 2100.[32] This impact would be even greater when considering the cumulative emissions from air-conditioning for the entire building sector.

xi See below for more information on refrigerants, and see section 3 for more information on the different types of cooling equipment available today.

FIGURE 2.6: CO_2 EMISSIONS ASSOCIATED WITH ELECTRICITY CONSUMPTION (OR INDIRECT EMISSIONS) OF AIR CONDITIONERS



Source: International Energy Agency 2019.[33]

REFRIGERANTS: AN IMPORTANT PART OF THE SPACE COOLING DISCUSSION

The Role and Challenge of Refrigerants

Given that vapor compression–based air-conditioning is the predominant space cooling equipment, the role of refrigerants becomes an important part of the space cooling discussion. Refrigerants are critical to vapor compression air-conditioning and are responsible for their direct emissions. Contained within the coils of an AC, these fluids aid the process of cooling the indoor air. These fluids have unique physical and chemical properties that allow them to expand and contract under pressure at room temperature and serve as an excellent medium for heat exchange.

Many of the prevalent refrigerants have a negative effect on the environment because of their ozone depletion potential (ODP) and high GWP. The damage to the environment from refrigerants is typically due to inadvertent leaks during the O&M and service or repair of an AC and at the end of life of an AC.

Since their first use in the 1830s, refrigerants have gone through several phases of evolution. Synthetic refrigerants, such as CFCs, were one of the earliest refrigerants to be adopted, because they had higher relative energy efficiency and no safety concerns. However, these refrigerants were causing extensive damage to the ozone layer. HCFCs were the next generation of refrigerants. They had many of the same characteristics as CFCs, except they had a much lower ODP value.

The Montreal Protocol on Substances That Deplete the Ozone Layer, one of the most successful international agreements to date, came into effect in 1989 and has since focused on phasing out the substances that damage the ozone layer. CFCs have been banned from production globally since 2010;

HCFCs are also being phased out gradually, with a target for complete phaseout by 2030 globally. As a result of the Montreal Protocol, industry shifted completely from CFCs and is shifting from HCFCs to other commercially viable alternatives, such as HFCs, hydrofluoroolefins (HFOs), and natural refrigerants. HFCs today are the most widely deployed refrigerants in air conditioners globally. While HFCs have an ODP of zero, they are hundreds to thousands times more potent as a greenhouse gas than is CO_2 in contributing to climate change. Studies have shown that if the future demand for refrigerants between now and 2050 is increasingly met by HFCs (a demand that can mostly be attributed to the rising demand for air-conditioning), up to 27 percent of all global warming will be attributable to those refrigerants by 2050.[34]

In 2016, the Kigali Amendment to the Montreal Protocol was adopted to phase down the consumption and production of HFCs globally; it entered into force on January 1, 2019. The proposed phased down schedule—to be completed in three different timelines—depends on a country's categorization as either a member of non-Article 5 parties (developed countries) or a member of Article 5 parties, which includes Group 1 developing countries and Group 2 developing countries.[35]

- The Kigali Amendment requires developed countries (non-Article 5 parties) to bring down their HFC production and consumption by at least 85 percent by January 1, 2036, compared to the baseline consumption/production, which is determined by the average HFC consumption during 2011–13 and 15 percent of the HCFC baseline (HCFC consumption in 1989 plus 2.8 percent of CFC consumption in 1989). For Belarus, Russia, Kazakhstan, Tajikistan, and Uzbekistan, also non-Article 5 parties, the baseline formulation for 2011–13 is different, and in these countries, the first two phasedown steps are different from other non-Article 5 parties.[36]

- A large group of developing countries—including China, Brazil, and South Africa (Article 5 parties, Group 1)—upon consenting to be bound by the Kigali Amendment, are mandated to reduce their HFC production and consumption by 80 percent by January 1, 2045, compared to the baseline consumption/production, which is determined by the average HFC consumption between 2020 and 2022 and 65 percent of the HCFC baseline (average HCFC consumption in 2009 and 2010).

- Article 5 parties, Group 2—Bahrain, India, the Islamic Republic of Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and the United Arab Emirates—are required to cut down their HFC use by 85 percent by January 1, 2047, compared to the baseline consumption/production, which is determined by the average HFC consumption between 2024 and 2026 and 65 percent of the HCFC baseline (average HCFC consumption in 2009 and 2010).

- For countries or parties to the Kigali Amendment that observe high ambient temperature conditions and where viable alternatives are not available, an exemption is provided regarding compliance with the HFC phasedown for an initial four-year period, and subsequent deferrals are subject to review and approval by the appropriate committee.[37, xii]

The Kigali Amendment also recognized the importance of maintaining or enhancing energy efficiency as part of the refrigerant transition and opening a window to redesign cooling equipment to be more efficient, thereby maximizing the climate benefits of the transition.

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xii Countries with high ambient temperature conditions include Algeria, the Arab Republic of Egypt, Bahrain, Benin, Burkina Faso, the Central African Republic, Chad, Côte d'Ivoire, Djibouti, Eritrea, The Gambia, Ghana, Guinea, Guinea-Bissau, Iraq, the Islamic Republic of Iran, Jordan, Kuwait, Libya, Mali, Mauritania, Niger, Nigeria, Oman, Pakistan, Qatar, Saudi Arabia, Senegal, Sudan, the Syrian Arab Republic, Togo, Tunisia, Turkmenistan, and the United Arab Emirates.

Choosing the Right Refrigerant

Different refrigerants have different characteristics. The ideal refrigerant would have no toxicity or flammability, an ODP of zero, a GWP of zero, high energy efficiency, and a commercially attractive cost. However, no refrigerant scores perfectly on all the desired characteristics. The low-GWP alternatives used today in cooling systems—such as hydrocarbons (HCs) and HFO blends—have either potential safety concerns related to flammability or are limited to use in specific applications due to efficiency and cost aspects.[xiii]

Hence, selection of the most appropriate refrigerant is often based on trade-offs. For example:

- R-290, a hydrocarbon refrigerant, has an ODP of zero and a GWP of three (most HFCs have a GWP in the thousands). The thermodynamic performance of R-290 has also been observed to be comparable with or better than the dominant R-22 (an HCFC) or R-410A (an HFC blend) refrigerants in small air-conditioning equipment.[38] However, the higher flammability of R-290 restricts the amount of refrigerant that can be used for indoor applications, due to occupant safety concerns. Thus, it is used only in small (low-charge) residential/room air conditioners today. Specifically, a number of Indian and Chinese manufacturers have developed R-290 room air conditioners for their markets.[39]
- Similarly, carbon dioxide (R-744) and ammonia (R-717), two natural refrigerants with ODPs of zero and negligible GWP (carbon dioxide has a GWP of one, and ammonia has a GWP of less than one), have limitations involving high operating pressures and toxicity, respectively. These factors generally restrict their use to large commercial- and industrial-scale applications.
- HFOs and HFO blends, on the other hand, while still synthetic, are more environmentally friendly compared to HCFCs and HFCs. HFOs and HFO blends have low to medium GWP values and ODPs of zero, and have minimum safety concerns (low flammability and toxicity). However, to date, their application has been limited to large chillers or mobile air-conditioning because of lower efficiency and higher costs compared to commonly used refrigerants in the residential sector.

The choice of the refrigerant in an AC will depend on several aspects, such as the following:

- **Refrigerant efficiency.** Refrigerant performance is characterized by a variety of parameters, such as coefficient of performance (COP), volumetric refrigeration capacity, and compressor discharge temperature. These parameters depend on the refrigerant's thermodynamic and physical properties, such as its critical temperature and pressure, latent heat of vaporization, vapor density, and specific heat. Since no refrigerant has favorable properties across all these parameters, a combination of these performance characteristics, along with several other aspects (noted below), is considered when choosing a refrigerant. In this primer, refrigerant performance is defined using a combination of COP and volumetric refrigeration capacity.
  - Volumetric refrigeration capacity is the amount of cooling effect produced (kilojoule or kilowatt [kW]) per unit volume (cubic meters) of refrigerant. Thus, for the same cooling capacity, a refrigerant with a higher volumetric refrigeration capacity will require less volume of refrigerant, which in turn would result in a smaller compressor size requirement.
  - COP is the ratio of refrigeration or cooling effect in kW to power consumed by the compressor in kW.

xiii While a detailed discussion of refrigerant blends is beyond the scope of this publication, more information on refrigerants and refrigerant blends can be found in the following report: Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019, *Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee 2018 Assessment Report*, United Nations Environment Program, Nairobi, Kenya, https://ozone.unep.org/sites/default/files/2019-04/RTOC-assessment-report-2018_0.pdf.

Table 2.1 presents a comparison of the performance of various refrigerants based on COP and volumetric refrigeration capacity. Since performance is a relative parameter, all the refrigerants are compared with respect to R-22 (an HCFC refrigerant). It is also to be noted that while important, refrigerant and compressor efficiency are only two components of a cooling system's efficiency; the overall system efficiency also depends on the heat exchanger design and components such as fans, motors, and ducts (if any).

- **Environmental impact.** The environmental impact of refrigerants is measured in terms of their GWP and ODP. The refrigerants in use today in most new air conditioners have zero or negligible ODP; however, their GWPs range widely, from less than 5 to about 2,000. Refer to table 2.1 for the GWP of commonly used refrigerants.

- **Safety.** The safety aspect of a refrigerant—an important consideration—involves its toxicity and flammability. The International Organization for Standardization (ISO) classifies refrigerants based on their toxicity and flammability under the ISO 817:2014 standard. For toxicity, the refrigerants are classified either as Class A or Class B, with the latter denoting high toxicity. For flammability, the refrigerants are classified as 1, 2L, 2, or 3. The low to high scale denotes increasing flammability. For example, the R-290 refrigerant is given an A3 rating, which means it has low toxicity but is highly flammable. Ammonia, or the R-717 refrigerant, is given a B2L rating, which means it is mildly flammable but has high toxicity. Both toxicity and flammability are related to the concentration of a refrigerant in a given volume of space and, therefore, are key considerations in choosing a refrigerant for a particular application.

  The International Electrotechnical Commission (IEC) and ISO have developed standards that consider the toxicity and flammability of refrigerants and determine the charge quantity (in kilograms) that can be used for a specific application. For example, R-290, because of its high flammability, can be used only in a limited quantity based on the IEC (and ISO) standard, thus restricting its use to small air-conditioning equipment.

- **Other considerations.** Some other aspects to consider for refrigerants include cost and non-corrosiveness, among others. While the cost of refrigerants used today is not significant compared to the cost of the air-conditioning equipment, restrictions on high-GWP refrigerants and phasedown of HFCs may result in an increased cost of these fluids. Similarly, it is critical that refrigerants do not exhibit corrosion or scaling properties, which could otherwise degrade the performance and estimated life of the air-conditioning equipment.

Table 2.1 compares some of the most commonly used refrigerants today with select emerging or niche refrigerants, based on their efficiency, environmental, safety, and cost characteristics.

Given the diversity and complexity around refrigerants, it is important to make appropriate information available to guide end-users on how to safely operate equipment with higher risk refrigerants. Capacity building and training of the service sector is important to ensure safe and proper handling, or disposal, of refrigerants during AC maintenance.

Simultaneously Addressing Both Direct and Indirect Emissions

Efforts to date (such as the Montreal Protocol and the 2016 Kigali Amendment) have largely focused on addressing the direct emissions from space cooling by targeting the phaseout of ODP refrigerants and phasedown of high-GWP refrigerants and by providing a pathway to eliminate these sources of emissions over time. However, as noted in the Technology and Economic Assessment Panel (TEAP) report, the indirect emissions from electricity consumption can constitute up to 80 percent of the total annual emissions

TABLE 2.1: REFRIGERANTS IN APPLICATION OR UNDER EXPLORATION IN THE SPACE COOLING SECTOR

	COMMONLY USED REFRIGERANTS (PLANNED FOR PHASEOUT/ PHASEDOWN UNDER THE MONTREAL PROTOCOL AND KIGALI AMENDMENT)			EMERGING OR NICHE REFRIGERANTS			
				NATURAL REFRIGERANTS			SYNTHETIC REFRIGERANTS
PROPERTIES OF REFRIGERANT	R-22 (HCFC)	R-410A (HFC)	R-32 (HFC)	R-290 (HC)	R-717 (AMMONIA)	R-744 (CARBON DIOXIDE)	HFOs
Global warming potential (GWP)	1,760	1,924	677	3	0	1	< 1–1,200
Ozone depleting potential (ODP)	0.05	0	0	0	0	0	0
Refrigerant performance (coefficient of performance [COP] relative to R-22 for cooling only)[a]	N/A	Similar	High	High	High	Low	Mostly low
Refrigerant performance (volumetric refrigeration capacity relative to R-22)[b]	N/A	High	High	Low	High	Very high	Mix of low and high
Toxicity	Low	Low	Low	Low	High	Low	Low
Flammability	None	None	Low	High	Low	Low	Low
Cost	Low	Medium	Low	Low	Low	Low	High
Typical application	Small air-conditioning equipment, for example, room air conditioners				Large vapor compression and absorption chillers at industrial scale	Large vapor compression chillers at industrial scale, as well as food and transport refrigeration systems	Large vapor compression chillers and vehicle air-conditioning systems

Source: Intergovernmental Panel on Climate Change 2013.[40]

a. McLinden, Mark, J. Steven Brown, Riccardo Brignoli, Andrei F. Kazakov, and Piotr A. Domanski, 2017, "Limited Options for Low-Global-Warming-Potential Refrigerants," *Nature Communications* 8, 14476, https://doi.org/10.1038/ncomms14476.

b. Ibid.

from the cooling equipment, depending on the size of the equipment and grid reliance on fossil fuels—leaving the efficiency opportunity to reduce emissions largely untapped in relation to its potential.[41]

To neutralize the impact of the projected growth in cooling and enable access to cooling for all without contributing further to warming the planet, it is important to capture the opportunity to address both indirect and direct emissions in parallel—that is, work on a targeted reduction in the electricity used for space cooling and successfully transition to low-GWP refrigerants, as contemplated under the Kigali Amendment to the Montreal Protocol.[xiv] Doing so will reduce the overall cost of transition for the industry and may represent a rare opportunity to drive both, that is, a reduction in indirect and direct emissions together for accelerated impact. The Kigali Cooling Efficiency Program (K-CEP) estimates that improving the energy efficiency of air conditioners and other cooling equipment can double the climate benefits of the Kigali Amendment while delivering economic, health, and development benefits.[42, xv]

TRANSFORMATIVE APPROACH TO ADDRESSING THE SPACE COOLING CHALLENGE

The need of the hour is a transformative approach to cooling—one that achieves human thermal comfort within buildings through energy-efficient practices and technologies and more climate-friendly refrigerant approaches that collectively result in lower energy-system impact and climate impact than business-as-usual cooling. Defined as **sustainable space cooling,** this approach includes a combination of energy-efficient building design and construction, efficient cooling technologies and practices, more climate-friendly refrigerants, and optimal operating practices and behaviors.

Sustainable space cooling is especially important for the hot and humid parts of the world that are at the cusp of an exponential growth in cooling demand. Sustainable Energy for All (SEforAll), in their report *Chilling Prospects: Providing Sustainable Cooling for All*, identified nine countries (Bangladesh, Brazil, China, India, Indonesia, Mozambique, Nigeria, Pakistan, and Sudan) that are at the greatest risk from lack of access to cooling. All of these are populous countries with hot and humid climates (figure 2.7), underscoring that addressing space cooling has strong underlying social drivers.[43] Particularly, shifting efforts toward more sustainable space cooling—that is, broadening access to cooling while limiting its environmental impacts—will require a more holistic approach.

While the tactics to achieve cooling can vary widely in nature, the following constitute the underlying considerations for addressing space cooling needs most efficiently:

- An integrative approach that reduces cooling loads through building efficiency measures that improve thermal performance, serves the cooling loads as efficiently as possible through appropriate choice of cooling solution and utilization of the most efficient cooling equipment available, and optimizes the performance of cooling through its operation (this approach, foundational to sustainable space cooling, is discussed in greater detail in section 3);
- A robust combination of push strategies (policies that drive positive changes), pull strategies (market demand for efficient cooling options to enable mainstreaming), and awareness raising through communications and demonstrations; and
- Alignment among multiple stakeholders across the cooling value chain such that efforts are prioritized toward a common goal.

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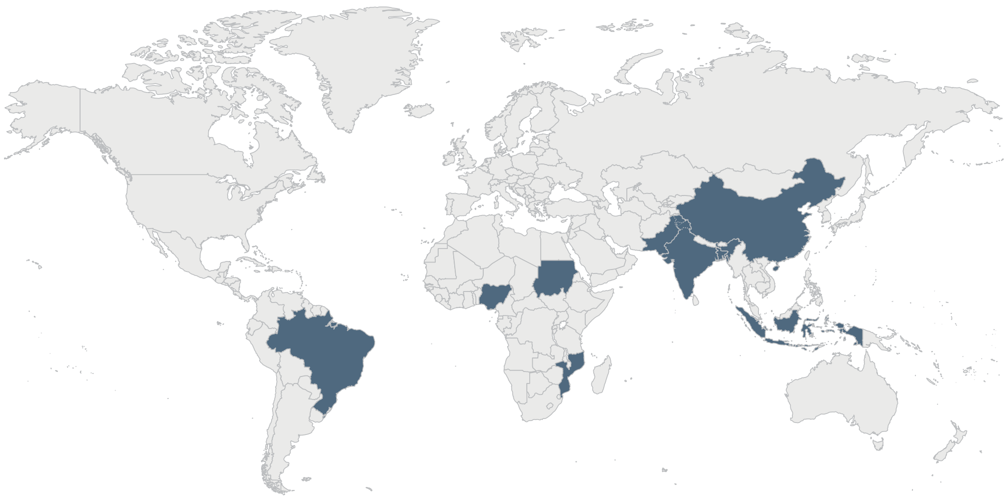
xiv The Kigali Amendment to the Montreal Protocol is an international agreement that will help reduce the production and consumption of hydrofluorocarbons (HFCs)—potent greenhouse gases (GHGs)—and thus avoid global warming by up to 0.4°C this century.
xv K-CEP is a philanthropic program that collaborates with Montreal Protocol institutions and associated agencies, parties, and companies with the aim at supporting developing countries in integrating energy efficiency into the hydrofluorocarbon transition, thereby cutting pollution and costs, and improving access to clean, efficient cooling.

FIGURE 2.7: COUNTRIES AT GREATEST RISK FROM LACK OF ACCESS TO COOLING



Source: Sustainable Energy for All 2018; and United Nations n.d.[44]
Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city, or area.

UNDERSCORING A CASE FOR SCALING UP SUSTAINABLE SPACE COOLING

While the growing need for space cooling is in alignment with the development needs of countries, this growth must be addressed with responsibly designed strategies and solutions to avoid severe economic, power system, and environmental impacts. The good news is that **technologies and strategies exist that can deliver today's space cooling needs with less than half of the energy use** while delivering a lower life cycle cost to users and consumers.

However, the potential benefits of these technologies and strategies remain largely unexploited. A case in point is that the average efficiency of room air conditioners sold today is less than half that of the commercially available best-in-class (that is, the most energy-efficient units); in most developing countries, the potential benefits and cooling load reduction opportunities of thermally efficient buildings remain largely untapped.

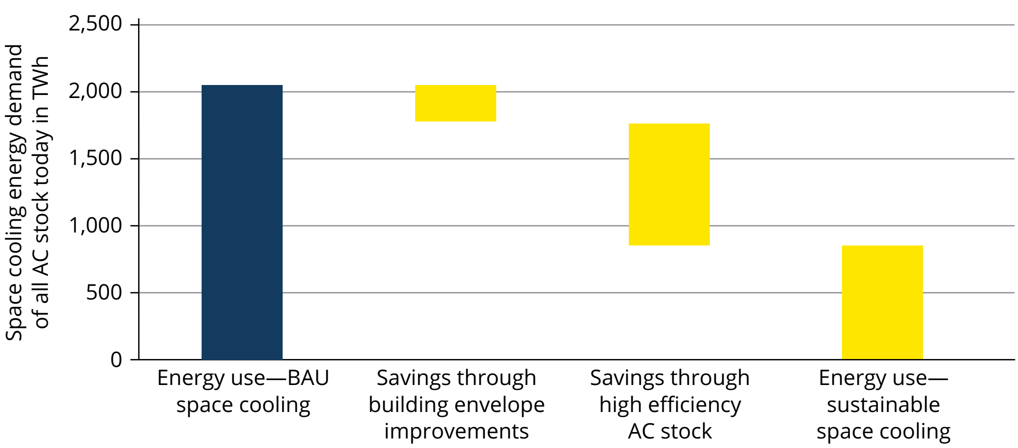
A few organizations have envisioned future scenarios with available and cost-effective aspects of sustainable space cooling scaled up and analyzed the potential impacts. As discussed in section 1, building envelope improvements alone can reduce space cooling energy demand by 15 percent by 2050 in developing countries.[45] IEA's Efficient Cooling Scenario envisions that stronger policy action on minimum energy performance standards (MEPS) of cooling equipment can reduce the energy needs for space cooling by more than 45 percent.[46] The primary strategy of the Efficient Cooling Scenario is transitioning to ACs with 50 percent higher efficiency in 2030 and 80 percent higher efficiency in 2050.

The Opportunity Cost of Today's Space Cooling Practices

In producing this primer, a high-level analysis was undertaken to get a view into the opportunity cost to society of not adopting best-in-class existing technologies and strategies that have demonstrated a lower life cycle cost for users and consumers. Using the Efficient Cooling Scenario as the basis, this analysis takes into account the impact of switching today's space cooling equipment stock (using a baseline of 1.6 billion residential and commercial air conditioning units) from a business-as-usual technology efficiency level to a higher efficiency level that is already commercially available and the impact of improvement in building envelopes, and highlights the following (figure 2.8):[xvi]

- **Impact on energy use.** The energy required to provide space cooling could have been **reduced by about 58 percent (or 1,177 terawatt-hours)** by switching to commercially available high-efficiency technology in conjunction with building envelope improvements achievable today that have demonstrated a lower life cycle cost.
- **Impact on power systems. Nearly 500 GW of power generation capacity** to meet space cooling needs could have been avoided, translating to around US$345 billion in capital investment (not including the associated transmission and distribution costs) that could have been directed to address other priorities.
- **Impact on GHG emissions.** The current total indirect emissions (1,135 million tons CO_2) from space cooling operation would have been **less than half (540 million tons CO_2).** In addition, the avoided space cooling capacity would have resulted in lower use of refrigerants and associated direct emissions.
- **Impact on consumers.** Meeting cooling needs with efficient equipment could have cost consumers dramatically less over the equipment's lifetime. For instance, in the Indian market, an average entry-level room air conditioner can **cost the consumer almost two times more** over its lifetime

FIGURE 2.8: OPPORTUNITY COST TO SOCIETY OF NOT ADOPTING BEST-IN-CLASS EXISTING TECHNOLOGIES AND STRATEGIES THAT HAVE DEMONSTRATED A LOWER LIFE CYCLE COST FOR CONSUMERS



Source: RMI analysis based on RMI, *Solving the Global Cooling Challenge,* 2019, and IEA, *Future of Cooling,* 2018.
BAU = Business-as-usual.

xvi Using IEA's Efficient Cooling Scenario as the basis—that is, the projected savings in year 2050 through efficiency improvements in 5.6 billion air conditioners, and through building envelope improvements—the high-level analysis applies a linear logic to arrive at savings for the current air conditioner stock. The key assumptions are that about half of the 5.6 billion ACs would be installed in new buildings and the remaining half in the relatively inefficient existing buildings, and that a larger portion (roughly two-thirds) of the savings from envelope improvements would come from new buildings and the remaining one-third from improvements in existing buildings. To determine the investment required, the average cost of construction of natural gas power generators in the United States (US$696 per kilowatt) is used as a proxy for the most common power generator.

(as highlighted in figure 2.5), compared with commercially available high-efficiency RAC units (even more where electricity is not or less subsidized).

It is important to note the above analysis does not take into account the positive impacts of systemwide solutions (such as district cooling), innovative early stage technologies yet to be fully commercialized, or any emerging radical technology solutions.[xvii]

The opportunity costs of today's cooling practices are too high to ignore, and the impact will only be further compounded through the projected growth in space cooling demand if countries continue on the business-as-usual pathway. While it is not possible to recover the opportunity cost of the past, there is an opportunity to avoid increasing the opportunity cost in the future by shifting to sustainable space cooling practices.

Reducing the requirement for mechanical cooling through efficient buildings and scaling access to sustainable cooling equipment, along with optimizing cooling loads, will collectively achieve significant benefits supporting several of the United Nations Sustainable Development Goals (SDGs)—for example, good health and well-being, decent work and economic growth, sustainable cities and communities, reduced inequalities, affordable and clean energy, responsible consumption and production, and climate action. Sensitization of end-users toward the full cost of cooling—that is, the broader social and environmental implications—and reinforcement of sustainable cooling practices has to be foundational to future efforts to address and expand cooling access.

KEY TAKEAWAYS

- Growth in space cooling demand is inevitable and significant, and is driven predominantly by developing countries in tropical climates, which may see up to five times more growth between now and 2050.
- If not proactively and responsibly managed, this growth can lead to severe social, economic, and environmental impacts in the form of high operating costs for consumers, significant investments in power systems, increased GHG emissions and global warming, and these impacts' cascading effect on the well-being of people.
- Available refrigerants have diverse characteristics—with respect to efficiency, environmental impacts, safety, and cost—and hence, selection of the most appropriate refrigerant needs to be undertaken with reference to these characteristics and the different cooling equipment categories and applications.
- Technologies and strategies exist that can deliver today's space cooling needs with less than half the energy use, while delivering a lower life cycle cost to users and consumers—however, these remain largely unexploited. While it is not possible to recover this opportunity cost of the past, there is an opportunity to avoid increasing the opportunity cost in the future, by acting now to make the shift to sustainable space cooling practices.
- To neutralize the impact of the projected growth in cooling and enable access to cooling for all without contributing further to warming the planet, it is important to accelerate a shift toward sustainable space cooling, collectively addressing building energy efficiency, indirect and direct emissions of cooling equipment, and optimized operation of cooling equipment.

xvii For example, in 2018, Rocky Mountain Institute launched a global innovation challenge—the Global Cooling Prize—focused on reducing both direct and indirect emissions related to space cooling. Through this challenge, eight viable technology solutions have been identified that can deliver residential cooling with five times less climate impact than the most commonly sold units—through use of a combination of significantly enhanced energy efficiency and no- or low-GWP refrigerants. Once commercialized, the winning technology solution could be a game-changer, avoiding up to 0.5°C of global warming by 2100 by residential air-conditioning alone despite a 3.7 times increase in their installed stock.

Rooftop Air System, Skyscraper, Hong Kong (XXXL).
Credit: 4FR/istock.

3. AN INTEGRATED APPROACH TO ADDRESS SPACE COOLING SUSTAINABLY

An integrated approach—one that reduces cooling loads through building efficiency measures that improve thermal performance, serves the cooling load as efficiently as possible through appropriate choice of cooling solution and utilization of the most efficient cooling equipment available, and optimizes the performance of cooling through its operation—is foundational to sustainable space cooling and should be pursued to the fullest extent possible. This section discusses the three strategies of the integrated approach to optimally address space cooling.

AN INTEGRATED APPROACH TO OPTIMALLY ADDRESS SPACE COOLING NEEDS

A sequential and integrated approach to designing cooling solutions (figure 3.1) is key to addressing space cooling needs in an optimal and resource-efficient manner. This approach calls for the following actions:

1. **First, reduce the cooling loads through energy efficient building design and passive cooling measures.** Climate-responsive and thermally efficient building design in both new and existing buildings, driven by effective policies and practices such as building energy codes, is an important means to inherently reduce the cooling requirements of the building sector. Existing buildings can cost-effectively enhance thermal performance and lower the energy demand for cooling through carefully timed passive cooling measures and retrofits (to coincide with building renovation and refurbishment cycles), and new buildings can avoid cooling loads through efficient building design and construction, and passive cooling practices.

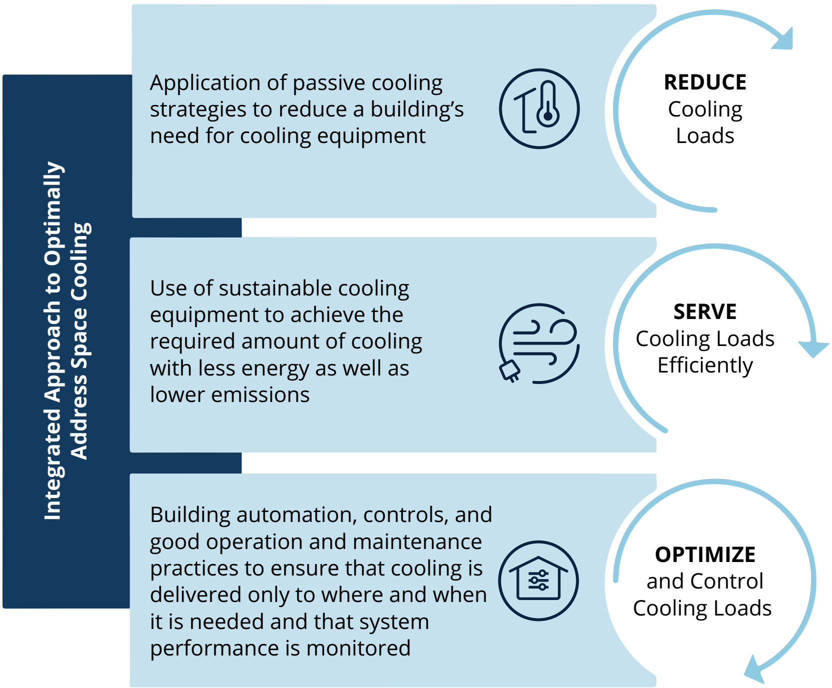
2. **Then, serve the cooling loads efficiently, with appropriate and efficient cooling equipment.** Sustainable cooling equipment—that is both an appropriate fit for the application and highly energy efficient—should be leveraged to deliver the required amount of cooling with less energy and lower overall emissions.

3. **Finally, optimize the operation of cooling equipment.** Institute building controls and sensors and user adaptations to ensure that cooling is delivered only to where and when it is needed—essentially enabling part-time and part-space cooling behaviors.[xviii] Also, ensure appropriate maintenance of cooling systems to sustain design performance. These are effective means to eliminate wasteful cooling and optimize space cooling demand.

Such an approach to space cooling will maximize the potential benefits through integrative effects and should be pursued to the fullest extent possible. Accompanying measures that further the transition to power that comes from renewable sources will be important contributors to further lowering the greenhouse gas (GHG) impact of cooling solutions.

xviii The concepts of part-time and part-space cooling behavior are introduced in the International Energy Agency's 2019 report *The Future of Cooling in China*.

FIGURE 3.1: INTEGRATED APPROACH TO OPTIMALLY ADDRESS SPACE COOLING



Source: RMI Infographic based on RMI, *Integrative Design.*[47]

REDUCE COOLING LOADS

Energy-efficient or passive building designs can reduce the overall heat gain and enhance the thermal comfort in a building, thereby significantly decreasing the cooling energy needed for active cooling. Particularly in hot and humid climate zones, active cooling can represent a significant portion of building energy use; vapor compression systems, in such climates, consume over 50 percent of total energy used in buildings, increasing to 80 percent at peak times.[48]

While passive cooling strategies generally are easiest and most cost-effective to incorporate during new construction—thereby avoiding a significant portion of the future cooling demand—they can also apply to, and benefit, existing buildings. Some passive cooling strategies particularly suited to existing buildings include installing high-performance windows, adding insulation, adding shading devices, and installing cool roofs.[xix]

Passive cooling strategies have been proven to achieve an over 25 percent reduction in cooling loads, even in hot climates. For example, Aranya Bhawan, a public office building located in the hot and dry climate of Jaipur, India, achieved a 28 percent reduction in cooling system size (tons of refrigeration [TR]) using a combination of efficiency measures including roof and wall insulation, a reduced glazing area, and double-glazed windows with high-performance glass.[49] Dubai Silicon Oasis, a housing project,

xix The Energy Sector Management Assistance Program primer on "cool cities" (published in July 2020) includes a more detailed discussion on cool roofs.

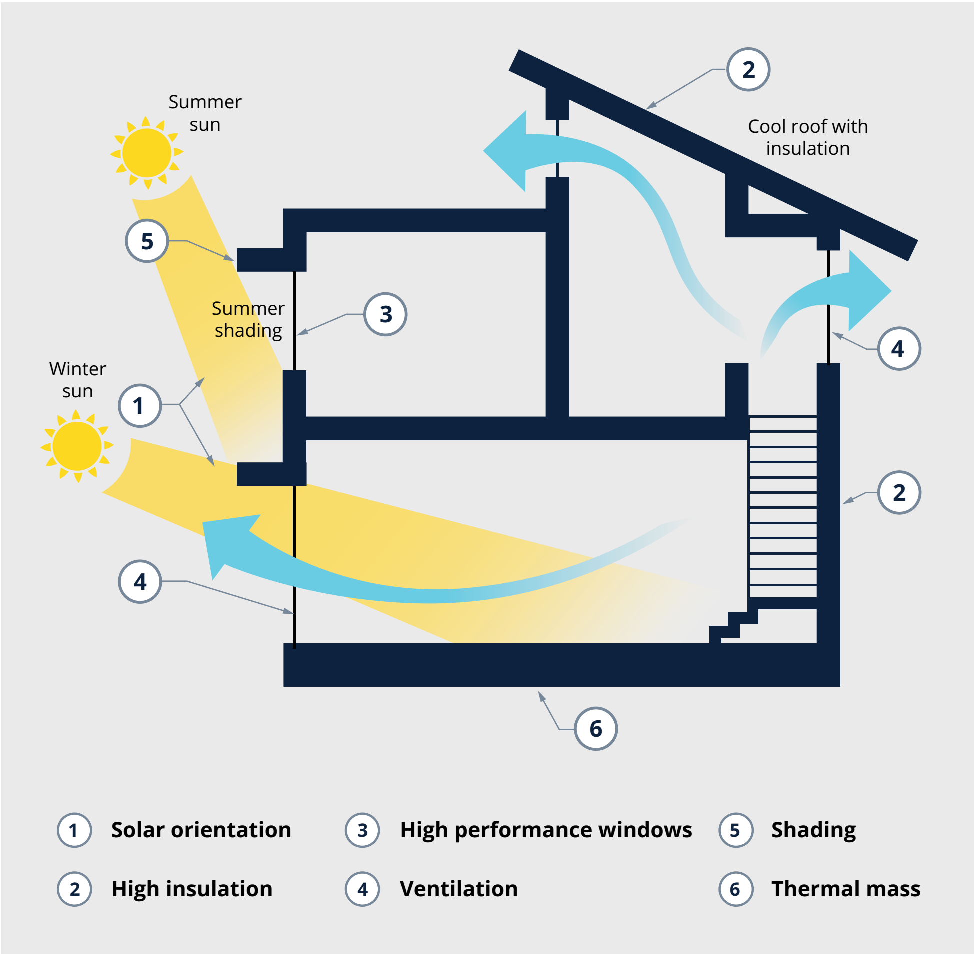
incorporated passive design strategies and achieved a total annual energy reduction of 23 percent—a significant portion of it due to reduced space cooling needs.[50]

Some of the key design strategies to reduce cooling loads in buildings include the following:

- **Building orientation.** Appropriate orientation can minimize direct heat gain and increase natural ventilation.
- **Envelope.** A combination of appropriate materials and design features in the building envelope minimizes heat gain due to thermal transmittance. Key features include the following:
  - Insulation—Insulation acts as a barrier to heat flow, reducing heat loss in winter to keep the interior of a building warm and reducing heat gain in summer to keep the interior of a building cool. Inadequate insulation and air leakage are key reasons for heat gain or loss in buildings. Sealing up air leaks also helps manage moisture intrusion in buildings in hot and humid climates.
  - Cool/green roofs—Studies show that the roof is one of the main solar heat gain points in a building, so using a high level of insulation and surface treatment can reduce heat conduction to the interior of the building. Common examples include highly reflective surfaces that reflect more sunlight and absorb less heat than a standard roof and use of vegetation that can provide a high level of insulation.
  - Windows—Windows are typically a significant source of heat gain in a building and therefore should be carefully positioned, keeping the local climate and latitude in mind. For example, in the southern Indian states, where the climate is tropical, north-facing windows help to keep the interiors cool naturally. In comparison, in the northern part of the United States, windows should be on the south to maximize the solar gains from the winter sun while protecting the building (using shading devices) from intense solar gain in summer. The use of appropriate materials in windows is also critically important for controlling heat transfer. Common strategies include using double- or triple-paned windows and using high-performance glass that controls thermal conductance and solar heat gain.
  - Shading—Shading is a simple method to block the sun before it can enter the building and is akin to putting a wide-brimmed hat on the building. By minimizing the incident solar radiation and thus keeping the building cool, shading can have a meaningful impact on building energy performance. This is commonly achieved through trees and foliage, architectural features such as overhangs, and shading devices such as louvers and canopies.
- **Ventilation.** Air movement cools people by increasing evaporation, and ventilation cools the building naturally at lower ambient temperatures by removing heat. When outdoor temperature, humidity, and air quality allow, free cooling through open windows (also referred to as "natural ventilation") may be all that is required to improve temperature and humidity in closed indoor spaces.
- **Thermal mass.** Thermal mass is a property of the mass of a building that enables it to store thermal energy, providing inertia against temperature fluctuations. Materials used for thermal mass are typically heavy and dense, including concrete or filled concrete block, stone, or masonry usually used in floors or walls. Used properly—the right amount in the right place, with proper external insulation—thermal mass stabilizes interior temperatures by leveraging daily outdoor temperature swings to flatten interior temperature peaks and troughs, thus saving energy that would otherwise be used for active cooling or heating. In hot climates, thermal mass in a building should be shaded from direct sunlight to the extent possible and be exposed to cooling breezes to provide some cooling on hot days and nights.

Figure 3.2 summarizes the key principles of passive cooling. These should be utilized and optimized based on the climate condition for a region.

FIGURE 3.2: PASSIVE COOLING PRINCIPLES



Source: Authors, composed by Rocky Mountain Institute.

Passive Design Strategies: Constraints and Considerations

Passive design strategies can be most holistically and cost-effectively integrated into a building during its design and construction (compared to in an existing building), when the incremental cost is at its lowest. Therefore, developing countries are a particularly rich target for accelerating the adoption of passive cooling strategies, considering that a significant portion of the building stock has yet to be built. Considering the typical 30-year first life of a building, the decisions made during design and construction can lock in a long period with either a thermally efficient building with a relatively low need for active cooling or an inefficient building that will need significant active cooling, resulting in high operation costs. Further, the next opportunity to remedy these issues could be in 30 years' time, when major refurbishment and renovation occur. Therefore, it is critical to view the incremental costs (perceived or actual) of high-efficiency construction within the broader perspective of a building's operational costs over its life.

However, often, the entity constructing a building is typically not the same as the entity operating the building post-construction and does not stand to gain from the potential savings in reduced future operational costs. Therein lies the challenge of split incentives.

Also, the perception that highly efficient buildings have a greater cost of construction seems more magnified than the reality. A literature review of data on the incremental costs to design and build energy-efficient buildings in the United States suggests that the cost premiums ranged from 1 percent to 7 percent. In most cases, the cost premium was less than 4 percent.[51] A similar analysis in Singapore, a particularly hot and humid country, points out that construction of certified energy-efficient buildings costs up to 5 percent more than regular buildings, but the additional costs are offset by savings from reduced energy and water consumption within three to six years.[52] While several factors impact the overall cost of construction—there are expensive green buildings, and there are expensive conventional buildings—multiple studies suggest that the public dramatically overestimates the marginal cost of a green building.[53, xx]

Given the challenge of split incentives and the perception that energy-efficient construction costs more, building developers are generally not motivated to incorporate energy-efficient building practices unless buyers demand it or strict enforcement mechanisms are in place. In this regard, building energy codes play an important role in driving the adoption of efficient building practices by promoting appropriate energy-efficient building designs and materials.[xxi]

Code adoption is commonplace in developed economies (figure 3.3) such as the European Union (EU) and the United States, and is already manifesting cumulative positive outcomes. For instance, the model energy codes in the United States are projected to result in cumulative benefits, from 2010 to 2040, of

- $126 billion in energy cost savings,
- 841 million metric tons (MMT) of avoided carbon dioxide (CO_2) emissions, and
- 3,757 terawatt-hours (TWh) of primary energy (for perspective, the primary energy consumption of the entire US commercial and residential sectors in 2015 was estimated at 11,137 TWh).[54, xxii]

However, in most developing countries, the adoption and effective implementation of building energy codes to deliver the benefits of energy-efficient buildings remain low. Of the 65 low- or lower-middle-income countries in the Regulatory Indicators for Sustainable Energy (RISE) data set,[55] only 16 have energy-efficiency codes for new residential buildings, and 19 have such codes for new commercial buildings.[xxiii] While the theoretical potential of energy building codes is promising (table 3.1), in reality,

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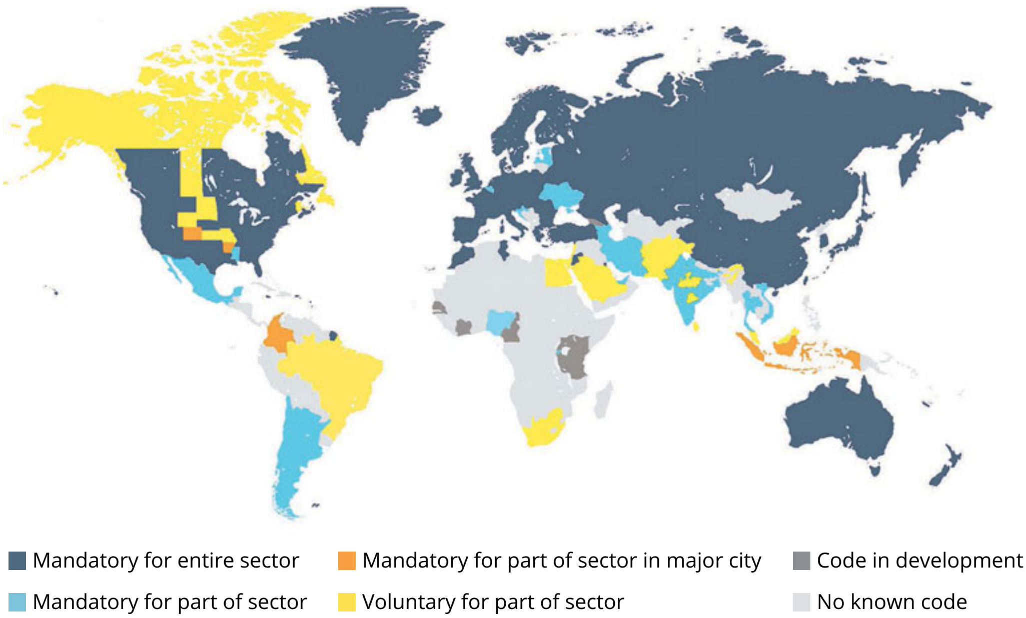
xx A 2007 public opinion survey conducted by the World Business Council for Sustainable Development found that respondents believed, on average, that green features added 17 percent to the cost of a building, whereas a study of 146 green buildings found an actual average marginal cost of less than 2 percent.

xxi For more information on building codes and good practices of implementation, with examples, please see P7, *Accelerate the adoption of passive cooling strategies through national building energy codes with a robust enforcement mechanism* in the Compendium.

xxii The model energy codes are the International Energy Conservation Code for residential buildings and the American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard 90.1 for commercial buildings (42 U.S.C. § 6833).

xxiii For more information on building code compliance in low- and lower-middle-income countries, see intervention P7, *Accelerate the adoption of passive cooling strategies through national building energy codes with a robust enforcement mechanism* in the Compendium.

FIGURE 3.3: STATUS OF BUILDING ENERGY CODES GLOBALLY



Source: Adapted from IEA.[56]

Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city, or area.

this potential is largely untapped due to many implementation and enforcement barriers that typically fall within the following categories:[xxiv]

- **Institutional challenges.** These could include lack of coordination among local agencies and lack of institutional capacities.
- **Regulatory challenges.** Even if national building codes are established, monitoring and enforcement frameworks are challenging to establish and require significant resources.
- **Market mechanisms.** Countries may face a lack of tools and enabling mechanisms for market creation and sustenance.
- **Stakeholder challenges.** Such challenges involve lack of awareness or motivation among end-users and building sector professionals, and split incentives.

Some innovative examples to help address barriers to building code adoption or energy-efficient construction in general include the following:

- In the US city of Chicago, Illinois, energy-efficient buildings get fast-track approval by the city, thus creating an immediate reward and motivation for the developer.

xxiv For an overview of the World Bank's work with building codes and the lessons learned as of 2010, please see Liu, Feng, Anke S. Meyer, and John F. Hogan, 2010, *Mainstreaming Building Energy Efficiency Codes in Developing Countries*, The International Bank for Reconstruction and Development/The World Bank, Washington, DC, http://documents.worldbank.org/curated/en/284341468324865236/pdf/578770PUB0Main101public10BOX353783B.pdf.

TABLE 3.1: THEORETICAL POTENTIAL OF PASSIVE COOLING THROUGH BUILDING CODE ADOPTION AND IMPLEMENTATION

China	Changing the building envelope can reduce cooling demand in China by more than 10% by 2030. A study in China showed that natural ventilation could reduce the hours of air-conditioning required by up to 40% without decreasing indoor comfort.[a]
Dubai	Passive cooling strategies could reduce residential cooling loads in Dubai by up to 23.6%.[b]
India	A reduction potential of around 20% in cooling load could be achieved by 2037–38 through climate-appropriate building envelopes driven by a higher adoption of building energy codes in upcoming commercial buildings.[c]
Nigeria	A study in Abuja, Nigeria, showed that passive cooling strategies can reduce indoor temperatures by more than 5°C[d]—and thus limit current and future use of active cooling to provide thermal comfort.

Source: Authors, composed by Rocky Mountain Institute.

a. International Energy Agency, 2018, *The Future of Cooling,* Paris, https://www.iea.org/reports/the-future-of-cooling.

b. Taleb, Hanan, 2014, "Using Passive Cooling Strategies to Improve Thermal Performance and Reduce Energy Consumption of Residential Buildings in U.A.E. Buildings," *Frontiers of Architectural Research* 3 (2): 154–65, https://doi.org/10.1016/j.foar.2014.01.002.

c. Ministry of Environment, Forest and Climate Change, 2019, *India Cooling Action Plan,* Government of India, New Delhi, http://ozonecell.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf.

d. Adaji, Michael Utenwojo, 2017, *Thermal Comfort in a Hot-Humid Climate through Passive Cooling in Low-Income Residential Buildings in Abuja, Nigeria*, University of Kent, UK, https://kar.kent.ac.uk/67935/.

- To fast-track the implementation of India's Energy Conservation Building Code in the commercial sector, India's Bureau of Energy Efficiency (BEE) is addressing some of the institutional challenges through regional workshops that provide training and help ensure alignment among state and local agencies.

- A noteworthy example for promoting energy-efficient construction is the International Finance Corporation (IFC) green building certification system for emerging markets, Excellence in Design for Greater Efficiencies (EDGE), and its web-based tool. EDGE is designed to steer construction in rapidly urbanizing economies onto a more energy-efficient and low-carbon path. A free design tool, the EDGE App enables building designers and developers to determine the optimum combination of design strategies for the best return on investment. Directly targeting the perception of higher cost as a barrier to energy-efficient construction, IFC partnered with Georgetown University to conduct research to analyze the most cost-effective green interventions to achieve the EDGE standard, across several countries and building types. The analysis shows that, for instance, in residential construction in East Asian, South Asian, and African countries, the payback period of energy-efficient building construction is typically under one year, and in the case of a few countries, it is up to two years.[57]

In summary, while the benefits of passive cooling and energy-efficient buildings are well documented, there is much progress to be made in the implementation of these strategies. The potential benefits—enhanced thermal comfort in buildings, reduced cooling loads, and resulting energy system and climate benefits—remain largely untapped, particularly within developing countries, due to a lack of enabling policies and implementation challenges. A supporting policy framework, strong institutional capacities, and enhanced awareness among consumers (as well as trained building industry professionals) will be key to realizing this potential. Leveraging the untapped potential of energy-efficient buildings—and locking in energy savings for buildings' lifetimes—can be a significant long-term and cost-effective contributor toward enhancing thermal performance of buildings and reducing space cooling energy demand.

SERVE COOLING LOADS EFFICIENTLY

Conventional Space Cooling Technologies

Multiple cooling equipment options are prevalent to actively cool buildings, such as vapor compression systems, fans, and air coolers. The vapor compression systems constitute a broad category, including several technologies of varying complexity, such as room air conditioners (RACs), central air conditioner (AC) systems, variable refrigerant flow (VRF) systems, and chillers.[xxv] A vapor compression cycle operates on four primary components: an evaporator, a compressor, a condenser, and an expansion valve. Refrigerants, with the ability to undergo phase change by absorbing and releasing the latent heat at relatively lower temperatures, operate in a closed-loop cycle and transfer heat from one space to another, thus producing a cooling effect. The heat is absorbed by the refrigerant from the space to be cooled in the evaporator section and is rejected to the ambient atmosphere in the condenser section. A variety of refrigerant options—both synthetic and natural—is available for vapor compression systems, and they have their own respective characteristics, as discussed in section 2 (table 2.1). Currently, refrigerant blends are also being explored to identify additional refrigerant options that are safe (low toxicity and flammability) and efficient, and have zero ozone depleting potential (ODP) and low global warming potential (GWP).[xxvi]

Some of the vapor compression systems—such as RACs, central ACs, and VRF systems—are also known as direct expansion (DX) systems, because the air to be supplied for cooling is directly cooled at the evaporator section (figure 3.4). In chillers, however, chilled water is produced at the evaporator section and circulated through a piping network to distributed heat exchangers (air handling units or fan coil units), where the room air is cooled by the chilled water. The condenser section of a chilled-water system can be either air cooled, as is typical with DX systems, or water cooled, which uses a cooling tower as an effective heat sink to circulate cool water to the condenser section to more efficiently reject the heat to the outdoor environment. Figure 3.5 shows a chiller system with a water-cooled condenser.

Each type of cooling equipment has varying degrees of performance efficiency, typically measured in terms of cooling output per unit of energy consumed. While several factors can influence what cooling equipment is chosen, the appropriate choice depends primarily on the building scale and function (type of usage) to be served (figure 3.6). Other influencing factors are discussed later in the section (figure 3.15).

In figure 3.6, the building scale is categorized into four types: room level, small buildings (such as residential and small commercial), large buildings (such as those for commercial, industrial, and public uses), and districts (such as campus or city-scale buildings). The horizontal gradient bars denote

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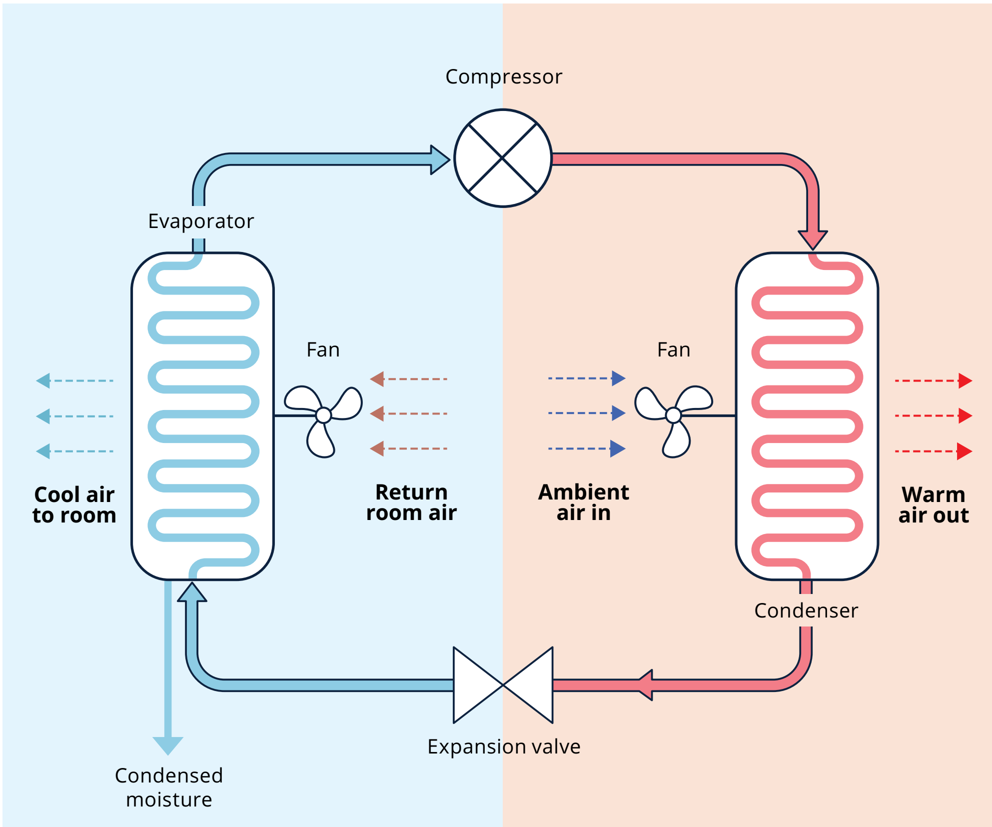
xxv The term "heat pump" applies to any vapor compression equipment in which the vapor compression cycle is also able to operate in reverse cycle and provide heating as well as cooling. Heat pumps are relevant in moderate to hot climates that require some heating in addition to cooling. Because it is a technology adaptation that could be incorporated across a range of vapor compression equipment, the heat pump is not included as a separate equipment type in this primer.

xxvi While a detailed discussion of refrigerant blends is beyond the scope of this publication, multiple sources exist for more information. A comprehensive resource is Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019, *Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee 2018 Assessment Report,* United Nations Environment Program, Nairobi, Kenya, https://ozone.unep.org/sites/default/files/2019-04/RTOC-assessment-report-2018_0.pdf.

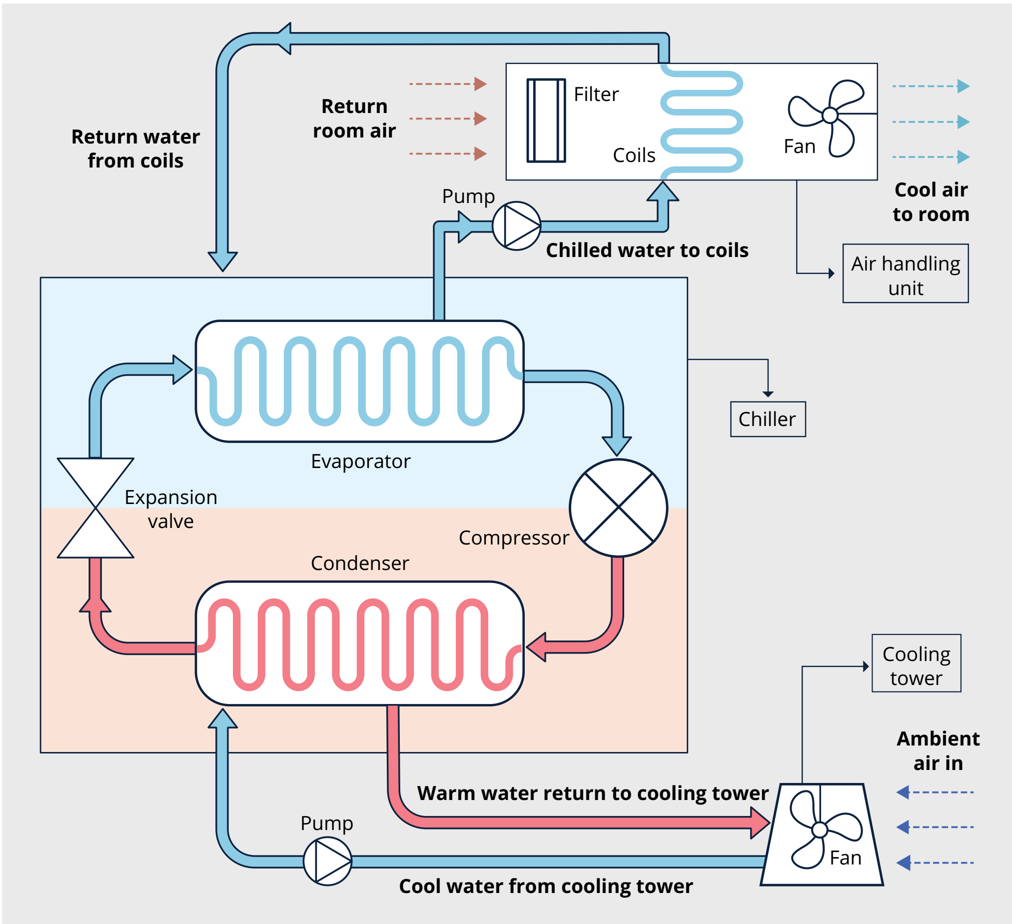
FIGURE 3.4: OPERATING PRINCIPLE OF TYPICAL DIRECT EXPANSION SYSTEM BASED ON VAPOR COMPRESSION CYCLE



Source: Authors, composed by Rocky Mountain Institute.

different types of cooling equipment that serve these building scales: the darker shade denotes the cooling equipment that is typically most applicable or relevant for that building scale. As shown in the figure, cooling equipment such as fans, air coolers, and room air conditioners are operated across all levels; however, these are the most widely used at room, residential, and small commercial scales. As the building scale moves toward offices and large commercial and industrial scales, cooling equipment such as multi-split AC, variable refrigerant flow ACs, and chillers become the common choice, primarily due to better control, ease of maintenance, and the improved overall efficiency of centralized systems over individual AC or cooler units. As the building scale expands to include multiple buildings within a region or entire district, district cooling approaches can become a viable choice. Subject to sufficient scale and density, as shown in figure 3.6, district cooling can provide the lowest life cycle cost incorporating all the benefits typically associated with a service delivery model, and can even economically serve small buildings within the distribution network. (Further analysis of key considerations applicable to district cooling is available later in this section and in F4 in the Compendium.)

FIGURE 3.5: OPERATING PRINCIPLE OF TYPICAL CHILLED-WATER SYSTEM BASED ON VAPOR COMPRESSION CYCLE



Source: Authors, composed by Rocky Mountain Institute.

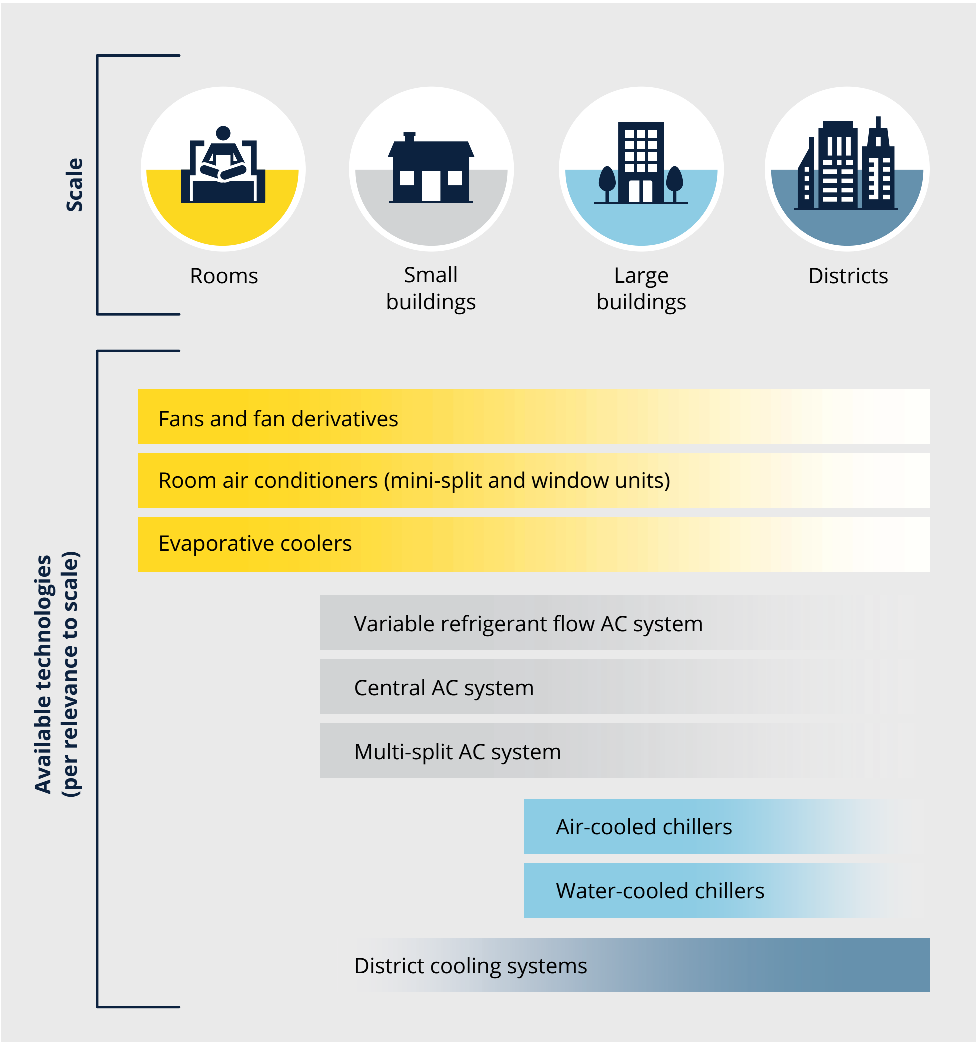
The following sections discuss each of the figure 3.6 cooling equipment types in detail.

Fans and Fan Derivatives

Fans are one of the most widely used non-refrigerant–based pieces of cooling equipment, especially in low- and middle-income countries. Fans provide comfort to people by aiding air movement over the human body, which causes an evaporative effect. They do not cool the space by removing heat. Fans can be ceiling or wall mounted, as well as portable (pedestal or table fan), and are an affordable choice to provide comfort to people in rooms or small office spaces. Fans consume relatively low power (typically 30 to 75 watts) compared to other cooling equipment, and energy efficient fans are thus a viable option for weak-grid or off-grid locations.[xxvii]

xxvii Suitability of fans for weak-grid and off-grid location is discussed in S5 in the Compendium.

FIGURE 3.6: COOLING EQUIPMENT TO SERVE COOLING LOADS



Source: Authors, composed by Rocky Mountain Institute.
Note: Shading represents each cooling equipment's applicability at the corresponding building scale.

Despite this, fans still contribute significantly to the total residential electricity consumption in many parts of the world, resulting in relatively high operating expenses.[58] A key reason for this is the wide range of energy efficiency of fans that are available in the market. For example, in the United States, the most efficient fans are over five times more efficient than the least efficient models when operating at their highest speed.[59]

In 2016, there were an estimated 2.3 billion residential electric fans in use globally, consuming more than 80 TWh of electricity, and this number is expected to grow to 3.9 billion by 2050.[60] The global growth projection of fans may, in fact, be underestimated—given that many countries in Asia and Africa are working on electrification programs for rural households. This is expected to generate a greater demand for fans as the first point of access to cooling. Fans, thus, are a unique segment of space cooling due to their link to energy access.

In many countries with hot and humid climates, it is common practice to use fans in conjunction with room air conditioners. For example, a residential cooling survey in India indicates that around 66 percent of the households prefer using a fan while operating their AC.[61] India projects that even with the rapidly growing penetration of air conditioners, fans and coolers will maintain substantial use in the next 20 years, consuming nearly as much energy as all commercial air-conditioning systems combined—amounting to roughly one-fourth of India's 2037–38 space cooling energy demand.[62, xxviii] Given the large and growing numbers of fans, and therefore their aggregate contribution to residential electricity consumption, it is important to advance the energy efficiency of fans.

Efforts toward this end are already underway. For example, in 2015, Pakistan launched an energy labeling program for fans.[xxix] In addition, the Bureau of Energy Efficiency in India, since August 2019, has revised the previously voluntary star labeling program to make it mandatory and increased the stringency of the minimum energy performance standards (MEPS).

Limitations: The use of fans is generally limited to places that experience hot and dry climatic conditions, because moving air with higher humidity does not aid the evaporation of sweat from the human body effectively and thus does not produce the desired cooling effect. As such, despite their affordability, fans are unable to provide thermal comfort when soaring summer temperatures (40°C and above) are accompanied by the high humidity experienced in many parts of the world today. Because of these limitations, there is an increased shift toward cooling technologies that can bring down the air temperature and humidity to desired levels of thermal comfort.

Advantages: Due to the low first costs, as well as the relatively low energy requirements to operate fans, these appliances can play an important role in enabling access to cooling for poor households and in underdeveloped areas with limited access to electricity (or in off-grid locations in combination with solar power). Further, depending on the climate and building design, they could continue to meet a meaningful share of growing residential space cooling needs.

Air Coolers (evaporative cooling)

Air coolers are a non-refrigerant–based cooling equipment that works on the principle of evaporative cooling. Water is allowed to fall over special material pads, and a fan blows air over the pads, causing the water to evaporate. The process of evaporation requires energy, which is extracted from the surrounding air being blown, thus cooling it in the process.

Air coolers can be broadly classified into two types: direct evaporative coolers and indirect evaporative coolers. Direct evaporative coolers are the most common type in which the air and water streams mix with each other. This raises the humidity of the air, which, in some cases, could be undesirable for comfort. Indirect evaporative coolers are an alternative option in which the room air exchanges heat with another stream of evaporatively cooled air via a heat exchanger, thus allowing the room air to be cooled without increasing its humidity.

xxviii Fans and air coolers represent roughly one-fourth of India's 2037–38 space cooling energy demand, commercial ACs represent another one-fourth, and the remaining share is room air conditioners.

xxix This is covered in more detail in intervention P2 (Leverage labeling as an effective, low-cost way to orient consumers toward sustainable purchasing decisions) in the Compendium.

Limitations: The operational effectiveness of air coolers depends on the humidity of ambient air and the availability of water for cooling. Air with low humidity facilitates the evaporation of water, and in the process, the temperature of air is reduced, making indoor environments thermally comfortable. In regions with high humidity, however, air coolers might not cool the air to the desired temperature, due to the limited capacity of air to hold additional water vapor.

That said, there are emerging technology solutions that have the potential to address this limitation, and thereby expand the application of evaporative cooling, through accompanying novel dehumidification materials and systems.[xxx]

Advantages: Whether using direct or indirect evaporation technology, air coolers are commonly used to cool rooms in households and small to medium-sized commercial buildings in regions with low humidity levels (generally below 50 percent). With first costs that can be up to 10 times lower than conventional vapor compression–based air-conditioning systems, air coolers offer an affordable—and significantly low-energy and low-emissions—alternative to air conditioners.[xxxi]

Room Air Conditioners

RACs are the smallest of all the vapor compression–based air-conditioning systems, with typically up to 15 kilowatts (kW) or 4.5 tons of refrigeration (TR) of cooling capacity, and are usually used to cool a single room in a home, an apartment, or a small office. With an RAC, the refrigerant absorbs heat at the evaporator of a vapor compression system and moves this heat (absorbed from air in the space) to the condenser, where the fan blows the ambient air over the condenser coils, which absorb the heat from the refrigerant. The refrigerant is compressed in the process, releasing the heat from the space to the ambient air.

The compressor is the heart of any vapor compression–based cooling system. The most common type is a fixed-speed compressor, which operates in a binary (on/off) mode based on the temperature set points. Because of this continuous cycling, fixed-speed compressors are relatively inefficient in their operation and have higher power consumption while meeting the aggregate cooling demand. Inverter compressor technology is an alternative to fixed speed. It allows the compressor to vary its speed depending on the cooling demand, that is, the actual room temperature with respect to the temperature set point. Thus, the RAC with inverter compressor technology can maintain the temperature of the space more precisely and consumes less electricity than a RAC with fixed-speed technology—typically consuming about 30 percent less power to deliver the same amount of aggregate cooling. In addition, because an inverter RAC does not cycle on and off continuously, it is generally quieter and has longer-lasting parts than a fixed-speed RAC unit.

RACs come in a packaged (window or through-the-wall) and split-type configuration (ductless mini-split). (See figure 3.7.) A packaged unit houses all components of the vapor compression cycle in one enclosure, whereas a split-type unit has a separate outdoor unit (housing the compressor and condenser) and an indoor unit (housing the evaporator and expansion valve) connected via refrigerant piping. The indoor unit of the split-type configuration can be wall, ceiling, or floor mounted.

Limitations: RACs are usually among the most power-consuming appliances in a home. Thus, inefficient RACs can significantly increase operating costs for a household. As noted earlier (see figure 2.5),

xxx In November 2019, two of the eight selected finalists of the Global Cooling Prize (a groundbreaking competition designed to incentivize development of a residential cooling solution that will have at least five times less climate impact than standard residential/room air conditioner units in the market today) proposed technology solutions that can meet cooling loads equivalent to those able to be met by a room air conditioner by using evaporative cooling in conjunction with novel dehumidification materials and systems. See https://globalcoolingprize.org/finalist-global-press-release/.

xxxi This estimate is based on 2018 average prices for household air coolers and room air conditioners in India.

FIGURE 3.7: ROOM AIR CONDITIONERS IN WINDOW AND SPLIT-TYPE CONFIGURATIONS

Source: Image courtesy of istockphoto.com.

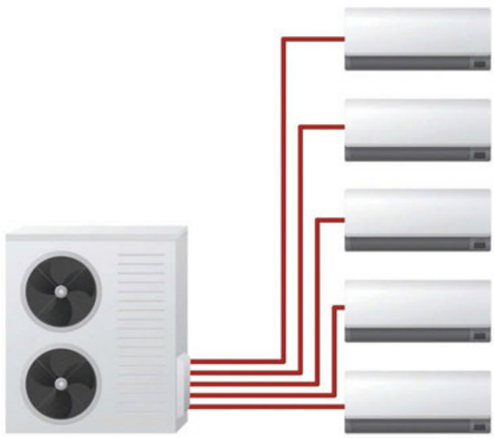
there exists a wide range of efficiency levels, and even the most stringent energy performance standards lag far behind the most efficient product available in the market. While inverter compressor technology and advanced design features can bring down the energy consumption of these appliances significantly, inverter compressor technology is associated with a first-cost premium that limits uptake. In addition, most RACs lack the capability to separately dehumidify the air, and thus overcooling is often carried out to bring the humidity of the air to desired levels, which results in even higher energy consumption.

Advantages: Due to their relative first-cost affordability, compactness, and ease of installation and operation, RACs are generally a preferred choice for middle-class consumers—and increasingly so for the lower middle class—in dense urban environments to achieve the desired level of cooling during the hot and humid summer season. Some RAC manufacturers also offer RACs with enhanced dehumidification features—for example, provision of a dry mode—thus allowing occupants to better control the humidity as well as the temperature in a space.

Multi-Split AC Systems

A multi-split vapor compression system (figure 3.8) is similar in operating principle to a ductless mini-split RAC system, except that the former has multiple indoor evaporator units (typically two to eight) connected to a common condenser unit through a refrigerant piping network. With this network, each room or confined space has a separate indoor unit—that is, an evaporator section of the vapor compression system—located at the point of cooling demand. This is in contrast with the central AC system (discussed in the next section), in which the evaporator is centrally located and the cool air is circulated via ducts to rooms.

FIGURE 3.8: MULTI-SPLIT AIR-CONDITIONING SYSTEM



Source: Image courtesy of istockphoto.com.

Multi-split AC systems can be operated either on fixed-speed or inverter technology. The major advantage of an inverter technology–based multi-split system is that it allows occupants to precisely control and maintain temperature set points for different rooms of a home or an office building, thus generating significant energy cost savings.

Limitations: While multi-split AC systems allow for aesthetically appropriate placement of the outdoor unit, limitations on refrigerant piping (total length and vertical height) and refrigerant leakage risk apply to these systems. Thus, they are typically limited to larger single-family homes, small to midsize commercial buildings, and small multifamily apartment buildings.

Advantages: Multi-split AC systems are particularly suitable where ductwork (required for central AC systems) is aesthetically unacceptable or is cost prohibitive.

Central AC Systems

These vapor compression systems are similar to RACs in operation. In addition to the typical components of an RAC system, a central AC system (figure 3.9) contains supply and return air ducts and a blower as part of the system. The warm air from the space is channeled via the return air duct to the evaporator section, where it is cooled and circulated back to multiple rooms by a blower fan via the supply duct.

FIGURE 3.9: CENTRAL AIR CONDITIONER SYSTEM

Source: Image courtesy of istockphoto.com.

However, in terms of performance efficiency, central AC systems differ from RACs. With RACs, the efficiency of the appliance is considered, whereas with central AC systems, the efficiency of the whole system (that is, vapor compression unit and the ducts) is factored in. Overall system-level efficiency includes the losses across the added components, such as fans necessary to circulate the conditioned air, air vents/ducts, and so on. Central AC systems also come in a packaged or split-type configuration and are typically used to cool a complete home or a small office building.

Central AC systems are often used to provide a constant temperature in all rooms of a home or office. However, the air distribution from a central AC system can be configured through individual room thermostats and dampers or variable air volume boxes in the ducts to supply cooling to only the rooms where it is required, thereby increasing overall system efficiency.

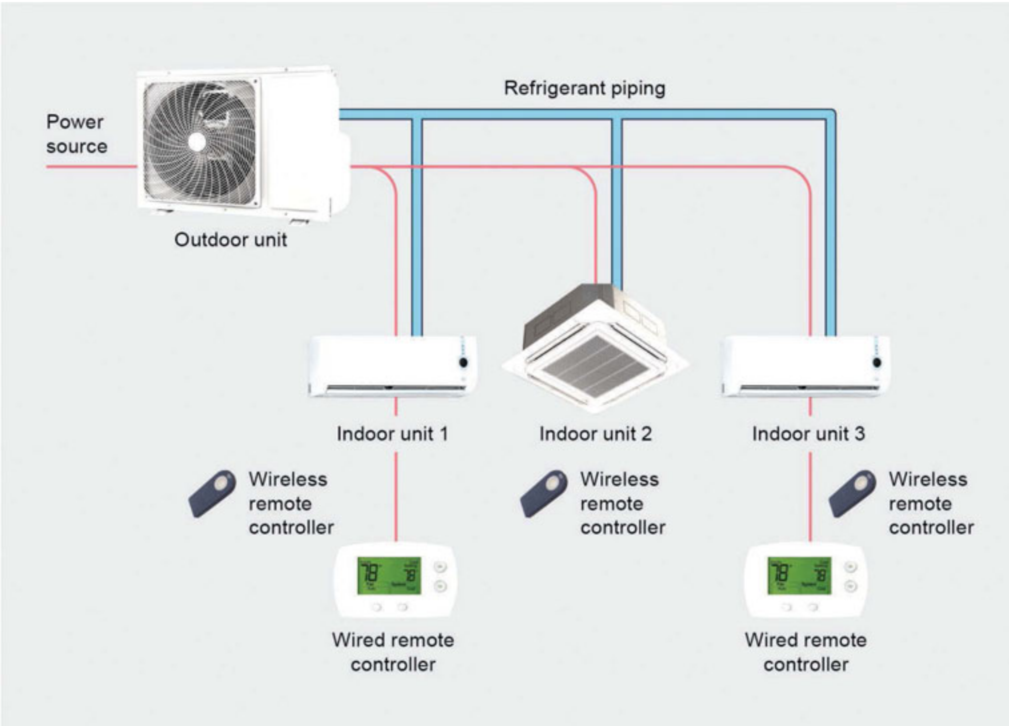
Limitations: Maintenance of ducts and fans is required to ensure minimum losses across the system and optimize performance. Further, similar to RACs, central AC systems also have limited dehumidification capacity. Thus, overcooling and reheating is typically required to achieve the desired humidity levels in the space.

Advantages: Central AC systems are best suited when a constant temperature is to be maintained throughout a large space with minimum involvement or interference from the user. Further, due to the provision of ducts, these systems are better suited for incorporating ventilation and mixing a portion of fresh outside air at low temperature (free cooling) with the conditioned air.

Variable Refrigerant Flow Systems

VRF systems are like inverter technology multi-split AC systems in operation. A single outdoor unit is connected to multiple individual indoor units via a refrigerant piping network. However, VRF systems are designed for a relatively larger scale and can connect up to 50 indoor units to a common condenser unit. Similar to a multi-split AC system, a VRF cooling system allows occupants to precisely control and maintain temperature set points for different rooms of an office or an apartment building, thus generating significant energy cost savings.

FIGURE 3.10: VARIABLE REFRIGERANT FLOW SYSTEMS



Source: Authors, composed by Rocky Mountain Institute. Images courtesy of iStock.[63]

Limitations: VRF systems are likely to have higher first costs in new construction scenarios, compared to central AC systems or air-cooled chilled-water systems at a similar implementation scale, because of their sophisticated control equipment and refrigerant piping requirement.[64] Also, as is the case with multi-split systems, limitations on refrigerant piping runs and leakage risk apply to VRF systems, and thus, they are typically limited to midsize commercial buildings and multifamily apartment buildings.

Advantages: Despite their higher first costs in new construction scenarios, VRF systems will typically have lower operational costs and bring significant energy savings over their lifetime, particularly when there is varying cooling demand across the building(s). One type of VRF system also allows simultaneous heating and cooling—that is, some rooms can be heated, and some can be cooled at the same time using one condenser unit. VRF is also well suited for installation in existing buildings that are not air-conditioned or don't have a provision for the installation of ducted systems due to compact size and relative ease of installation.

Chillers

Chillers are vapor compression–based systems that produce chilled water, typically at about 4°C to 6°C, which then cools the air by transferring its energy via a heat exchange process. The primary difference between chillers and direct expansion systems (such as RACs, central AC systems, and VRF systems) is that in direct expansion systems, the air to be supplied for cooling is directly cooled at the evaporator

FIGURE 3.11: AIR-COOLED CHILLER SYSTEM

Source: Image courtesy of iStock.[65]

section, whereas in chillers, chilled water is circulated through a piping network to distributed heat exchangers (air handling units or fan coil units) where the air is cooled by the chilled water. There are two types of chiller systems:

- **Air-cooled chillers.** The operation of air-cooled chillers (figure 3.11) differs from the typical RAC. Heat is absorbed from water and not the air in the space. The refrigerant then moves this heat to the condenser, where the fan blows the ambient air over the condenser coils, and this allows the refrigerant to reject heat to the air.

  The efficiency of an air-cooled chiller—as is the case with RACs, central AC systems, multi-splits, and VRF systems—is limited by the ambient air temperature, because heat rejection at the condenser will be less effective at high temperatures. Further, the operation of all air-cooled vapor compression systems exacerbates the urban heat island effect,[xxxii] which not only will reduce the efficiency of the system but also require longer operating hours. Air-cooled chillers are typically suitable for large commercial or industrial buildings (and are commonly placed on the rooftops), due to the relatively lower infrastructure requirements and first costs compared to water-cooled chillers, since they require no cooling tower or condenser water pump. Air-cooled chillers also have lower maintenance requirements. However, these chillers have a much shorter shelf life than water-cooled chillers, due to exposure to the elements associated with rooftop placement.

- **Water-cooled chillers.** These systems are similar to air-cooled chillers, except that at the condenser section, the refrigerant rejects its heat to a source of water that typically comes from a cooling tower—that is, the cooling tower acts as a heat sink. The cooling tower must be provided with a source of makeup water to maintain the quantity and appropriate temperature of cooling water. Due to the higher efficiency of a water-cooled condensing cycle (figure 3.12), especially at higher air temperatures, these systems (when well maintained) are significantly more efficient than air-cooled chillers. However, a water-cooled chiller system can have a significant water footprint and might not be suitable in areas with an acute water shortage.

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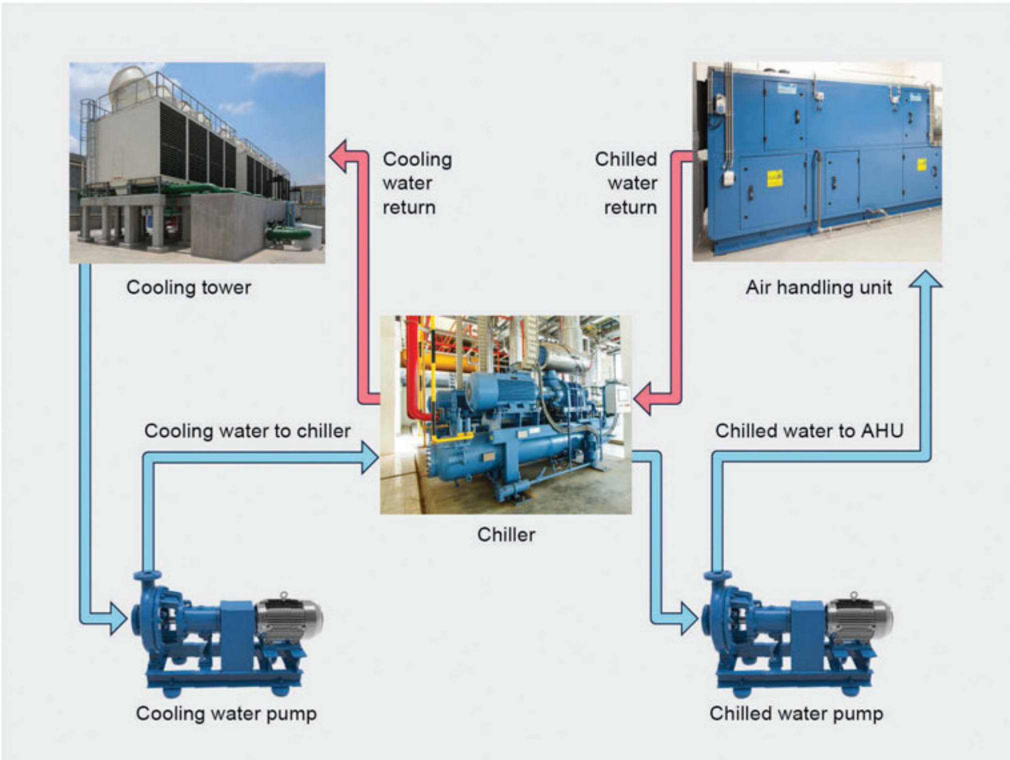
xxxii Please refer to the (2020) ESMAP publication *Primer for Cool Cities: Reducing Urban Heat* primer on “cool cities” for more details on urban heat island effects.

FIGURE 3.12: WATER-COOLED CHILLER SYSTEM



Source: Authors, composed by Rocky Mountain Institute. Images courtesy of iStock.[66]

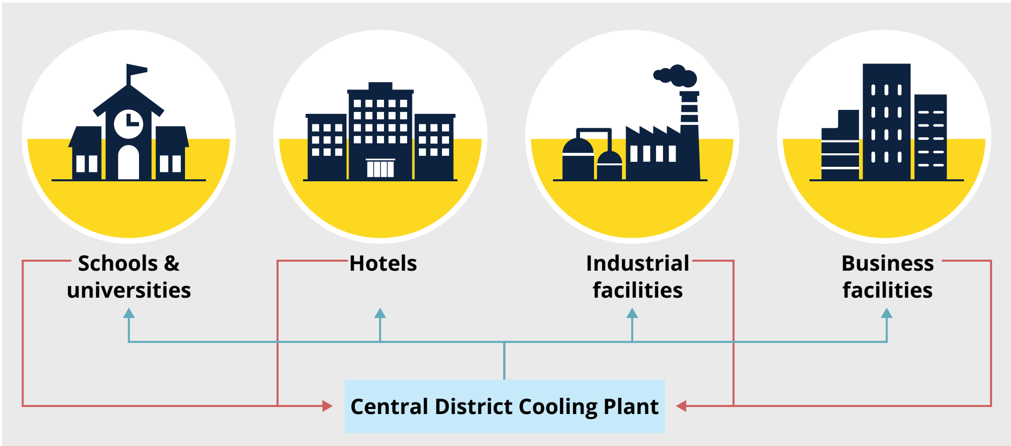
Limitations: Depending on the type of chiller system, various auxiliary systems—including chilled-water pumps, condenser water pumps, cooling tower fans, and air handling units—are required for full functionality. The overall efficiency and economic viability of a chilled-water system depends not only on the efficiency of the chiller but also on all of these auxiliaries. Therefore, for these cooling systems, overall cost and system efficiency need to be fully evaluated when comparing them with other cooling solutions. In addition, with the increased complexity of these chilled-water systems, it is important to ensure that they are adequately maintained and balanced for optimum performance of the system as a whole. Maintenance of the water side of the system is particularly important for preventing the buildup of bacteria in cooling towers, which can be harmful to people if it becomes airborne.

Advantages: In general, chillers are a preferred option when the building scale is a large commercial, industrial, or public facility where installation of a centrally located chilled-water system will improve operational efficiency. Thus, installing chillers makes economic sense for large buildings, compared to providing cooling via individual distributed units.

District Cooling Systems

In district cooling systems (figure 3.13), chilled water is produced at a central chiller plant (typically comprising multiple water-cooled chiller systems) and then distributed to nearby buildings. The air handler units in these buildings cool the supply air by exchanging heat with the provided chilled water, and

FIGURE 3.13: CENTRALIZED DISTRICT COOLING PLANT



Source: Authors, composed by Rocky Mountain Institute.

they deliver the air-conditioning demanded by the building. Depending on the scale and density of the buildings to be served, the efficiency losses through pumping the chilled water to multiple buildings can be more than recovered through the high efficiency of large industrial water-cooled chillers, which can more economically use available heat sinks. These cooling systems are typically sized for the highest aggregate cooling load, as opposed to the sum of the highest individual building loads. Such sizing takes advantage of the noncoincident cooling peaks that occur across multiple buildings with different cooling load profiles, bringing some first-cost benefits that help overcome the additional costs of chilled-water piping and pumps.

District cooling systems enable higher flexibility to incorporate multiple energy vectors (heat sinks, solar cooling, and waste thermal energy) to meet cooling requirements and leverage thermal (cold) energy storage options to shift the cooling peak load.[xxxiii]

District cooling systems have been used in many world-famous building districts, including the US Pentagon and Europe's largest business district, La Défense, in Paris. Dubai invested US$150 million between 2009 and 2014 to construct the world's largest district cooling network. Through this network, Dubai expects to meet 40 percent of its cooling demand through district cooling by 2030, cutting the city's power consumption for air-conditioning in half.[67] China has seen significant growth in district cooling projects in the last two decades and has implemented several large-scale district cooling systems, including the 911 megawatt (MW) system for the island of Hengqin in Zhuhai and the 441 MW system for Guangzhou University City.[68] In 2016, La Alpujarras district cooling plant in Medellín, Colombia, was the first thermal district operating in Latin America, with a capacity of 3,600 tons of refrigeration to supply cooling to several public buildings.

Limitations: District cooling requires significant up-front infrastructure investment, which private sector developers will typically consider only if there is sufficient assurance of future offtake from building

xxxiii "Solar cooling" is the use of solar energy to operate the cooling system. Electricity generated from a solar photovoltaic system can be used to operate the electrical chillers, or solar thermal energy can be used to operate absorption cooling systems. "Waste cold" is the cooling energy available (for example, during the regasification process of liquified natural gas) that can be used for producing chilled water instead of wasting it.

owners. This assurance will typically require a combination of the granting of concession rights, long-term agreements from high-credit-worth primary offtakers (sometimes referred to as “anchor” offtakers or clients), and development covenants that direct building developers to connect to the supply. Hence, this is not a solution that can be effectively deployed one building at a time and will primarily apply to new construction zones, districts, or cities. With the combination of large, up-front investments, and the need for an enabling regulatory framework and planned urban development, district cooling is not yet common in most developing countries.

Advantages: Because district cooling systems leverage the diversity of cooling loads served and are able to incorporate multiple energy vectors, they can achieve reduced overall system capacity, compared to conventional distributed cooling systems. What is perhaps most important, however, is the service model that such an approach enables (Cooling as a Service, or CaaS, discussed more fully as an intervention under F4 in the Compendium). Under such a model, buildings pay for the cooling that they use, and system developers and operators earn their highest returns through lowest life cycle system costs being incentivized under long-term supply agreements.

Conventional Cooling Technologies: Constraints and Considerations

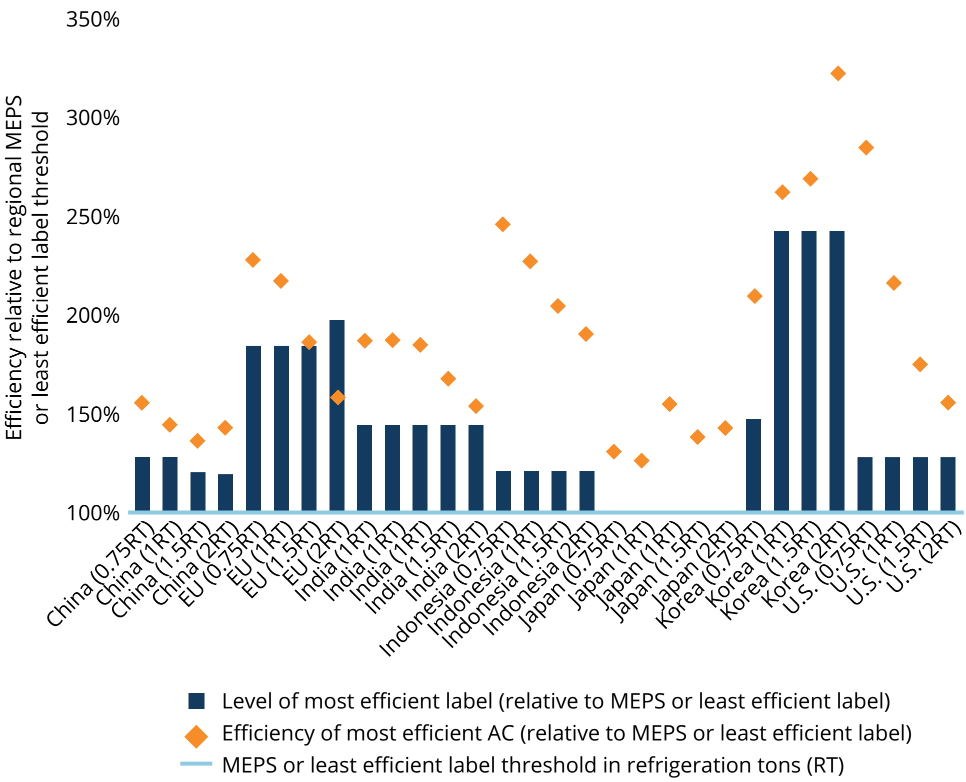
In addition to the intrinsic efficiency of the different conventional cooling equipment types discussed in this section, the differing behaviors of buyers across the cooling technology spectrum (such as the first-cost focus of RAC buyers and life cycle cost focus involved in complex district cooling systems) have impacted the average market efficiency of available equipment.

The largest market failures lie in the RAC segment—predominantly used in residential space cooling—where customers focus on low first costs as opposed to life cycle costs. Research by the Lawrence Berkeley National Laboratory points out that in most regions of the world, there exists a wide range of efficiency levels for residential air conditioners, and even where there are minimum energy performance standards, the most stringent lag far behind the most efficient product available in the market (figure 3.14).[69]

The customer focus on low first costs has driven the AC industry to focus on achieving economies of scale to optimize first costs, resulting in a highly consolidated industry. There are fewer than 500 AC manufacturers worldwide, with two Chinese companies representing over 35 percent of global room air conditioner production.[70] AC manufacturers’ strategies revolve around meeting consumer demand for low prices at efficiencies that simply meet or marginally exceed MEPS. To put this in perspective, while some of the adjacent industries—such as solar photovoltaic (PV) and light-emitting diode (LED) lighting—have seen rapid innovations in the recent past, RACs have achieved only about 14 percent of their theoretical maximum efficiency (figure 3.15).[71]

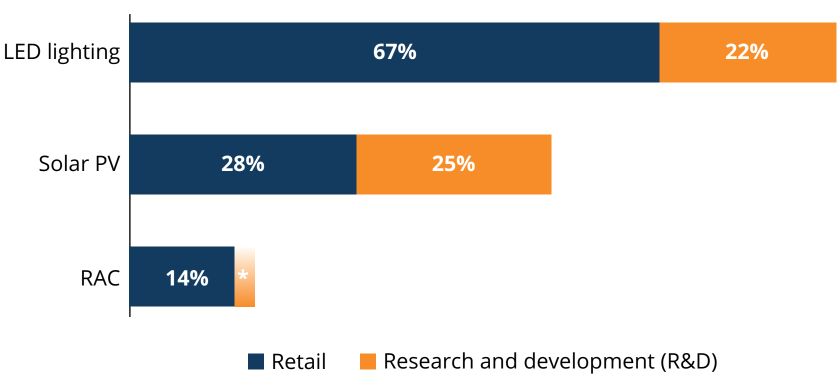
The consumer preference for lowest-first-cost units further exacerbates the impact of cooling equipment on energy systems and climate. A sizable population group—specifically, 2.3 billion people in the increasingly affluent lower-middle class in developing countries—is on the brink of purchasing the most affordable, and likely least efficient, low-first-cost air conditioners.[75] Entry-level units typically use twice the energy as commercially available high-efficiency models, adding a major operating cost burden on consumer pockets, stress on the electricity systems, and high emissions. Rocky Mountain Institute (RMI) estimates that the number of entry-level RACs sold will likely drive peak load and new-generation investment of approximately US$0.80 for every US$1 of RAC unit sales value.

FIGURE 3.14: ENERGY EFFICIENCY OF THE MOST EFFICIENT MODELS RELATIVE TO REGIONAL MINIMUM ENERGY PERFORMANCE STANDARDS (MEPS)



Source: Park, Shah, and Gerke, 2017, © Lawrence Berkeley National Laboratory. Reproduced with permission from Lawrence Berkeley National Laboratory; further permission required for reuse.[72]

FIGURE 3.15: RAC INDUSTRY PROGRESS TOWARD THEORETICAL EFFICIENCY



* = Imperceptible R&D

Source: Sachar, Campbell, and Kalanki, 2018, *Solving the Global Cooling Challenge*.

In comparison to the RAC segment, the dynamics are somewhat different in the chiller market, where life cycle cost is often an important consideration and buyers tend to be more informed.

Consequently, the type of intervention strategies for deploying technologies at different scales would vary from one technology to another and would also depend on several local factors. For example, market failure in the smaller equipment segment will require policy interventions in a way that may not be necessary in the large (or complex) equipment segment, where the buyers are generally better informed.

Alternate Cooling Technologies

A multitude of available or evolving alternate cooling equipment types break away from traditional air-conditioning systems' reliance on a vapor compression cycle using a gaseous refrigerant. These technologies may also be integrated with vapor compression technologies or with evaporative cooling systems as a hybrid solution. Some examples include the following:

Absorption Cooling Systems

These systems are driven by heat and use a sorption material in combination with a refrigerant. They differ from a conventional vapor compression system in the way that the electrical compressor is replaced by a thermally driven absorber-generator system. The two most common types are water–lithium bromide (LiBr), in which LiBr is the sorption material and water is the refrigerant, and ammonia-water, in which water is the sorption material and ammonia is the refrigerant.

The absorption chillers generally require greater space for installation and are more complex than vapor compression–based chillers, thus resulting in relatively higher capital costs for the absorption cooling system. In addition, absorption chillers are less energy efficient compared to vapor compression–based chillers. While the intrinsic efficiency of absorption systems may be low, these systems are best suited, and both more cost efficient and environmentally friendly, where waste heat or solar thermal energy is available and cooling demand can be aggregated (for example, industrial applications, government buildings, airports, and hotels). For instance, absorption chillers can be added downstream of a combined heat and power (CHP) plant (known as trigeneration) to further optimize the waste heat source to produce cooling. Rooftops of government buildings and hotels can be utilized to install the solar collectors, which provide the required thermal energy for absorption chillers. For example, the Swiss embassy in India, in 2017, installed a solar thermal vapor absorption system to produce chilled water at 7–10ºC for cooling its buildings. It has resulted in a 40 percent reduction in cooling-related electricity consumption of the building complex.[73]

Solid-State Cooling Systems

These emerging technologies do not use liquid refrigerants like conventional vapor compression systems. Instead, they take advantage of material properties of solids to transfer heat. Some types of solid-state cooling technologies include the following:

- **Magnetocaloric cooling.** In this system, a material is cooled by being exposed to a changing magnetic field. This technology is more common for low-temperature applications, and it is not currently applied to space cooling. However, the technology has potential applications in space cooling that are under exploration.

- **Thermoelectric cooling.** The underlying principle in this type of cooling is that passing an electric current through semiconductor material results in a temperature difference. Currently, this technology is used in electronic components, portable coolers, scientific devices, and others. This technology also has potential applications in space cooling that are under exploration.
- **Elastocaloric cooling.** This is also known as thermoelastic cooling and involves a solid material being cyclically compressed (by applying stress) and uncompressed (by removing stress), causing its temperature to change. When the stress is applied, the material's temperature increases, and this heat can be rejected to a heat sink. When the stress is removed, the material cools down such that it can absorb heat from the space, producing cooling. The material used in elastocaloric cooling possesses superelastic properties—that is, it returns back to its original shape when stress is removed—and is sometimes referred to as "shape memory alloy." Various materials that have been tested in labs show an elastocaloric effect, the most effective to date being nickel–titanium alloy or nitinol.
- **Barocaloric cooling.** This system uses solid-state phase transitions in organic molecular plastic crystals reversibly to absorb a large amount of heat to provide cooling. This technology uses "plastic crystals," which can undergo a change in their molecular orientation upon application of pressure. These plastic crystals are relatively soft materials that can be deformed by applying pressure. The process of applying and releasing pressure on the barocaloric material results in solid-to-solid phase changes, which results in temperature changes because of the change in molecular and lattice orientation of the crystals. A heat transfer fluid, air or water, can then be used to extract this heat resulting from the temperature difference to produce cooling. This cooling technology is in an early stage of development and has not been used in commercial applications to date.

Personalized Cooling Systems

Personalized cooling systems work on the principle of creating a microclimatic zone around the user such that cooling is deployed only where it is needed. Although this technology is still evolving, some personalized cooling systems are available today in the form of chairs and handheld or wearable devices.

These alternative cooling technologies are mostly either limited in application to specific sectors or are in the early stages of technical demonstration. However, these cooling solutions are likely to play an increasing role in the future of cooling that is climate friendly and free of hydrofluorocarbons (HFCs), starting in the sectors that align best to the specific attributes of these technologies.

Cooling Options for Off-Grid/Energy-Access-Constrained Populations

With rising global temperatures, enhancing cooling options for energy-access-constrained populations is becoming increasingly important. Strategies include the following:

- Off-grid solar home systems to power fans and other low-energy cooling options,
- Community cooling centers and local heat-action plans,[74, xxxiv] and
- Integration of passive cooling measures in design and retrofits—such as cool roofs, high-insulation envelopes, and innovative construction materials—with supplementary low-energy (solar) cooling.

xxxiv Community cooling centers are common in the United States and Canada, and there are several in Europe as well. However, this concept is less utilized in developing countries. One recent example is the Ahmedabad Heat Action Plan in India, which includes cooling centers.

COMPARATIVE SUMMARY OF SPACE COOLING TECHNOLOGIES

The multitude of available space cooling technologies introduces complexity in terms of choosing the appropriate solution. Each technology has its own set of advantages, limitations, and considerations—summarized in table 3.2—that should be considered in the selection of the best fit cooling technology. In table 3.2, cost has not been reflected as one of the main selection considerations other than for fans and air coolers, because like function and efficiency, the cost per unit of cooling capacity (ton or kW) is similar across all vapor compression technologies. Cost differential occurs where function or efficiency is materially different, or due to local country factors including domestic manufacturing, tariffs, and labor costs associated with design and installation.

TABLE 3.2: SUMMARY OF SPACE COOLING TECHNOLOGIES

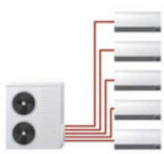
NON-REFRIGERANT TRADITIONAL COOLING EQUIPMENT
THIS GROUP TYPICALLY INCLUDES FANS AND AIR COOLERS, WHICH ARE WIDELY USED IN HOT AND DRY CLIMATE CONDITIONS IN MANY PARTS OF THE WORLD TO PROVIDE THERMAL COMFORT.

Fans 	**Advantages** • Low first cost • Low energy consumption enabling deployment for weak-grid locations, or off-grid locations in combination with solar kits	**Limitations** • Space is not cooled; only air movement over the body results in thermal comfort • Not effective when air contains high humidity	**Considerations** • Effective for small-scale application, such as a room • Enables wider access to enhanced thermal comfort
Air coolers 	**Advantages** • Affordable compared to air conditioners • Low energy consumption compared to air conditioners • Space is cooled as temperature of air is reduced due to evaporation effect	**Limitations** • Not effective when air contains high humidity • Requires separate dehumidification component to achieve comfort outside of dry climate zones	**Considerations** • Effective for small-scale application, such as a room or small buildings

(continued)

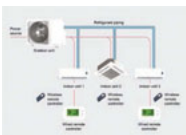
TABLE 3.2: CONTINUED

AIR-CONDITIONING EQUIPMENT BASED ON TRADITIONAL VAPOR COMPRESSION CYCLE
THIS GROUP OF EQUIPMENT ACTIVELY COOLS THE SPACE IN A BUILDING USING MECHANICAL SYSTEMS AND INCLUDES **SEVERAL TECHNOLOGIES OF VARYING COMPLEXITY, SUCH AS ROOM AIR CONDITIONERS (RACS), CENTRAL AC SYSTEMS, VARIABLE REFRIGERANT FLOW SYSTEMS, AND CHILLERS.**

RACs (window)  **(or ductless split)** 	**Advantages** • Space is cooled and dehumidified • Equipment is compact and easy to install • Available at range of costs and in many efficiency levels • Independent controls by units support part-time and part-space operation	**Limitations** • Efficiency is limited by ambient air temperature • Limited dehumidification capacity, requiring separate dehumidification component or overcooling and reheating to achieve comfort in humid conditions • Space is often overcooled; that is, temperature is set lower than desired to achieve effective moisture removal • Does not incorporate ventilation	**Considerations** • Consumer preference is typically for low-first-cost product despite its lower efficiency • Effective for small-scale application, such as a room or small buildings
Multi-split AC 	**Advantages** • Multiple rooms can be cooled and dehumidified • Inverter-based system allows occupants to precisely control conditions in different rooms, supporting part-time and part-space operation • Particularly suitable where ductwork (required for central AC systems) is aesthetically unacceptable or is cost prohibitive	**Limitations** • Efficiency is limited by ambient air temperature • Limited dehumidification capacity, requiring separate dehumidification component or overcooling and reheating to achieve comfort in humid conditions • Refrigerant piping (total length and vertical height) limits the scale of application • Increased risk of refrigerant leakage exists due to complex piping network • Does not incorporate ventilation	**Considerations** • Can connect up to eight indoor units to one outdoor condenser unit • Effective for larger single-family homes, small to midsize commercial buildings, and small multifamily apartment buildings

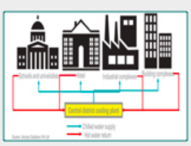
(continued)

TABLE 3.2: CONTINUED

Central AC 	**Advantages** • Space is cooled and dehumidified • Duct(s) supplies air to multiple rooms or large space, allowing it to be maintained at desired conditions with minimum involvement from the user • Free cooling can be used effectively when outside temperature and humidity is appropriate	**Limitations** • Efficiency is limited by ambient air temperature • Limited dehumidification capacity, requiring separate dehumidification component or overcooling and reheating to achieve comfort in humid conditions • Maintenance of ducts and fans is required to ensure minimum losses across the system	**Considerations** • Efficiency should be considered for the whole system—that is, vapor compression unit and the ducts • Effective for larger single-family homes, small to midsize commercial buildings, and small multifamily apartment buildings
Variable refrigerant flow system 	**Advantages** • Multiple rooms can be cooled and dehumidified • Allows occupants to precisely control conditions in different rooms, with provision of simultaneous heating and cooling in some systems, supporting part-time and part-space operation • Lower operational costs and higher energy savings over lifetime use, compared to stand-alone units • Can be installed in existing buildings that are not air-conditioned or that do not have provision for the installation of ducted systems	**Limitations** • Efficiency is limited by ambient air temperature • Limited dehumidification capacity, requiring separate dehumidification component or overcooling and reheating to achieve comfort in humid conditions • Refrigerant piping (total length and vertical height) limits the scale of application • Increased risk of refrigerant leakage exists due to complex piping network • Higher first costs in new construction scenarios, compared to central AC systems or air-cooled chilled-water systems at a similar implementation scale, because of their sophisticated control equipment and refrigerant piping requirement	**Considerations** • Can connect up to 50 indoor units to one outdoor condenser unit • Effective for midsize commercial buildings and multifamily apartment buildings

(continued)

TABLE 3.2: CONTINUED

Air-cooled chiller 	**Advantages** • Large spaces can be cooled and dehumidified • Lower infrastructure requirements and first cost compared to water-cooled chillers	**Limitations** • Efficiency is limited by ambient air temperature • Limited dehumidification capacity, requiring separate dehumidification component or overcooling and reheating to achieve comfort in humid conditions • Shorter life compared to water-cooled chillers, due to exposure to the elements associated with rooftop placement	**Considerations** • Efficiency should be considered for the whole system—that is, air handling unit, chilled-water pump, and piping • Effective for large commercial or industrial buildings (and commonly placed on rooftops)
Water-cooled chiller 	**Advantages** • Large spaces can be cooled and dehumidified • Higher efficiency compared to air-cooled chillers, as condensing heat is rejected to a cooling tower	**Limitations** • Limited dehumidification capacity, requiring separate dehumidification component or overcooling and reheating to achieve comfort in humid conditions • Regular maintenance of the water side of the system is critical for preventing the buildup of bacteria in cooling towers, which can be harmful to people • Water availability is critical to operation of the system	**Considerations** • Efficiency should be considered for the whole system—that is, air handling unit, chilled-water pump, cooling tower system, and piping • Effective for large commercial or industrial buildings or public facility
District cooling system 	**Advantages** • Meets cooling demand at community or city level at lowest life cycle cost • Thermal energy storage can be leveraged to optimize system capacity and meet peak cooling demand • Higher flexibility to incorporate multiple energy vectors (heat sinks, solar cooling, and waste thermal energy) to meet cooling requirements	**Limitations** • Limited dehumidification capacity (since it is a chiller system), requiring separate distributed dehumidification component or overcooling and reheating to achieve comfort in humid conditions • Significant up-front infrastructure investment • Suited for new construction zones, districts, or cities	**Considerations** • Sizing is done for the highest aggregate cooling load, as opposed to the sum of the highest individual building loads • Sufficient assurance of future offtake from building owners is key to developing the system • Effective to meet the demand for multiple buildings, communities, and districts

(continued)

TABLE 3.2: CONTINUED

ALTERNATE COOLING TECHNOLOGIES **THIS GROUP OF EQUIPMENT CAN ACTIVELY COOL THE SPACE BY USING AN ALTERNATE APPROACH TO THE TRADITIONAL VAPOR COMPRESSION CYCLE OR BY BREAKING AWAY FROM USING REFRIGERANT GASES. THE GROUP INCLUDES TECHNOLOGIES SUCH AS THE ABSORPTION COOLING SYSTEM AND A VARIETY OF SOLID-STATE COOLING SYSTEMS (FOR EXAMPLE, BAROCALORIC, MAGNETOCALORIC, ELASTOCALORIC, AND THERMOELECTRIC).**			
Absorption cooling system	**Advantages** • No electrical compressor is used, which reduces the power demand compared to vapor compression system • Use of natural refrigerants with zero global warming potential (GWP), such as water and ammonia, is common in absorption chillers • Viable solution where waste heat or solar energy is readily available	**Limitations** • System efficiency is lower compared to vapor compression system at similar implementation scale, as large amount of thermal energy is required • Limited dehumidification capacity, requiring separate dehumidification component or overcooling and reheating to achieve comfort in humid conditions • Requires greater space, due to complexity, and has higher cost compared to vapor compression system at similar implementation scale	**Considerations** • Effective for large industrial or public facility where waste heat source or solar-based systems are installed • System can be added downstream of a combined heat and power (CHP) plant (known as trigeneration) to produce cooling
Solid-state cooling technology *(for example, barocaloric, magnetocaloric, elastocaloric, and thermoelectric)*	**Advantages** • Potential to transform the traditional vapor compression cooling approach • Does not use refrigerant gases to remove heat from the space • Some technologies have limited to no moving parts, resulting in less noise and vibration	**Limitations** • Some technologies have been used in niche applications at small scale, while others are in early stages of development	**Considerations** • Potential to integrate with conventional vapor compression system or dehumidification system as a hybrid solution

Source: Authors, composed by Rocky Mountain Institute.

CONTROL AND OPTIMIZE COOLING LOADS

In addition to the thermal performance of buildings and the efficiency of cooling technologies, occupant behaviors and usage patterns can be important variables in the overall energy utilization for space cooling. Several strategies can be applied to ensure that cooling is delivered only where and when it is needed and that system performance is monitored and maintained, thus avoiding any wasteful cooling. Collectively, such strategies control and optimize cooling utilization.

Controls and Sensors

Control systems regulate the operation of an air-conditioning system using a sensing device to compare the actual state (for example, the temperature) with a target state. Depending on the scale of the building being served, the systems can be simple—such as a programmable thermostat—to very complex, geographically distributed controllers that can control various processes throughout a group of buildings, either from a central host computer or over the Internet from a unit that combines the functions of a host computer and web server. The objective is to use controls and sensors to eliminate wasteful utilization of equipment (or energy). Common methods include the following:

- Sensing demand across zones through thermostats, occupancy sensors, and air quality sensors;
- Modulating supply to meet demand by providing just enough cooling and delivering it only to the spaces that have demand; examples include variable air volume, VRF, and variable speed motors or inverters; and
- Optimizing the use of free cooling when outdoor weather conditions (temperature, humidity) are favorable through sensors and motorized dampers.

The key notion is to encourage part-time and part-space cooling behavior; that is, cooling is delivered only to where and when it is needed. This includes building operations guidelines, and even policies, that encourage or require occupancy sensors and smart cooling appliances that monitor current cooling demand, use learning algorithms to predict near-term cooling demand, and auto-adjust operations to meet that predicted cooling demand as efficiently as possible.

Load Shifting

Peak load constraints can be alleviated using strategies to stagger the load, such as the following:

- **Thermal energy storage.** Thermal energy storage refers to the technology that enables a building's cooling-related electricity demand to be shifted away from the peak load period, easing capacity strains on the grid and reducing demand charges and utility bills for customers. Thermal energy storage is like a battery for a building's air-conditioning system. It uses standard cooling equipment and an energy storage medium such as chilled water, ice, or other phase-change materials (organic and inorganic salts) in an insulated tank. The energy storage medium is charged during the off-peak times, either during the night when the ambient temperature is cooler or during low power demand periods, and discharged during the peak demand period, thereby meeting cooling needs at all times without compromising thermal comfort. Thermal energy storage is most commonly seen in large installations in cities and industry. It is most economically deployed at scale in district or centralized cooling scenarios but can be used at lesser scales if there is sufficient financial incentive. (For examples of thermal energy storage in district cooling systems, please see F4 in the Compendium.)

- **Demand response measures.** Demand response provides an opportunity for users to play a significant role in the operation of the electric grid by reducing or shifting their electricity usage during peak periods in response to time-based rates or other forms of financial incentives. For space cooling, a common demand response approach is for power companies, in collaboration with building owners and operators, to cycle ACs on and off during periods of peak demand in exchange for a financial incentive and lower electric bills. Power companies can also incentivize customers to raise thermostat settings during a demand response event. Smart meters and other enabling technologies (for example, connected devices) are making it easier to implement demand response strategies.[xxxv] (For more on demand response measures, please see F8 in the Compendium.)

User Adaptations and Behavior Changes

User behavior can adapt to optimize cooling demand without materially decreasing comfort. Consumers are largely unaware of the amount of energy their cooling equipment consumes. This lack of awareness—coupled at times with low electricity prices—gives consumers very little incentive to better manage their cooling use. However, fostering energy-conserving behavior can decrease energy use without sacrificing comfort, health, or productivity. Common strategies include the following:

- **Nudges for behavior change.** The role of behavior change—at the level of government, corporations, and individuals—has gained traction in the larger context of energy efficiency and energy transition. Centered around "nudge theory," a concept in behavioral science and behavioral economics that proposes positive reinforcement and indirect suggestions to influence the behavior and decision making of groups or individuals, the behavior change approach can also apply to the drive for sustainable space cooling. Several measures can be applied to influence behavior change, including information-based programs such as home energy reports (this is discussed in greater detail in F8 in the Compendium), community-based programs or competitions, and education and training programs.[xxxvi] A meta-analysis of programs in the United States has shown that 2–20 percent in energy saving is possible from behavior change programs.

  Behavior change programs can often be a low-cost option to inform and engage users and stakeholders in the drive toward sustainable cooling, and they should be leveraged to the extent possible. While well-designed behavior change initiatives can reinforce part-time and part-use cooling behaviors, one caveat is the difficulty in maintaining impact from behavior change strategies over time; this is where automation through sensing and controls can ensure persistency.

- **Adaptive thermal comfort.** People have a natural tendency to adapt to changing conditions in their environment. This natural tendency is the basis of the theory of adaptive thermal comfort, which suggests that a human connection to the outdoors and control over the immediate environment allow people to adapt to—and even prefer—a wider range of thermal conditions than is generally considered comfortable. The adaptive approach to thermal comfort could have a tremendous impact on comfort conditions in buildings and on resulting energy consumption and carbon emissions.

  The India Cooling Action Plan (ICAP) advocates adaptive thermal comfort as an effective strategy to reduce cooling energy use in the building sector, suggesting that by increasing the indoor design

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xxxv While a deep dive into smart meters is outside the scope of this publication, detailed information is readily available, for example, see https://utilityanalytics.com/2018/11/new-uses-of-smart-meter-data-are-coming-to-utilities/.
xxxvi See also Energy Sector Management Assistance Program's 2020 forthcoming publication, "A Practitioner's Guide to Integrating Behavior Change in Energy Efficiency Projects in Developing Countries."

temperature from 20°C to 24°C or 26°C in India's tropical climate, savings of 20 percent and 28 percent, respectively, can be achieved in a building's annual cooling energy use.

- **Free cooling.** When outdoor temperature, humidity, and air quality allow, free cooling through open window ventilation may be all that is required to improve temperature and humidity in closed indoor spaces.

Good Operation and Maintenance Practices

Regular and timely maintenance and calibration of cooling equipment can ensure that the equipment performs at its designed efficiency levels. With proper maintenance and servicing of cooling equipment, as much as a 50 percent decline in performance can be avoided.[75] Market sources suggest that for large cooling systems, regular retrocommissioning could achieve energy savings in the range of 10–20 percent.[xxxvii] Retrocommissioning takes a relatively modest up-front investment. According to a study by Lawrence Berkeley National Laboratory, the average cost for retrocommissioning in the United States is $0.30 per square foot. But the return on that investment comes quickly: per the same study, the median payback time is a little more than a year, and the median energy savings is 16 percent.[76]

The impact of regular equipment maintenance and calibration could be even greater in developing countries, where poor maintenance practices are common and lead to reduced cooling capacity, greater energy use, and refrigerant leakage. For instance, in India's RAC sector alone, proper servicing and maintenance has the potential to contribute up to 20 percent improvement in overall performance.[77] Good practices include the following:

- Establishing operation and maintenance (O&M) guidelines, including requirements for efficient operations, regular retrocommissioning, and maintenance that includes cleaning of filters, coils, and fins; and

- Better refrigerant management during equipment servicing, not only to maintain cooling system performance at design efficiency levels but also to reduce the environmental impact associated with the release of these refrigerants into the atmosphere.

Capacity Building in the Service Sector

Closely related to good O&M practices is the need to build capacities and skills in the service sector. The space cooling service sector (which includes service and repair technicians) is largely informal in developing economies and is fraught with inefficiencies, such as lack of appropriate training, suboptimal repair practices, and poor refrigerant management. Technicians who service equipment for cooling performance typically do not look at its energy efficiency or follow appropriate refrigerant management protocol. Educating technicians and promoting service-sector best practices for all cooling equipment could reduce cumulative emissions by 30 gigatons of CO_2 globally by 2050.[78, xxxviii] A skilled technician workforce is key for ensuring proper installation and O&M of cooling equipment and facilitating wider use

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xxxvii Commissioning of existing buildings, or retrocommissioning, is a systematic process applied to existing buildings for identifying and implementing operation and maintenance improvements and for ensuring optimal performance of building systems over time. Using a whole-building systems approach, retrocommissioning seeks to identify operational improvements that will increase occupant comfort and save energy.

xxxviii Note that this number includes all cooling equipment, not just space cooling equipment. It accounts for both direct emissions from refrigerants and indirect emissions from electricity usage.

of sustainable cooling solutions. For example, appropriately trained technicians are critical for maintaining more complex—but more sustainable—water-cooled systems. Capacity building is also key for better refrigerant management by reducing the incidence of refrigerant leakage into the atmosphere during the servicing and end-of-life disposal of cooling equipment. Training programs should focus on raising awareness of and developing the appropriate skills to handle alternative refrigerants, which may come with higher risks of toxicity and flammability. India has developed a program to offer training to 100,000 service technicians in good servicing practices, including familiarity with alternative refrigerants.[79]

CONTRASTING OPTIMAL SUSTAINABLE SPACE COOLING SOLUTIONS TO THE DEFAULT MARKET APPROACH

Throughout this section, we have covered the need for an integrative approach to space cooling that starts with reducing cooling loads, serving residual loads efficiently, and controlling and optimizing loads, along with applying appropriate technologies to differing building scales. In addition to scale, there are a number of other important variables to consider to determine the optimal sustainable cooling solution for a building. These are summarized in figure 3.16.

FIGURE 3.16: FACTORS THAT INFLUENCE THE CHOICE OF SPACE COOLING TECHNOLOGIES AND SOLUTIONS

- **Building scale.** The technology choices and solutions for cooling are strongly dependent on the scale of the built environment they will serve—that is, whether the cooling solution is being designed to serve the cooling needs of a district, a community, a single building, or a home. (This is represented in figure 3.6).
- **Type of construction.** Cooling solutions will vary depending on whether they are being designed for new building construction, a major renovation, or an existing building retrofit.
- **Building ownership profile.** Investor-owners will behave differently from owner-occupiers, and short- or uncertain-term owners (typically private sector) will behave differently from long-term owners (such as those in the public and institutional sectors). In the case of investor-owners, they will invest in building energy efficiency and sustainable space cooling to the extent that they see a financial return. With tenants typically responsible for the energy costs of their space, the opportunity for a direct return will be limited, and the opportunity for an indirect return through increased value of the building—to tenants and future buyers—depends on the ability of the market for buildings (and the market for leased space) to fairly value a building's energy performance.
    - Short- or uncertain-term owner-occupiers will typically invest in building energy efficiency and sustainable space cooling for the period that they expect to be assured as the owner-occupier of the building, as that is the period that they would realize the direct return of energy savings. As is the case with the investor-owner, the indirect savings of the increased value of the building are dependent on the ability of the market to fairly value a building's energy performance.
    - Long-term owners, such as public and institutional owner-occupiers, typically have the incentives necessary to invest in building energy efficiency and sustainable space cooling, as they would benefit from the energy savings and could be assured they would directly realize the full value of these investments through the long-term ownership of their buildings.

(continued)

FIGURE 3.16: CONTINUED

- **Climate zone.** Typically, the climate zones that have the most need for cooling can be categorized as hot and humid, hot and dry, and composite (which shows characteristics of both). The macro-climate of a region impacts the cooling demand as well as the choice of effective cooling strategies. For instance, evaporative cooling and fan options may work for a hot and dry climate but are less effective for a hot and humid climate.
- **Country-specific factors.** Labor costs, cooling equipment import tariffs, service-sector capacity and capability, and utility rates all impact the choice for an optimal solution.
- **Environmental attributes.** Immediate environmental attributes—such as urban versus suburban setting, building density, available heat sinks, soil conductivity, and solar irradiance—will impact cooling needs and choices.
- **Grid factors.** The availability of grid electricity and the reliability of power supply will influence cooling strategies. Off-grid applications for cooling should be considered for areas where grid electricity cannot be supplied. *Note:* The World Bank's procurement guidelines are restricted in preferential bidding; to apply the Sustainable Procurement strategy, project borrowers must obtain prior approval. http://www.worldbank.org/en/projects-operations/products-and-services/brief/procurement-new-framework

Source: RMI 2020 © Rocky Mountain Institute.

Multiple variables—and their possible combinations—can add significant complexity to choosing the right cooling solution. The interplay of these variables is perhaps best illustrated by reviewing hypothetical scenarios contrasting the optimal sustainable cooling solution to the default market approaches. This contrast also highlights the principal market barriers to the adoption of sustainable cooling solutions.

Scenario 1:

Building scale	Large commercial office building
Construction	New construction
Ownership	Investor-developed and -owned, and tenant-occupied when complete
Climate	Hot climate zone
Other factors	Established cooling service sector

The optimal sustainable space cooling solution under this scenario would start with a building design to minimize cooling loads through passive measures, such as an efficient building envelope, and measures to reduce solar heat gain and incorporate free cooling. Since this is new construction, the cost of these measures that impacts project economics is just the incremental cost of construction over and above the default market approach.

Once the cooling load has been reduced through design to the point where the net present value of further measures no longer meets investment hurdle requirements, the next step is to look at how best to serve the load with a minimal energy and emissions footprint. If an existing district cooling system is available or planned in a timeline that fits with the construction of the office building, this will provide the economic benefit of not having to invest in a central building cooling system and lower operating costs due to the higher efficiency of a professionally managed and maintained district cooling system. Thus, district cooling would be preferred.

Where district cooling is not available or viable, the next most sustainable cooling solution would be a water-cooled chiller system that can take advantage of available heat sinks, including cooling towers, to achieve significantly higher levels of efficiency and lower life cycle costs. Further, with a chiller, refrigerant is contained in a central plant where release through operation is much less likely to occur compared to distributed solutions, where refrigerant is contained in multiple units and, in the case of VRF, piped throughout the building.

To ensure energy-efficient operation, building controls and the capability to modulate cooling supply to better match sensed demand will enable part-time and part-place operation.

In contrast, the default market approach will typically result in the investor investing in reducing load to the extent required by standards or to the extent that the investment has a return on investment in the form of higher building resale value or higher realized rents. Without market pull or policy push, the investor will focus on minimizing first cost outside of the aesthetic features visible and valued by future buyers and occupants.

To serve the cooling load, district cooling (if available or planned in a timeline that fits with the construction of the office building) would again be the preferred option, as this would provide the economic benefit of not having to invest in a central building cooling system and lower operating costs. If district cooling is not an option (and considering that a future buyer or tenants will typically be responsible for the energy consumption of their space in the building), the investor will look to the lowest first-cost solutions that can meet market threshold acceptability and not compromise building aesthetics. As such, the investor would likely focus on lower first-cost solutions, as well as solutions that provide the opportunity for modular installation aligned to specific tenant space, such as packaged ACs, air-cooled chillers, and VRF systems, despite these carrying greater risk of refrigerant leakage and lower levels of relative efficiency compared to the optimal sustainable cooling solution described above.

From an operations perspective, the focus will be on low first-cost, tenant-centric controls and dedicated modular equipment. This would enable tenants to determine comfort in their space with no incentive for the investor to invest in part-time and part-space capability that would reduce building energy consumption, assuming that energy costs, directly measured or allocated, are the responsibility of the tenants.

In contrasting the optimal sustainable space cooling solution with the default market approach, the barriers to sustainable space cooling start to become visible. In this scenario, the most notable barriers include the following, which are discussed in more detail in section 4:

- **Lack of awareness.** There is systemic indifference to or low awareness of the broad benefits of sustainable space cooling, including through building energy efficiency.
- **Lack of transparency.** There is little transparency and verifiability of cost savings of energy-efficient buildings and sustainable cooling equipment. As a result, the efficiency of buildings is not understood or visible.
- **First-cost bias.** In this case, the investor-developer chooses the lowest first-cost option, as they may not be aware of the life cycle benefits of a sustainable cooling solution, which typically comes at a higher first cost (or, as is more typical, they are not motivated to choose such a solution since they are not the end-user).

- **Lack of valuation of efficiency.** Building efficiency is not fully considered or valued in purchasing and leasing decisions.
- **Split incentives.** In this case, the investor-developer is not the end-user and, therefore, does not stand to gain from a sustainable space cooling solution. The tenant is directly responsible for energy costs associated with their space.
- **Complexity of choice.** Multiple technology choices and trade-offs between refrigerant options cause complexity.

Scenario 2:

Building scale	Large office building
Construction	Existing building; renovating and seeking to add cooling
Ownership	Owner-occupied
Climate	Hot climate zone
Other factors	Nascent cooling service sector

The optimal sustainable space cooling solution under this scenario would start with an understanding of the scope of the renovation to the building itself to determine if there is an opportunity to minimize cooling loads through passive measures. As a result of integrating cooling measures with the planned building renovation, the incremental costs can often justify measures that would not otherwise be economically justifiable. For example, if windows are being replaced, upgrading to triple-pane, high-efficiency windows would usually have a relatively small incremental cost compared to installing single- or even double-pane windows, but the upgrade could deliver significant energy savings. On the other hand, if windows are not part of the renovation, replacing functioning windows with high-efficiency windows would likely have a full cost that would make it hard to secure a return within an economically acceptable timeframe. A renovation scenario is an opportunity to integrate measures to improve the building envelope, second only to the time of the new construction of the original building, and should always be fully evaluated.

Once the cooling load has been reduced to the point where the net present value of further measures no longer meets investment hurdle requirements, the next step is to look at how best to serve the load with a minimal energy and emissions footprint. If an existing district cooling system is available or planned in a timeline that fits with the renovation of the office building, this would provide the economic benefit of not having to invest in a central building cooling system and lower operating costs due to the higher efficiency of a professionally managed and maintained district cooling system. Thus, district cooling would be preferred. However, district cooling systems are typically developed in conjunction with the development of *new* urban centers or zones. It is unlikely that an older building would be proximate to a district cooling system.

While the most sustainable cooling solution would be built around a water-cooled chiller that can take advantage of available heat sinks (including cooling towers) to achieve significantly higher levels of efficiency and lower life cycle costs, the building may not have provision for a central chilled-water plant, cooling towers, air handling units, or ductwork for air distribution. Also, with a nascent cooling service sector, the capability to maintain and operate the system at full design efficiency is a further consideration. Taking these considerations together, the next most sustainable space cooling solution would likely be a VRF system that is able to operate part-space and part-time and be centrally managed to enable efficient O&M.

In contrast, the **default market approach** would typically focus on adding cooling to the building and would generally not consider envelope improvements, which do not directly deliver savings. Savings would be realized through downsized cooling equipment and lower operating hours, which are difficult to calculate and outside of the typical rules of thumb used by many building professionals. To serve the cooling load, the owner or contractor may consider a VRF system an efficient and relatively competitive first-cost solution, subject to the availability of qualified installers. In contexts where the service sector is nascent, appropriate managing, monitoring, and maintenance of complex systems would be viewed as challenging. Therefore, decentralized RACs, packaged cooling solutions and multi-split systems—despite lower levels of relative efficiency—are the more likely default market pathway due not only to the lower first cost but also ease of installation and service.

In this scenario, the most notable barriers include the following (discussed in more detail in section 4):

- **Lack of awareness.** There is systemic indifference to or low awareness of the broad benefits of sustainable space cooling, including through building energy efficiency.
- **Lack of transparency.** There is little transparency and verifiability of cost savings of energy-efficient buildings and sustainable cooling equipment. As a result, the efficiency of buildings is not understood or visible.
- **First-cost bias.** In this case, the building owner chooses the lowest first-cost option, as they may not be aware of the life cycle benefits of a sustainable cooling solution, which typically comes at a higher first cost.
- **Complexity of choice.** Multiple technology choices and trade-offs between refrigerant options cause complexity.

Scenario 3:

Building scale	Small building: multifamily residential building
Construction	New construction
Ownership	Investor-developer (will transition to fractional ownership once complete)
Climate	Hot climate zone
Other factors	Established cooling service sector

The optimal sustainable space cooling solution under this scenario would start with a building design to minimize cooling loads through passive measures, such as an efficient building envelope and measures to reduce solar heat gain and capture free cooling. Given that this scenario involves new construction, the relevant cost consideration affecting project economics is the incremental cost of construction over and above the default market approach.

Once the cooling load has been reduced through design to the point where the net present value of further measures no longer meets investment hurdle requirements, the next step is to look at how best to serve the load with a minimal energy and emissions footprint. If an existing district cooling system is available or planned in a timeline that fits with the construction of the multifamily residential building and is able to serve smaller buildings, this would provide the economic benefit of not having to invest in an independent building cooling system and lower operating costs due to the higher efficiency of a professionally managed and maintained district cooling system. Thus, district cooling would be preferred.

Where district cooling is not available or viable, the next most sustainable cooling solution for a small multifamily residential building would be built around a VRF solution. VRF systems, when combined with tenant-centric building controls, are able to operate part-space and part-time and be centrally managed to enable efficient operations and maintenance.

In contrast, the **default market approach** would typically result in the investor-developer investing in reducing load only to the extent required by building standards or to the extent that the investment has a return back to the investor in the form of higher building resale value or higher realized rents. Without market pull or policy push, the investor will likely focus on first cost and the aesthetic features visible and valued by future buyers and occupiers.

When it comes to serving the load, depending on market norms, the investor-developer may choose not to include cooling at all but simply ensure (for example, by providing exterior shelves) that occupiers can install RAC units themselves. If market norms require provision of cooling, district cooling—if available or planned in a timeline that fits with the construction of the multifamily residential building and if able to serve small buildings—will again be the preferred option, as this will provide the economic benefit of not having to invest in building cooling equipment and be delivered at a lower operating cost. If it is not, and considering that buyers of individual units will typically be responsible for the energy consumption of their space in the building, the investor developer will look to lowest first-cost solutions that can meet market threshold acceptability and not compromise building aesthetics. As such, the investor developer would usually focus on low first-cost solutions that are dedicated to individual occupier units, such as decentralized RACs, packaged cooling solutions, and multi-split systems—despite lower levels of relative efficiency. These solutions have lower first costs and dedicate equipment to individual occupier units, making O&M costs and provision of a cooling system a direct responsibility and cost of the occupiers.

In this scenario, the most notable barriers include the following:

- **Lack of awareness.** There is systemic indifference to or low awareness of the broad benefits of sustainable space cooling, including through building energy efficiency.
- **Lack of transparency.** There is little transparency and verifiability of cost savings of energy-efficient buildings and sustainable cooling equipment. As a result, the efficiency of buildings is not understood or visible.
- **First-cost bias.** In this case, the investor-developer chooses the lowest first-cost option, as he/she may not be aware of the life cycle benefits of a sustainable cooling solution, which typically comes at a higher first cost (or, as is more typically the case, the investor developer is not motivated to choose such a solution since he/she is not the end-user).
- **Lack of valuation of efficiency.** The efficiency of buildings is typically not considered in purchasing and leasing decisions.
- **Split incentives.** In this case, the investor-developer is not the end-user and, therefore, does not stand to gain from a sustainable space cooling solution. The tenant is directly responsible for energy costs associated with their space.
- **Complexity of choice.** Multiple technology choices and trade-offs between refrigerant options cause complexity.

KEY TAKEAWAYS

- While space cooling can be addressed in many different ways, an integrated approach to cooling will maximize potential benefits and should be pursued to the fullest extent possible. This approach advocates, first, reducing cooling loads through better building design and passive cooling measures then serves cooling loads in the most efficient manner with better cooling equipment, systems, and technologies. Finally, this approach optimizes cooling loads by implementing part-time and part-space cooling behaviors and regulating the operation of cooling equipment.

- Many space cooling strategies and equipment types are available, each with its own advantages and limitations within given applications and conditions. As such, there is no single optimal solution; the most appropriate space cooling solution will depend on the best fit for the factors—both enabling and limiting—and interrelated variables that characterize the cooling needs of a particular space.

ACROS (Asian Crossroads Over the Sea) Fukuoka Prefectual International Hall at Tenjin Central Park, Fukuoka, Japan, 04-06-2015. Architect: Emelio Ambasz.
Credit: Noa/istock.

4. MARKET BARRIERS TO SUSTAINABLE SPACE COOLING AND INTERVENTION STRATEGIES THAT CAN OVERCOME THEM

Scaling up sustainable space cooling practices and solutions has thus far been an implementation challenge due to many factors broadly similar to those for the energy-efficiency sector in general. A key factor is the nature of space cooling itself, characterized by (1) very heterogeneous buildings (and end-users), including residential buildings, commercial and institutional buildings, public buildings, and off-grid users; and (2) diverse and numerous technologies and strategies, including passive cooling, smart controls, simple appliances such as fans and coolers, multiple types of air conditioners (ACs), and complex multibuilding equipment and systems, such as district cooling. Scaling up access to—and adoption of—sustainable space cooling (that is, energy-efficient buildings, efficient cooling technologies, and optimized operations and user adaptations) requires a multidimensional approach that combines awareness and capacity building with smart policy, financing, and enabling mechanisms.

UNDERLYING MARKET BARRIERS TO SUSTAINABLE SPACE COOLING

The challenges of scaling up or investing in sustainable space cooling practices can be fundamentally attributed to a lack of market demand for sustainable space cooling. This lack of market demand results from a number of underlying market barriers, which together are the core reason why market solutions and enablers (such as financial mechanisms and policy measures) are necessary.[xxxix] These underlying market barriers—which are also interrelated and reinforcing—are presented in table 4.1.

More often than not, a combination of barriers is at play in any country, with interrelated effects. Thus, addressing space cooling challenges effectively requires multipronged efforts and a comprehensive approach tailored to a country's specific market conditions. The following discussion presents intervention strategies to help address these barriers and accelerate access to sustainable space cooling effectively.

xxxix Commonly, a discussion of barriers to sustainable cooling or energy efficiency at large includes lack of policy and financial instruments, but we posit that policies, regulations, and financial instruments serve as solutions to the problem. Their lack is not the underlying reason for the problem itself or why the market demand for sustainable cooling practices does not exist.

TABLE 4.1: UNDERLYING MARKET BARRIERS TO SUSTAINABLE SPACE COOLING

MARKET BARRIER	BRIEF DESCRIPTION
Lack of awareness	There is a systemic indifference to or low awareness of the broad benefits of sustainable space cooling, including through building energy efficiency. The general public, as well as the space cooling industry and government stakeholders, is often not sensitized to the need for and benefits of sustainable space cooling practices, including energy-efficient buildings and sustainable cooling equipment and operations. Lack of information on sustainable space cooling practices further perpetuates the challenge.
Lack of transparency	Typically, there is little transparency and verifiability of cost savings of energy-efficient buildings and sustainable cooling equipment. Even though energy-efficient buildings and sustainable cooling equipment have lower life cycle costs, owners, operators, and users of these buildings and cooling infrastructure are often not aware of or not confident in these savings. Lack of reliable normalized data to validate cost savings and other benefits further reinforces the systemic indifference to sustainable space cooling practices.
First-cost bias	An overarching market characteristic that impacts sustainable space cooling is that the decisions made by those specifying and procuring buildings and cooling infrastructure are typically made with a focus on the first cost. Longer-term owners, operators, and users of these buildings and cooling infrastructure have insufficient transparency of performance, lack of clarity or understanding of life cycle costs, or lack of overall awareness and, thus, little motivation to demand better. Without awareness of the longer-term benefits of efficiency and sustainable space cooling options and transparency of the benefits, there is little or no demand. We are left with a market failure where the lowest first cost, which is often the highest life cycle cost, reigns. This focus on first cost is more prevalent with infrequent buyers, such as residential consumers, but is often reinforced by policy with professional buyers who may be compelled to procure the lowest first-cost conforming bid. First-cost bias is particularly prevalent in developing countries where affordability is an important consideration and there may be competing priorities for the cash-in-hand. The combination of up-front affordability and lack of financing drives the buyer to the lowest first-cost option (even when there may be awareness that the overall costs are lower over time).
Split incentives	Often, the purchaser (or developer, in the case of buildings) is not responsible for the energy bills and, therefore, is rarely motivated to pursue cooling equipment energy efficiency or passive cooling measures in buildings—sustainable space cooling options that typically come at a higher first cost. This further reinforces the first-cost bias in the space cooling sector.
Lack of valuation of efficiency	Building efficiency is typically not considered in purchasing and leasing decisions. This is particularly true in developing countries, where awareness and institutional frameworks to support building sector interventions are less mature. Even if examples of efficient buildings exist, there is a lack of appropriate valuation of a building's energy performance, and the markets do not recognize, *nor are they primed* to pay a premium for, a high-performance building, contributing to a lack of market demand for high-performance buildings.

(continued)

TABLE 4.1: CONTINUED

Complexity of choice	Diverse strategies to address space cooling (for example, simple appliances, complex cooling systems, passive cooling, and smart controls and automation systems) and their interplay add significant complexity in selecting the best cooling solution. Consumers lack knowledge of the appropriate applicability of the range of available solutions and as a result, often default to the lowest first cost. Refrigerant options further add to the complexity. There are trade-offs between refrigerant options, as they each have their own environmental, safety, or health considerations. These trade-offs—and the type of cooling applications under which they apply—can be complex and not widely understood. Actual experience at scale with some options is evolving, making it difficult to get a clear picture. For instance, some markets lack safety standards for AC with low GWP but flammable refrigerants, making it difficult for typical consumers to know under which conditions they could be used.
Misaligned policies	Certain policies can inadvertently hinder the adoption of energy efficiency and sustainable space cooling practices. A common example involves subsidies that lower energy prices.[xli] Low energy prices will result in lower returns on investment for energy-efficient buildings, high-efficiency cooling equipment, and retrofits, thus adding further to the barriers that limit the adoption of these practices. Another example involves policies that favor local manufacturing, which prevent best-available technologies from being competitively imported into the country.

Source: Authors, composed by Rocky Mountain Institute.

INTERVENTIONS TO ADDRESS MARKET BARRIERS AND PROMOTE SUSTAINABLE SPACE COOLING EFFECTIVELY

Broadly, opportunities to address market barriers and advance sustainable space cooling practices can be grouped into three overarching strategies that together can overcome the underlying barriers that appear in multiple segments of the market. These strategies encompass the following components:[xl]

- **Policy and regulation.** Establish a supportive policy and regulatory environment.
- **Financing.** Create sustainable financing and enabling mechanisms.
- **Supporting instruments.** Enhance consumer and stakeholder awareness, strengthen institutional and professional capacities, and promote technology advancement.

Within each of the overarching strategies, we discuss specific interventions that can promote sustainable space cooling practices, collectively referred to as **sustainable space cooling interventions.** This

xl Policies to reform energy pricing and tariffs (which would have an impact beyond incentivizing energy efficiency in cooling) are beyond the scope of this publication. More information on this topic is available at the website for the Energy Sector Management Assistance Program's Energy Subsidy Reform Technical Assistance Facility, https://www.esmap.org/energy_subsidy_reform.

section provides an overview of the interventions. Greater detail, including over 100 real-world examples covering implementation of these interventions and related insights, is included in the Compendium.

Interventions in this primer are meant to be options to inform strategies, implementation mechanisms, and road maps for countries that are seeking to increase sustainable space cooling through a combination of reducing cooling loads, serving cooling needs efficiently, and optimizing and controlling cooling loads. There is not one “right” solution, as each country’s context and need will vary. For instance, many developing countries may face greater barriers from institutional capacities, regulatory frameworks, and enabling financial mechanisms, and as a result, some of the interventions may not immediately apply without first taking the steps to build initial demand. As an example, without policy measures to build awareness and transparency, which are foundational to establishing market demand, it would make little sense to prioritize interventions that help bolster supply, such as financing and capacity building. Each country, thus, will need to develop its own path according to its priorities, opportunities, and constraints.

On the same note, while interventions are presented in a certain sequence, the sequence is not meant to be prescriptive. The sequencing of interventions, as presented in this primer, is based on an assessment of the relative ease of implementation, required resources, and critical interdependencies. However, depending on a country’s context and priorities, a different sequence may serve its needs better.

Establish a Supportive Policy and Regulatory Environment

In some regions of the world, policies and regulations have helped push buildings and cooling appliances to be more energy efficient over time, but these pushes have been incremental and unequal. In many countries, these policies either do not exist or are not implemented due to enforcement challenges. Given the lack of demand signals in combination with minimal or no policy push, the space cooling industry—particularly in the residential sector—has little motivation to advance technologies beyond regulated minimums. Similarly, building construction stakeholders typically have very little motivation to invest in efficient buildings that employ climate-appropriate passive cooling strategies, either during new construction or through building renovations, particularly when they come at a cost premium.

Common reasons resulting in an inadequate policy push toward sustainable space cooling include the following:

- Addressing cooling sustainably through energy-efficient buildings and efficient technologies and practices can take a lower priority among other pressing national (or local) priorities, particularly in the context of developing economies.
- The cross-cutting nature of cooling means that addressing cooling falls across several existing government agencies. As such, typically there is no single government entity (for example, “Ministry of Cooling”) to lead a unified policy action on cooling. Sustained inter-ministerial collaboration is required to prioritize action.
- There is a perception, or concern, that advancing sustainability of space cooling (such as accelerating energy efficiency of cooling equipment) comes at the cost of up-front affordability.[xli]

xli In contrast to the perception, efficiency and costs can be decoupled and there is evidence—such as Japan’s Top Runner Program—that costs have lowered or remained static even after improving the efficiency and performance standards of cooling equipment. This is discussed in more detail in P3 in the Compendium.

- There may be inadequate institutional capacities and skills among policy-making entities to advance sustainable space cooling. Thus, policies—even when they exist—may face implementation and enforcement challenges.

- There may be concern that local manufacturers may not have the capacity to meet higher energy efficiency standards.[xlii]

A supportive policy and regulatory environment, including government leadership by example, is a critical enabler of the right ecosystem to scale up access to sustainable space cooling practices. Active government intervention to enable markets to operate logically toward the lowest life cycle and system cost solutions will send the necessary signals to industry, driving and accelerating the adoption of best practices and innovation in sustainable space cooling.

In this context, the Energy Efficiency segment of the Regulatory Indicators for Sustainable Energy (RISE) provides a good overview of the elements that are generally considered good practice for setting up and enabling a regulatory or policy framework.[80, xliii]

Sustainable space cooling interventions discussed in this publication for facilitating a supportive policy and regulatory environment are summarized below (with more details and implementation examples in the Compendium).

Policy Interventions

P1. Conduct a country-specific assessment of the cooling landscape to build a case for sustainable space cooling and assess the need to elevate it as a government priority

A macro-level cooling assessment is suggested as a foundational intervention for any country as it presents a data-backed context to build the case for integrated and prioritized actions toward sustainable space cooling, and it can help catalyze alignment among stakeholders. Assessment findings can also provide baseline conditions and a readiness indicator for other interventions, including the appropriateness and timing of developing a nationwide cooling action plan (see P5 in the Compendium).

A country-specific assessment for cooling should incorporate all growth drivers and other local factors that will impact cooling demand to ensure that the assessment is forward looking and comprehensive. It should highlight the whole-system impacts of cooling growth and the benefits of addressing it proactively to support evidence-based policy making.

P2. Leverage labeling as an effective, low-cost way to orient consumers toward sustainable purchasing decisions

Energy labeling of cooling products and technologies enables consumers to compare the efficiency of different products and consider it in their buying decisions. Effective labeling programs can help increase awareness about and drive demand for sustainable space cooling and can deliver a significant impact at relatively low cost to the government.

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xlii While a valid concern, there is evidence that adequate and timely signals to the manufacturers to invest in innovation and research and development have enabled manufacturers to offer energy-efficient products to the market. This is discussed in P3 in the Compendium.
xliii While the 12 energy-efficiency indicators presented in Regulatory Indicators for Sustainable Energy (RISE) encompass the multidimensional aspects of energy efficiency at large, some specific indicators (such as labeling systems, building energy codes, minimum energy performance standards, and financing mechanisms) are very applicable to space cooling.

This intervention, given its fewer dependencies or prerequisites to be effective, should be considered one of the basic policy mechanisms that any country should have in place to advance sustainable space cooling practices. Labeling programs should be reinforced with parallel strategies, in particular, information and communication targeted at consumers and mechanisms to address the first-cost barrier typically faced with purchasing more energy-efficient cooling equipment. Establishing standardized systems, ensuring access to infrastructure for testing and certification of sustainable cooling equipment, and ensuring sufficient capacity for administering the labeling program are also important factors to support effective implementation.

(This intervention focuses on the labeling of cooling products and technologies. Labeling for energy-efficient buildings—due to differing enabling parameters and factors—is discussed separately in P6.)

P3. Establish minimum energy performance standards of cooling equipment and a mechanism to ratchet them up

Minimum energy performance standards (MEPS) set an “energy efficiency floor” below which appliances cannot be sold. By eliminating the lowest-performing appliances, MEPS effectively raise the average efficiency of appliances sold in the market. Establishing MEPS, if they do not already exist, is a key foundational policy intervention. Once established, the standards should be followed by a mechanism to ratchet up MEPS that automatically triggers to update MEPS periodically with reference to major regional or country efficiency benchmarks. An effective approach is to develop MEPS as part of an integrated policy approach, complemented with labeling programs, consumer and market awareness, and, potentially, incentives for consumers. Collectively, these strategies can accelerate meaningful adoption of energy-efficient equipment. Establishing monitoring, verification, and enforcement mechanisms is also key to ensure compliance with MEPS.

P4. Catalyze the market by leading by example through government budgeting and procurement strategies for energy-efficient buildings and sustainable cooling equipment

As large owners or lessees of buildings and purchasers of cooling equipment and systems, governments have a huge opportunity to save money and reduce their environmental impact by following sustainable space cooling strategies. In addition, their example can serve to instill confidence across the private sector and help drive down costs of sustainable space cooling.

Government lead-by-example strategies may first apply to efficient or sustainable cooling equipment, as they may be easier to implement and involve fewer interdependencies (compared to those for buildings). Lead-by-example strategies for energy-efficient buildings may generally require greater government oversight capacity. Training, tools, and incentives should be leveraged to modify procurement behavior toward energy-efficient or green procurement (supported by life cycle cost analysis) as the default option. It is important to monitor compliance and track impacts of initiatives for continuous improvement.

P5. Develop a nationwide cooling action plan or road map with meaningful targets and expected impacts

Such macro-level policy initiatives can define a comprehensive strategic vision for the country, create alignment between the necessary solution linkages across all barrier categories, harmonize efforts to use an integrative approach address the cross-cutting nature of cooling, and generate alignment among public and private entities to prioritize action toward sustainable space cooling. Developing a nationwide cooling action plan should typically be a cross-functional and collaborative intervention. Therefore, it may be important to first ensure critical stakeholder alignment on cooling as a priority area for action. Thus, while foundations and preparations can commence in the short term (such as during the country-specific cooling assessment in P1), it may take some time to fully develop a nationwide cooling action plan. Such an action plan should adopt a holistic approach to address cooling and establish clear actionable pathways for systemic change. The action plan should align with existing national priorities and policies, such as refrigerant transition plans, energy-efficiency targets, and nationally determined contributions.

Taking a cue from, and in alignment with, the national cooling action plan, subnational cooling action plans could be developed as well, for supplementing the national vision with action at local levels.

P6. Cultivate market demand for energy-efficient buildings by increasing visibility of building energy performance

Visibility of building energy performance helps the market place a value on energy-efficient buildings with lower operating costs. Visibility of building energy performance is achieved through building energy performance rating systems (asset ratings or operational ratings) and building energy disclosure requirements.

Countries may find it easier (or more palatable) to start with a voluntary rating system for new buildings, which can be made mandatory as market readiness increases. Once the institutional frameworks are advanced enough to take up existing building intervention models, the rating systems can be expanded to existing buildings. Developing (or leveraging existing) tools and capacities to manage building energy data and certify buildings will be important to ensure effective implementation. Bringing building sector stakeholders (including bodies representing architects, engineers, builders, developers, and auditors) on board will also be important.

P7. Accelerate the adoption of passive cooling strategies through national building energy codes with a robust enforcement mechanism

Building energy codes are regulations that aim to reduce building energy use. They typically apply to the building envelope, and can also incorporate codes and standards applicable to heating, ventilation, and air-conditioning (HVAC) systems, lighting, and water heating systems. They have potential for a large impact by locking in thermal efficiencies that will persist for the lifetime of each building. These strategies can be, generally, most holistically and cost-effectively integrated into a building during its design and construction (compared to in an existing building), when the incremental cost is at its lowest.

Establishing building energy codes typically starts with the engagement process for the development of new building codes. In parallel, establishing robust enforcement mechanisms, along with the appropriate training and tools for local authorities, is critical. Where the institutional frameworks are advanced enough to take up existing building intervention models, energy code adoption for new buildings can be expanded to existing buildings where a major renovation project triggers application of code.

Create Sustainable Financing and Enabling Mechanisms

Even when the right policy and regulatory systems are in place, financing and enabling mechanisms are often required to support and enable broader access to sustainable space cooling practices. Most markets, in particular in developing economies, see a lack of **fit-for-purpose financing** that can allow facility owners and consumers to procure the usually higher first-cost sustainable cooling equipment or energy-efficient buildings. This lack of fit-for-purpose financing is closely tied to the market barriers. As several of those barriers—such as awareness, transparency, and valuation of efficiency—are effectively addressed by policy and regulatory systems, the risks associated with financing sustainable cooling begin to lessen, creating an environment where financing and enabling mechanisms can be more effectively deployed.

Related to, and in parallel with, the market barriers, several factors contribute to the lack of access to financing, including the following:

- **Credit risk.** Financiers are generally unable to securitize against assets delivering energy savings because the cooling assets—both the equipment and building energy-efficiency measures—are usually integrated into the fabric of a building as a whole, which is itself generally indebted and could also be subject to fractional ownership in some cases.
- **Performance risk.** Energy performance is not transparent or immediately visible and is difficult to measure on a normalized basis with precision. The challenge is further compounded by a lack of standardization of measurement and verification practices for savings. Due to the uncertainty of energy savings, financiers are generally unable to securitize financing against sustainable space cooling energy savings.
- **Lack of access to affordable financing.** To address the uncertainty around performance and credit risks associated with sustainable space cooling interventions and resulting structural complexity, financiers will charge higher interest rates. This concern is particularly common in developing countries where experience and expertise in building energy efficiency have yet to be established.
- **Accounting considerations.** Due to the nature of projects pertaining to space cooling (that is, cooling assets being integrated into a building), there may be considerable complexity around who owns the financed assets, which can lead to accounting ambiguity around who records debt and whether the company delivering the project is able to even record a sale on the transaction. See Annex 2 for further discussion on the importance of accounting considerations in structuring fit-for-purpose financing.

With fit-for-purpose financing, demand for sustainable space cooling practices can be enabled, in turn leading to faster innovation and adoption of sustainable space cooling practices. Sustainable space cooling intervention strategies discussed in this publication to facilitate such enabling mechanisms are summarized below (with more details and implementation examples in the Compendium).

Financing Interventions

F1. Create incentive mechanisms to shift the market toward sustainable space cooling

In this publication, "incentives" are defined as any financial instrument designed to stimulate a transition to sustainable space cooling. Incentives can help address the first-cost bias among end-users—particularly in the price sensitive low- and middle-income groups, and generally entry-level buyers—by helping offset the typically higher first cost of efficient cooling equipment. By increasing market penetration of sustainable cooling solutions, incentive programs can thus help manufacturers achieve economies of scale and learning effects. Incentives can also be applied to spur investment in energy-efficient buildings.

This intervention can be used, where feasible, to reinforce desired policy outcomes by accelerating demand for sustainable space cooling in less mature markets. Incentive mechanisms should be carefully designed and well-calibrated and targeted to avoid misuse and to meet intended objectives. Incentives (and subsidies) should be structured in a way that allows them to be phased out and supplanted with appropriate market instruments as market adoption increases.

F2. Aggregate demand to drive down the acquisition cost of sustainable cooling equipment, build market confidence, and spur greater adoption

Demand aggregation is the practice of bringing together a sufficiently large demand for sustainable cooling equipment and leveraging the resulting scale to secure lower prices and higher-quality products from suppliers. Demand aggregation can be led by both the public and private sectors and is generally an effective way to enable bulk procurement to drive down the first cost of sustainable space cooling in markets where a sufficiently large volume of demand aggregation can be ensured. At larger scales, demand aggregation can transform a market, bringing scale to manufacturers and lowering prices for all consumers.

For effective implementation and scaling, demand aggregation programs should be driven by a well-resourced organization, with the necessary commitment from those that it is procuring for. Program design aspects—such as performance-based bid design and integrated procurement strategy—are also important and should be aligned to the market context. (These aspects are discussed in the Compendium.)

F3. Reduce the first cost of sustainable space cooling through debt subsidy and risk mitigation instruments

Affordable and accessible financing for sustainable space cooling allows facility owners and consumers to leverage future energy savings to undertake an energy retrofit of existing buildings or to purchase sustainable cooling equipment. Debt subsidy can lower the cost of capital, and risk mitigation instruments can enhance credit and default risk for commercial lenders. Both are key drivers in encouraging the financial sector to develop and offer sustainable space cooling financing and to help build familiarity and experience with sustainable space cooling, and building energy-efficiency financing in general.

Multiple debt subsidy instruments exist (for example, revolving loan funds and green credit lines) and may be applied as per the maturity level of the respective market and suitability by targeted sector. It is important to target well and ensure sufficient sustainability of underlying subsidies to support the establishment of a market that is able to successfully transition to full commercial self-sufficiency without the need for ongoing public funding.

F4. Implement Cooling as a Service, including district cooling and beyond

Cooling as a Service (CaaS) is an innovative business model that places ownership and operation of cooling equipment with a service provider, with offtakers paying for the availability and use of the cooling they receive rather than the physical product or infrastructure that delivers the cooling. Under this model, incentives are fully aligned: offtakers seek to minimize demand for cooling as a variable cost, and suppliers seek out the lowest life cycle cost of delivering cooling services, procuring the highest-efficiency cooling solution and high-quality operation and maintenance (O&M) practices.

There are two distinct models for this intervention, and the attributes of each determine sector applicability and likelihood of scaling. The first, and by far the largest, of these is the multiple offtaker model, more commonly known as district cooling. District cooling systems are suited to new construction and are relevant where significant new districts or cities are planned and certain preconditions are met. The preconditions include significant anchor loads, building density, and multiple offtakers with diversity in cooling loads, to enable a significant reduction in aggregate cooling capacity.

The second, relatively new model is the single offtaker model, based on a combination of a fixed cooling availability fee and variable cooling usage fee. An understanding of accounting considerations across market sectors is key to successfully structuring single offtaker contracts but can result in increased risk to the service provider. There are a range of risk mitigation strategies that can be incorporated, particularly when designing CaaS for higher-risk market sectors.

F5. Catalyze investment in sustainable space cooling through the development of an energy service company capability

Energy service companies (ESCOs) overcome one of the primary barriers to deploying energy efficiency: project performance risk. ESCOs shift performance risks away from facility owners and energy users and bring commercial finance into the market, allowing the energy-efficiency market to grow.[xliv]

To work effectively, ESCOs require a set of enabling regulatory, market, and financial conditions. Generally, a country may start with simpler ESCO models (for example, ESCO-as-a-borrower models) and then expand to more complex models (for example, facility-owner-as-a-borrower models) that enable larger projects once the market has been established. Providing technical assistance, financial support, and capacity building to ESCOs will help establish market capacity. Newer ESCO markets should also consider establishing a nodal entity to streamline administration of the ESCO program and adopting a standardized contract structure and energy and cost savings calculation methodology.

F6. Expand access to financing for sustainable space cooling through the development of energy service agreements and managed energy service agreements, derivatives of the energy service company model

Energy service agreements (ESAs) and managed energy service agreements (MESAs) are emerging efficiency financing structures that, similarly to ESCO models, overcome the two primary barriers to deploying energy efficiency: lack of availability of financing and project performance risks. Such projects are often undertaken by ESCOs that have developed expertise around project performance risk and measurement and verification practices. The primary difference from the ESCO models described in F5 is that ESAs and MESAs are designed to deliver off–balance sheet treatment for both the facility owner and the ESCO or contractor implementing the project.[xlv]

This intervention is most relevant in countries where the value of energy efficiency is well established and a robust ESCO market exists. Developing standardized contract structures and a savings calculation methodology will help support the emergence of ESA and MESA models. Generally, a country should start with the simpler ESA model and then expand to include the MESA model where assessed market opportunity is felt to be material.

F7. Leverage property assessed clean energy or environmental upgrade financing approaches to lower the first cost of energy-efficient construction

Property assessed clean energy (PACE) and environmental upgrade financing (EUF) are financing mechanisms being used in the United States and Australia, respectively, that enable building

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xliv It should be noted that while energy service company (ESCO) models hold significant potential to scale up energy efficiency, experience to date in most developing countries (with the exception of China) has been mixed due to financing, administrative, or regulatory barriers.

xlv For a comparison of the asset ownership and risk and savings allocation of CaaS with ESCOs, ESAs, and MESAs, please see Annex 3 in the Compendium.

developers (in the case of new construction) and building owners (in the case of existing buildings) to integrate deep efficiency measures in their buildings and have the cost paid off by the future building occupiers as the energy saving benefits accrue. Repayments are made through tax assessments, which are secured by the property. By default, the lien is associated with the property and not the owner, but repayment through property tax becomes the obligation of the current building occupiers each time the building is sold.

This intervention is more suited to new construction and particularly relevant where significant new districts or cities are planned and there is a strong property or land-based taxation program within the country. For successful implementation, strong property or land taxation programs and compliance mechanisms, at both the federal and state levels, are important.

F8. Manage peak cooling loads and cooling energy demand through utility-led demand-side management measures
Utilities, as the electricity network distributors, promote initiatives and technologies that encourage consumers to optimize their energy use. Collectively referred to as demand-side management (DSM), these measures aim to lower the electricity demand, which in turn reduces the energy bills for customers, optimizes the use of power systems and avoids new capacity addition, and brings associated benefits to the environment. Common DSM measures include energy efficiency programs that offer customers incentives to increase efficiency and, therefore, decrease overall electricity demand, and demand response programs that are designed to decrease customer demand during times of very high system demand or emergencies.

Robust financial health of the utilities and an enabling regulatory environment where utilities are mandated or incentivized to deliver on energy-efficiency targets are important for successful utility DSM implementation. While regulatory environments may not be in place in all countries, utility DSM can also make financial sense where the cost of capacity addition exceeds the cost of administering DSM programs. In addition, the unique credit enhancement that comes with on-bill financing can be leveraged by most countries where utility bill collection is robust. A utility's wide customer reach can also be leveraged for messaging to influence sustainable space cooling practices across the entire value chain.

While these interventions demonstrate a range of options, financing and enabling mechanisms will need to be adapted to local realities. What may be a good solution in one country may not be possible to implement or be the best option for another. Developing countries, in particular, will have a particular set of considerations, including weak enabling environments, cash-strapped utilities that may have difficulty financing DSM programs, fewer financial resources, greater difficulty accessing capital, and other important competing socioeconomic priorities. In that context, sustainable space cooling may be difficult to prioritize for allocation of public funding, particularly as cooling may still be perceived as benefitting the wealthier in the population. Also, affordability and first cost would be critical considerations for most of the population in developing countries and hence financial support instruments for consumers will play a critical role. Thus, financial and implementation models would have to be tailored accordingly and consider features such as (but not limited to) diversified funding sources, minimized consumer first costs, and mitigated perceived risk through performance guarantees.

Establish and/or Strengthen the Supporting Instruments

Coupling financing and enabling mechanisms with several enabling factors—in parallel with policy measures—can maximize impact and potential benefits. Collectively referred to as "supporting instruments” in this publication, the key enabling factors broadly fall within three categories of action: enhancing user and stakeholder awareness about the benefits of sustainable space cooling, strengthening institutional and professional capacities, and promoting and leveraging technology advancement.

The sustainable space cooling interventions discussed in this primer to facilitate supporting instruments are summarized below (with more details and implementation examples in the Compendium).

Supporting Instruments

S1. Enhance “cooling awareness,” or awareness of the importance and benefits of sustainable space cooling practices, to encourage individual actions and behavior changes
While end-users are typically seen as the key target audience for cooling awareness, advancing awareness across all stakeholder groups—such as policy makers, procurement officers, retailers, and lending institutions—helps promote decisions and actions that support and advance sustainable space cooling. The impact of almost every intervention can be maximized when accompanied by informed and aware users and stakeholders. This cross-cutting intervention can be applied in multiple phases per the local context and should reinforce contextualized messages that make the benefits of sustainable space cooling relatable.

S2. Build capacity in critical institutions, as well as among trade professionals and the buildings and heating, ventilation, and air-conditioning service sector
The term “capacity building” in this context refers to ensuring adequately skilled resources in regulatory and policy bodies and other critical institutions, and developing technical capacity within the trade institutions, including upskilling in the HVAC service sector, as well as complementing capacity building with adequate supporting infrastructure to effectively advance sustainable space cooling. Capacity building is a critical aspect to ensure appropriate enforcement and implementation of policy measures, as well as adequate delivery of sustainable space cooling solutions and services. This is a cross-cutting intervention that can increase the effectiveness and impact of other interventions, and it can be applied in multiple phases per local context.

S3. Leverage ongoing refrigerant technology transition activity (as required under the Kigali Amendment) to integrate energy efficiency in cooling equipment and maximize benefits
This intervention targets the manufacturing sector and is thus most relevant in countries with a sizable manufacturing base for cooling equipment. Such countries should create a policy push to drive the industry toward harmonizing refrigerant transition with the energy efficiency of sustainable cooling equipment. Studies suggest that integrating the ongoing refrigerant transition (hydrochlorofluorocarbon [HCFC] phaseout and hydrofluorocarbon [HFC] phasedown efforts under the Kigali Amendment to the Montreal Protocol) with efficiency improvements in cooling technologies could make the most impact for the lowest cost, potentially doubling the climate benefits of the Kigali Amendment. Technology transfer initiatives should be supplemented with adequate capacity building and training.

S4. Support and leverage a research and development, and innovation ecosystem that enables technology advancement
A research and development (R&D) and innovation ecosystem that involves all cooling stakeholders is important to promote technology advancement, which, in turn, allows policies and financial programs to have greater impact. Given the global context of cooling, international collaborations are important to leverage globally dispersed centers of excellence. In-country efforts should consider

alignment with best practices across national borders while being cognizant of domestic market readiness. In addition to promoting an R&D ecosystem, countries should also ensure signals of future demand to catalyze innovation in sustainable cooling equipment.

S5. Incorporate strategies to enable access to cooling in off-grid or weak-grid locations
This intervention is applicable in areas where a sizable portion of the population is in off-grid or weak-grid locations, to ensure adequate access to cooling for this population. An estimated 16 percent of the world's population has little or no access to electricity,[81] and a sizable share of this population lives in hot and tropical climates. In view of rising temperatures and the growing need for cooling, exploring viable off-grid options for cooling is important to expand cooling access to such communities. Successful strategies include comprehensive solutions that meet consumers' ability and willingness to pay through low-cost cooling technologies coupled with innovative business models or programs. Accelerating R&D for off-grid cooling solutions is also important.

The above overview covers diverse examples of cooling interventions, with the objective to inform strategies and options for countries that are seeking to increase sustainable space cooling. These interventions are discussed in more detail in the Compendium, including examples from across the world—both in developed and developing countries[xlvi]—with an aim to highlight real-life successful implementation and the respective key insights learned. The Compendium also seeks to serve as a reference for readers seeking more detailed information on sustainable space cooling.

Two noteworthy and broadly applicable considerations with respect to the above interventions are:

- The integrative effects of interventions working in combination, in general, will be greater than those of individual interventions. For instance, the impacts and benefits of policy measures can be maximized with measures to advance appropriate institutional capacities and enhance users' and stakeholders' awareness in parallel; catalyzing financing for sustainable space cooling will benefit from a multipronged approach, including investment support and appropriate market-based instruments, underpinned with institutional support and capacity building. Thus, addressing cooling challenges effectively will typically require a multipronged approach incorporating a combination of interventions (for example, information, policies and regulations, institutional capacities, financing and business models, and R&D) that are tailored to a country's market conditions.
- While navigating a pathway to sustainable space cooling, it is good practice for countries to include periodic assessments of interventions to make sure that they are still effective and serve their purpose, and to explore areas for improvement or additional interventions.

xlvi While the emphasis has been on presenting examples from developing countries to the extent possible, the Compendium contains a substantial number of examples from developed countries, simply because these are the countries where there has been more activity over a longer time to advance sustainable space cooling.

Convention Center Parking Garage and Cooling Plant, Austin, Texas.
Credit: Barnes Gromatzky Kosarek Architects © 2005 emphaticcreative.net

5. AN ILLUSTRATIVE IMPLEMENTATION ROAD MAP FOR ADVANCING SUSTAINABLE SPACE COOLING

Multiple factors will be at play in any given country, and cooling interventions will have to be tailored to local needs, contexts, and opportunities. While there is no single strategy or road map that will work equally well for every country, in this section we present a guiding framework as an illustrative road map for possible prioritization of the interventions discussed in this publication.

The suggested framework is structured around establishing and strengthening the policy and regulatory enablers as the primary underpinning for scaling up sustainable space cooling. The framework suggests addressing foundational policies and then progressing toward policy interventions that expand positive impacts and bring about systemic changes. In parallel with policy interventions, the framework suggests applying financial and supporting instruments based on the respective country's context and readiness. Using the appropriate financial and supporting instrument interventions in parallel with policy interventions can amplify their impact and maximize potential benefits. Collectively, interventions can advance access to sustainable space cooling by effectively stimulating demand for reducing cooling loads, serving cooling needs efficiently, and optimizing and controlling cooling loads.

The steps of the road map to advance access to sustainable space cooling are discussed in table 5.1. The sequencing of these steps, and the respective interventions, are based on an assessment of the relative ease of implementation, required resources, and critical interdependencies. For instance, it should be noted that while reducing cooling loads in buildings is the foundational strategy toward sustainable space cooling, it is not always an easy first step because of the nature of the barriers and the complexity, dependencies, and resources involved.

The suggested sequence is not meant to be prescriptive. Depending on a country's context, current state, readiness, and priorities, a different sequence may serve its needs better, or some of the interventions could be developed in parallel.

TABLE 5.1: AN ILLUSTRATIVE IMPLEMENTATION ROAD MAP FOR ADVANCING SUSTAINABLE SPACE COOLING

STEP 1: ELEVATE COOLING AS A PRIORITY AREA

The first step generally entails macro-level interventions that a country will have to undertake to establish the context and political will for starting and meaningfully advancing the drive for sustainable space cooling solutions. Even though cooling is closely tied to several Sustainable Development Goals (SDGs), for some nations, cooling may not be a visible problem at present, it may be one among other competing national priorities, or it may not be viewed as critical by all concerned stakeholders. Setting the context by doing an underlying assessment of a country's cooling landscape highlights the current and projected cooling demand and gaps; implications for energy systems, consumers, and emissions; and options to meet the cooling demand. Such context setting also helps to bring alignment among the diverse stakeholders associated with space cooling to prioritize collaborative action. Step 1 is suggested as a first or short-term action for a country looking to advance sustainable space cooling.

Suggested interventions include:	**P1.** Conduct a country-specific assessment of the cooling landscape to build a case for sustainable space cooling and assess the need to elevate it as a government priority **P5.** Develop a nationwide cooling action plan or road map with meaningful targets and expected impacts **S1.** Enhance "cooling awareness," or awareness of the importance and benefits of sustainable space cooling practices, to encourage individual actions and behavior changes

STEP 2: DEVELOP AND IMPLEMENT BASIC POLICIES TO SET THE FOUNDATION FOR SUSTAINABLE COOLING EQUIPMENT, AND LEVERAGE SUPPORTING INSTRUMENTS IN PARALLEL TO STIMULATE THEIR MARKET DEMAND

Interventions in this step can be viewed as foundational policy mechanisms to start scaling up sustainable space cooling practices. This step also includes supporting instruments, such as capacity building, that, when applied in parallel with policy mechanisms, will amplify their impact and effectiveness. Interventions in this step represent a well-established pathway of accessible measures that have been proven to be effective in many (mostly developed) countries and provide useful insights for developing countries seeking to scale up sustainable space cooling. With Step 2 interventions having less dependencies or prerequisites to be effective, they should be considered for implementation in the short term, subject to a country's readiness level and political will.

Suggested interventions include:	**P2.** Leverage labeling as an effective, low-cost way to orient consumers toward sustainable purchasing decisions **P3.** Establish minimum energy performance standards of cooling equipment and a mechanism to ratchet them up **P4.** Catalyze the market by leading by example through government budgeting and procurement strategies for energy-efficient buildings and sustainable cooling equipment **S2.** Build capacity in critical institutions, as well as among trade professionals and the buildings and heating, ventilation, and air-conditioning (HVAC) service sector **S3.** Leverage ongoing refrigerant technology transition activity (as required under the Kigali Amendment) to integrate energy efficiency in cooling equipment and maximize benefits **S4.** Support and leverage a research and development (R&D) and innovation ecosystem that enables technology advancement **S5.** Incorporate strategies to enable access to cooling in off-grid or weak-grid locations

(continued)

TABLE 5.1: CONTINUED

STEP 3: ESTABLISH POLICIES TO STIMULATE MARKET DEMAND FOR AND EXPAND STAKEHOLDER AWARENESS OF ENERGY-EFFICIENT BUILDING PRACTICES THAT SUPPORT SUSTAINABLE SPACE COOLING	
As per the integrated approach (section 3), promoting building energy efficiency and thereby reducing the cooling load of the building sector should be the first line of action toward sustainable space cooling. However, in many cases, policy interventions to drive building energy efficiency, such as through national building energy codes and mandatory energy labeling, can require a substantial level of dependencies and government institutional capacities. Typically, building-related interventions are also more complex to implement (versus interventions for cooling equipment and appliances) and require institutional frameworks that are advanced enough to take up strategies for new and existing building interventions. Hence, these interventions are placed as Step 3 in the framework, but if a country's context permits, energy-efficient construction of buildings should be addressed in conjunction with cooling technology-related interventions for maximizing the positive impacts and progress toward sustainable space cooling. Perhaps a logical place to begin to phase in building energy codes would be large buildings, since these are likely to have a qualified architect and contractors with the skills to meet the requirements and would capture significant impact for a relatively modest mobilization effort. Depending on a country's readiness level and political will—and on the specific measure considered—interventions to advance energy-efficient building practices may be short or medium term.	
Suggested interventions include:	**P6.** Cultivate market demand for energy-efficient buildings by increasing visibility of building energy performance **P7.** Accelerate the adoption of passive cooling strategies through national building energy codes with a robust enforcement mechanism
PARALLEL STEP: APPLY SELECTED FINANCIAL AND ENABLING MECHANISMS IN PARALLEL—AS APPROPRIATE—WITH POLICY AND SUPPORTING INTERVENTIONS TO ENHANCE THEIR EFFECTIVENESS AND SCALE UP A MARKET TRANSITION TOWARD SUSTAINABLE SPACE COOLING	
Even when the right policy, regulatory, and supporting systems are in place, enabling mechanisms of fit-for-purpose financing and market-based business models are required to support and enable broader adoption of sustainable space cooling practices. These interventions (which may take the form of debt subsidies or development of an energy service company [ESCO] capability, among others) are generally cross-cutting in nature and supplement the policy and supporting measures in all aspects of sustainable space cooling: reducing the cooling requirements of the built environment, advancing efficient cooling technologies, and enhancing institutional capacities and stakeholder awareness to accelerate access to sustainable space cooling. A country may implement the financing interventions in this category—noted in relative order of complexity—in the short to long term, subject to its readiness level and political will.	
Suggested interventions include:	**F1.** Create incentive mechanisms to shift the market toward sustainable space cooling **F2.** Aggregate demand to drive down the acquisition cost of sustainable cooling equipment, build market confidence, and spur greater adoption **F3.** Reduce the first cost of sustainable space cooling through debt subsidy and risk mitigation instruments **F4.** Implement Cooling as a Service, including district cooling and beyond **F5.** Catalyze investment in sustainable space cooling through the development of an energy service company capability **F6.** Expand access to financing for sustainable space cooling through the development of energy service agreements and managed energy service agreements, derivatives of the ESCO model **F7.** Leverage property assessed clean energy and environmental upgrade financing approaches to lower the first cost of energy-efficient construction **F8.** Manage peak cooling loads through utility-led demand-side management and financial measures

Source: RMI 2020 © Rocky Mountain Institute.

Santorini Island Oia Greece Greece Europe, sunset at the white village of Oia Santorini with old blue and white Greek churches at dusk Santorini Greece.
Credit: Fokke baarssen/shutterstock.

ANNEX 1. SUMMARY OF INTERVENTION EXAMPLES INCLUDED IN THE COMPENDIUM

Note: The “Components of the Project/Program” is indicative of the respective intervention under which a particular project is discussed and is not intended to indicate the full scope of the project.

		COMPONENTS OF THE PROJECT/PROGRAM																			
		COOLING ASSESSMENT	APPLIANCE LABELING	MEPS	GOVERNMENT LEAD-BY-EXAMPLE	NATIONAL COOLING ACTION PLANS	BUILDING ENERGY VISIBILITY	BUILDING ENERGY CODES	INCENTIVE MECHANISMS	DEMAND AGGREGATION	DEBT SUBSIDY	CaaS	ESCOs	ESAs	PACE AND EUF	UTILITY-LED DSM	AWARENESS	CAPACITY BUILDING	INTEGRATE EE AND REFRIGERANT TRANSITION	R&D ECOSYSTEM	OFF-GRID TECHNOLOGIES
COUNTRY	**NAME**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**S1**	**S2**	**S3**	**S4**	**S5**
Armenia	Armenia Energy Efficiency Project, World Bank													X							
Australia	Australia Energy Labels		X																		
	Policy on Energy Efficiency in Government Operations				X																
	National Australian Built Environment Rating System (NABERS)						X														
	Environmental Upgrade Financing (EUF)														X						
Bangladesh	Barrier Removal to the Cost-Effective Development and Implementation of Energy Efficiency Standards and Labeling (BRESL)*		X	X																	
	Walton Hi-Tech Industries Ltd.																		X		
Brazil	Energy-Efficiency Testing with Daikin									X											
Canada	Canadian Provinces' PACE														X						
China	Appliance Energy Label		X														X				
	MEPS			X																	
	Green and High-Efficiency Cooling Action Plan					X															
	BRESL*		X	X																	
	Building Energy Label						X										X				
	Building Energy Codes							X													
	Promoting Energy-Efficient Products for the Benefit of the People								X												
	China's ESCO Market												X								

*Barrier Removal to the Cost-Effective Development and Implementation of Energy Efficiency Standards and Labeling.

COUNTRY	NAME	COMPONENTS OF THE PROJECT/PROGRAM																			
		COOLING ASSESSMENT	APPLIANCE LABELING	MEPS	GOVERNMENT LEAD-BY-EXAMPLE	NATIONAL COOLING ACTION PLANS	BUILDING ENERGY VISIBILITY	BUILDING ENERGY CODES	INCENTIVE MECHANISMS	DEMAND AGGREGATION	DEBT SUBSIDY	CaaS	ESCOs	ESAs	PACE AND EUF	UTILITY-LED DSM	AWARENESS	CAPACITY BUILDING	INTEGRATE EE AND REFRIGERANT TRANSITION	R&D ECOSYSTEM	OFF-GRID TECHNOLOGIES
		P1	P2	P3	P4	P5	P6	P7	F1	F2	F3	F4	F5	F6	F7	F8	S1	S2	S3	S4	S5
Czech Republic	Program EFEKT												X								
France	Paris District Cooling Project											X									
Germany	Berlin Energy Agency																	X			
India	Demand Analysis for Cooling by Sector in India in 2027	X																			
	Bureau of Energy Efficiency (BEE) Standards & Labeling Program		X														X				
	BEE—Strategy for Energy Efficiency Campaigns																X				
	India MEPS			X																	
	Central Government Directive on Procurement of Energy-Efficiency Appliances				X																
	India Cooling Action Plan (ICAP)					X												X			
	Green Rating for Integrated Habitat Assessment (GRIHA)						X										X				
	Energy Conservation Building Code (ECBC)							X													
	Reliance Infrastructure Ltd.—Five-Star Split AC Pilot Program								X												
	Smart Grid Vision and Roadmap for India															X					
	Tata Power's Voluntary Pilot Demand Response Program															X					

		COMPONENTS OF THE PROJECT/PROGRAM																			
		COOLING ASSESSMENT	APPLIANCE LABELING	MEPS	GOVERNMENT LEAD-BY-EXAMPLE	NATIONAL COOLING ACTION PLANS	BUILDING ENERGY VISIBILITY	BUILDING ENERGY CODES	INCENTIVE MECHANISMS	DEMAND AGGREGATION	DEBT SUBSIDY	CaaS	ESCOs	ESAs	PACE AND EUF	UTILITY-LED DSM	AWARENESS	CAPACITY BUILDING	INTEGRATE EE AND REFRIGERANT TRANSITION	R&D ECOSYSTEM	OFF-GRID TECHNOLOGIES
COUNTRY	**NAME**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**S1**	**S2**	**S3**	**S4**	**S5**
India (cont.)	BSES Rajdhani Power Limited's Behavioral Energy Efficiency Pilot Program															X					
	Amravati District Cooling Project											X									
	Gujarat International Finance Tec-City (GIFT City)											X									
	Lodha Group Bulk Purchasing									X											
	EESL Super-efficient Air Conditioning Program (ESEAP)									X											
	EESL Partial Risk Sharing Facility (PRSF) project												X					X			
	EESL's Unnat Jyoti by Affordable LEDs for All (UJALA)									X			X								
	EESL's India Energy Efficiency Scale-Up Program																	X			
Indonesia	GREENSHIP						X										X				
	BRESL*		X	X																	
	Promoting Energy Efficiency for Non-HCFC Refrigeration and Air Conditioning (PENHRA)																		X		
Japan	Top Runner Program		X	X																	
	Green Purchasing Network				X																
	Japan's Eco-Point System								X												

*Barrier Removal to the Cost-Effective Development and Implementation of Energy Efficiency Standards and Labeling.

		COMPONENTS OF THE PROJECT/PROGRAM																			
		COOLING ASSESSMENT	APPLIANCE LABELING	MEPS	GOVERNMENT LEAD-BY-EXAMPLE	NATIONAL COOLING ACTION PLANS	BUILDING ENERGY VISIBILITY	BUILDING ENERGY CODES	INCENTIVE MECHANISMS	DEMAND AGGREGATION	DEBT SUBSIDY	CaaS	ESCOs	ESAs	PACE AND EUF	UTILITY-LED DSM	AWARENESS	CAPACITY BUILDING	INTEGRATE EE AND REFRIGERANT TRANSITION	R&D ECOSYSTEM	OFF-GRID TECHNOLOGIES
COUNTRY	**NAME**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**S1**	**S2**	**S3**	**S4**	**S5**
Kenya	Kenya MEPS			X														X			
	Community Solar Nano-Grid (SONGs)																				X
Mexico	Efficient Lighting and Appliances Project								X							X					
	EcoCasa Green Mortgages										X										
Nigeria	M-Kopa																				X
Pakistan	BRESL*		X	X																	
	Punjab—Standardization and Labeling		X																		
	Punjab Energy Efficiency and Conservation Agency (PEECA)		X															X			
Philippines	Philippines Efficient Lighting Market Transformation Project (PELMATP)																	X			
Republic of Korea	Republic of Korea Government Purchasing				X																
	Republic of Korea Carbon Cashbag Program								X												
Rwanda	Rwanda Cooling Initiative	X																			
	Rwanda National Cooling Strategy	X				X															
	Coolease											X									
Singapore	Singapore Building and Construction Authority's (BCA) Green Mark						X										X				
	The Marina Bay District Cooling Project											X									
	The National Environment Agency of Singapore Website																X				

*Barrier Removal to the Cost-Effective Development and Implementation of Energy Efficiency Standards and Labeling.

		COMPONENTS OF THE PROJECT/PROGRAM																			
		COOLING ASSESSMENT	APPLIANCE LABELING	MEPS	GOVERNMENT LEAD-BY-EXAMPLE	NATIONAL COOLING ACTION PLANS	BUILDING ENERGY VISIBILITY	BUILDING ENERGY CODES	INCENTIVE MECHANISMS	DEMAND AGGREGATION	DEBT SUBSIDY	CaaS	ESCOs	ESAs	PACE AND EUF	UTILITY-LED DSM	AWARENESS	CAPACITY BUILDING	INTEGRATE EE AND REFRIGERANT TRANSITION	R&D ECOSYSTEM	OFF-GRID TECHNOLOGIES
COUNTRY	**NAME**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**S1**	**S2**	**S3**	**S4**	**S5**
South Africa	PACE Program (under development at the time of the publication)														X						
Thailand	BRESL*		X	X																	
	Electricity Generating Authority of Thailand (EGAT) Labeling Program		X																		
	HCFC Phaseout Management Project																		X		
United Kingdom	Engineering and Physical Sciences Research Council of the United Kingdom's Strategic Plans and Annual Delivery Plans																			X	
United States	Energy Star		X				X										X				
	United States MEPS			X																	
	United States Government Procurement Policies				X																
	Home Energy Rating System (HERS)						X														
	Boston Building Energy Disclosures						X										X				
	New York City Building Energy Disclosures						X										X				
	Home Energy Score						X										X				
	United States Building Energy Codes							X													
	Massachusetts Building Energy Code							X													
	Virginia Beach Building Energy Code							X													
	California Green Building Standards (CALGreen)							X													

*Barrier Removal to the Cost-Effective Development and Implementation of Energy Efficiency Standards and Labeling.

		COMPONENTS OF THE PROJECT/PROGRAM																			
		COOLING ASSESSMENT	APPLIANCE LABELING	MEPS	GOVERNMENT LEAD-BY-EXAMPLE	NATIONAL COOLING ACTION PLANS	BUILDING ENERGY VISIBILITY	BUILDING ENERGY CODES	INCENTIVE MECHANISMS	DEMAND AGGREGATION	DEBT SUBSIDY	CaaS	ESCOs	ESAs	PACE AND EUF	UTILITY-LED DSM	AWARENESS	CAPACITY BUILDING	INTEGRATE EE AND REFRIGERANT TRANSITION	R&D ECOSYSTEM	OFF-GRID TECHNOLOGIES
COUNTRY	**NAME**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**S1**	**S2**	**S3**	**S4**	**S5**
United States (cont.)	City of Seattle Building Energy Code							X													
	Mass Save								X							X					
	United States Energy Efficiency Home Building Tax Credit								X												
	Upstream HVAC and Heat Pump Program Administered by National Grid								X												
	Advanced Rooftop Unit Campaign									X											
	California's SmartAC Program															X					
	Energy Efficiency Resource Standard (EERS)															X					
	New Jersey's Clean Energy Program															X					
	United States Property Assessed Clean Energy (PACE) Financing														X						
	The United States ESCO Market												X								
	Metrus Energy ESA Provider													X							
	Home Energy Reports (HERs)																X				
	Opower by Oracle																X				
	United States Department of Energy Strategic Plans																			X	
Vietnam	BRESL*		X	X																	

*Barrier Removal to the Cost-Effective Development and Implementation of Energy Efficiency Standards and Labeling.

REGION	NAME	COOLING ASSESSMENT P1	APPLIANCE LABELING P2	MEPS P3	GOVERNMENT LEAD-BY-EXAMPLE P4	NATIONAL COOLING ACTION PLANS P5	BUILDING ENERGY VISIBILITY P6	BUILDING ENERGY CODES P7	INCENTIVE MECHANISMS F1	DEMAND AGGREGATION F2	DEBT SUBSIDY F3	CaaS F4	ESCOs F5	ESAs F6	PACE AND EUF F7	UTILITY-LED DSM F8	AWARENESS S1	CAPACITY BUILDING S2	INTEGRATE EE AND REFRIGERANT TRANSITION S3	R&D ECOSYSTEM S4	OFF-GRID TECHNOLOGIES S5
		COMPONENTS OF THE PROJECT/PROGRAM																			
Africa	World Bank Group’s Lighting Africa Program																				X
Southeast Asia	Association of Southeast Asian Nations Harmonization of Test Standards		X																		
	ASEAN Regional Policy Roadmap for Harmonization of Energy Performance Standards for Air Conditioners			X																	
European Union	European Union Energy Labels		X																		
	European Union MEPS (Ecodesign Directive)			X																	
	Energy Performance of Buildings Directive						X										X				
	Energy-Efficient Mortgages Action Plan										X										
	EuroPACE														X						

		COMPONENTS OF THE PROJECT/PROGRAM																			
		COOLING ASSESSMENT	APPLIANCE LABELING	MEPS	GOVERNMENT LEAD-BY-EXAMPLE	NATIONAL COOLING ACTION PLANS	BUILDING ENERGY VISIBILITY	BUILDING ENERGY CODES	INCENTIVE MECHANISMS	DEMAND AGGREGATION	DEBT SUBSIDY	CaaS	ESCOs	ESAs	PACE AND EUF	UTILITY-LED DSM	AWARENESS	CAPACITY BUILDING	INTEGRATE EE AND REFRIGERANT TRANSITION	R&D ECOSYSTEM	OFF-GRID TECHNOLOGIES
GLOBAL	**NAME**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**S1**	**S2**	**S3**	**S4**	**S5**
	Basel Agency for Sustainable Energy (BASE)—CaaS Initiative											X									
	Leadership in Energy and Environmental Design (LEED)						X										X				
	International Institute for Energy Conservation (IIEC)																	X			
	International Energy Agency (IEA)																	X			
	TEAP Decision XXVIII/3 Report																		X		
	GIZ Green Cooling Initiative																		X		
	Gavi, the Vaccine Alliance’s Demand Aggregation																			X	
	Advanced Cooling Challenge (ACC)																			X	
	The Global Cooling Prize																			X	
	Mission Innovation																			X	
	CLASP’s Platform for Off-grid Appliances																				X
	Engineers Without Borders Chill Challenge																				X
	Efficiency for Access Coalition’s Low-Energy Inclusive Appliances (LEIA) Program																				X
	Global LEAP Awards																				X
	Global LEAP Off-Grid Appliance Procurement Incentives Program																				X
	Topten (consumer-oriented online search tool for appliances)																X				
	World Bank Group’s Green Bonds										X										

ANNEX 2. ACCOUNTING CONSIDERATIONS

In structuring and evaluating the potential efficacy of financing and enabling mechanisms against different sectors of the market, it is critical to understand the impact of accounting considerations—especially in relation to the private sector, where the impact is the greatest.

This is highlighted where relevant throughout the handbook, but to fully appreciate the importance of this topic, it is helpful to understand what drives companies and corporations to care about accounting considerations.

It starts with an established strong correlation between the financial measure of return on invested capital (ROIC),[82] which together with expectations of future growth drives overall company valuations, and overall company debt capacity. This correlation drives internal company metrics, which in turn drive market behavior and focus.

The first of these metrics, the numerator, is to maximize near-term return (profit), and profit is recognized when revenue (sales) are recorded. The recognition of revenue does not necessarily correlate to cash in the short term, and it is important to recognize the difference, as while a transaction can be cash neutral (or even positive) for a company, if it results in a deferral of revenue recognition, the return is deferred and the transaction will be viewed internally as less attractive.

The other primary metric flowing from ROIC is invested capital, which comprises equity and debt. Together they are the denominator of ROIC, and a smaller denominator is desired, driving internal metrics toward this outcome. As a result, transactions that create debt for a company will be viewed less favorably and may even be prohibited under internal guidelines or restricted by a requirement for higher returns associated with such transactions. Further, in some jurisdictions there are statutory debt constraints in the form of maximum permissible debt to equity ratios, where increased debt can result in a requirement to raise additional equity.

Whereas the return or revenue recognition component is a consideration unique to the implementing party (that is, an energy service company [ESCO]), the desire to minimize invested capital will lie with both the implementing party and the facility owner, with the facility owner typically seeing a solution with off–balance sheet potential as considerably more attractive.

In reviewing the efficacy of any financial intervention, understanding the timing of revenue recognition (sales treatment) and debt characterization for each of the parties involved is a critical consideration.

A bird's eye view of the terraces of the Principality of Monaco.
Credit: FineBokeh/istock.

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