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Working Paper

Future-proofing sustainable cooling demand

ADB Working Paper, No. 1316

Provided in Cooperation with:

Asian Development Bank Institute (ADBI), Tokyo

Suggested Citation: Peters, Toby; Sayin, Leylan (2022) : Future-proofing sustainable cooling demand, ADB Working Paper, No. 1316, Asian Development Bank Institute (ADBI), Tokyo

This Version is available at:

<https://hdl.handle.net/10419/267774>

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ADB Working Paper Series

**FUTURE-PROOFING SUSTAINABLE
COOLING DEMAND**

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No. 1316
May 2022

Asian Development Bank Institute

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Suggested citation:

Peters, T. and L. Sayin. 2020. Future-Proofing Sustainable Cooling Demand. ADBI Working Paper 1316. Tokyo: Asian Development Bank Institute. Available: <https://www.adb.org/publications/future-proofing-sustainable-cooling-demand>

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Abstract

The global cooling demand is expected to grow substantially during the 21st century. Apart from the increasing temperatures due to climate change, this demand will also be driven by a set of demographic characteristics, including population growth, urbanization, increasing incomes, social policies and commitments, and improved access to electricity. Indeed, space cooling demand could increase by 300% globally by 2050 and is concentrated in the hotter regions of the world with growing populations and incomes. However, this demand will likely contribute to its own growth if delivered along conventional patterns, significantly increasing GHG emissions due to high energy consumption as well as leakage of refrigerants, and hence compromising many of our economic, environmental, social, and political goals, targets, and commitments. This paper presents a system-level approach to cooling provision in buildings and urban environments, while also highlighting the need for a holistic consideration of the cooling demand across other sectors (e.g., transport), to ensure sustainability and resilience throughout the life cycle of buildings and wider infrastructure. It aims to drive a new system level thinking in key areas – how we mitigate, make, store, move, manage, finance, and regulate cold – to meet current and future cooling needs efficiently, sustainably, and affordably, while building resilience in line with the ambitions of the Paris Agreement, the Kigali Amendment to the Montreal Protocol, and the UN Sustainable Development Goals.

Keywords: cooling demand, urban environment, global warming

JEL Classification: Q2, Q4

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1. INTRODUCTION

Our planet is warming at an alarming rate. The global mean temperature by 2100 could be 3.4–3.9°C higher than before the Industrial Revolution began. Around 74% of the world's population could be exposed to deadly climatic conditions, and direct heat-related deaths could reach more than 255,000 per year by 2050, with impacts expected to be greatest in the South, East, and Southeast Asia regions [1]–[3]. In response, the cooling demand is set to grow substantially with the emerging need to adapt to higher temperatures and to survive in a world with more intense and frequent heatwaves and widespread droughts. This growth in demand is also exacerbated by multiple demographic and developmental changes such as rising populations, urbanization, increasing incomes, and improved access to electricity in developing nations that are often located in the parts of the world that are most vulnerable to climate change. The irony is, however, that conventional active cooling devices already account for more than 10% of global fossil CO₂ emissions, or 7% of all global greenhouse gas emissions (GHG), further warming the planet [4]. In the absence of any intervention, these GHG emissions from cooling may double by 2030, and triple by 2100 [5]. Hydrofluorocarbons (HFCs) are in fact the fastest-growing source of GHG emissions today, mainly due to the increasing global demand for cooling [6]. Yet cooling demand remains a critical blind spot in sustainability and climate debates.

The energy demand for space cooling more than tripled between 1990 and 2016, and it is the fastest-growing energy service in buildings worldwide. In 2016, space cooling accounted for more than 2,020 TWh of electricity, which was nearly 10% of the world's total electricity consumption, and almost 20% of all the electricity used in buildings [7]. Without any intervention, the electricity demand for space cooling could increase by 300%, reaching 6,200 TWh in 2050 – consuming as much electricity as the whole of the People's Republic of China (PRC) and India today [7]. In some hotter regions of the world, the share of space cooling in electricity consumption already reaches staggering numbers. For example, 70% of Saudi Arabia's electricity is used for air conditioning [8]. In India, the share of air conditioning in the peak electricity load is projected to reach 45% in 2050 from 10% today in the absence of any intervention [7].

While today only less than a third of households around the world own an air conditioner,¹ two in every three households around the world are expected to have one by 2050, with the PRC, India, and Indonesia accounting for half of this demand. Due to rising temperatures along with other drivers, many cities in the developing world that currently have a low number of air conditioners will see a big increase in air-conditioning purchases. This surging and highly variable space cooling demand will add massive additional electricity loads to the energy systems. As a result, these cities may struggle to deploy larger-capacity electricity infrastructure into existing urban areas due to limited space [9].

In order to achieve the 1.5°C target of the UNFCCC Paris Agreement, the International Energy Agency (IEA) estimates that direct building CO₂ emissions (refrigerants) need to be reduced by 50% and indirect building emissions (energy) by 60% by 2030 [10]. In this regard, how we deliver cooling in buildings will play a significant role given the increasing demand for energy consumption. However, cooling provision will not only be needed for thermal comfort in the built environment. Additional capacity will also be sought to address cooling needs across health, agriculture, and transport sectors.

¹ In 2018, air conditioner ownership was 90% among households in Japan and the US; however, among the 2.8 billion people living in the hottest parts of the world, air conditioner ownership was only 8% [7].

Projections suggest that the number of cooling devices – air conditioners, fans, and refrigerators – could increase to 9.5 billion globally by 2050 from today's 3.6 billion. Despite this anticipated increase, providing cooling for all who need it, and not just those who can afford it, will require 14 billion devices by 2050 – which is 3.8 times as many devices as are in use today [11]. This is an important issue as providing access to cooling for all is critical to achieving many of the UN's Sustainable Development Goals (SDGs). In parallel with failing to make sufficient progress towards meeting the Paris Agreement targets, the international community is not on track to deliver the SDGs by 2030. Access to cooling can reduce food loss, protect the quality and safety of food produced, and prevent productivity loss due to extreme heat, thereby contributing towards major global issues such as eradicating poverty, hunger, and malnutrition, especially in developing countries. It can prevent heat-related illnesses and deaths, and is often essential to maintain the quality, safety, and efficacy of vaccines, blood, and other temperature-sensitive medicines. These benefits not only provide strategic and social gains, but also often have a financial value.

How we meet this surging cooling demand across a variety of sectors will have important implications for our future climate and energy systems globally. The increasing need to adapt to higher ambient temperatures may result in rushed responses that are highly polluting and energy-intensive, resulting in technological lock-in. The multi-level, multi-sector, and multi-actor challenge that is faced by policymakers, financiers, business leaders, entrepreneurs, technology developers, and engineers today is how to meet surging cooling needs in a warming world sustainably, while also building resilience. Sustainability and resilience are two different concepts. While sustainability refers to meeting the needs of current generations without compromising the ability of future generations to meet their own needs, resilience denotes the ability of systems to bounce back and recover from disruptions quickly and adapt to inevitable changes. To deliver cooling in line with climate and developmental targets, we need to hit the sweet spot at the intersection of sustainability and resilience. As different countries face different needs and climate risks, and have varying levels of vulnerability, sustainability solutions that are effective in some locations may not be feasible in others. To manage the complexity and deliver cooling in the most cost-efficient way with minimum environmental impact, countries should focus on actions that play to their strengths (e.g., local energy resources and assets) and carefully define their strategies and priority actions – which is the key to building resilience. Furthermore, it is important to design solutions for the changing climate conditions. Under high ambient temperatures induced by climate change, current systems would fail or struggle to operate efficiently. Hence, in the short term, solutions will be needed to keep existing systems operating effectively, and in the long run, new system designs will be required.

The scope of energy provision today typically focuses on electricity and batteries, even though a large slice of our energy consumption comes in the form of thermal demands. In the transition to renewables, cooling demands may often be better served by thermal-to-thermal solutions and thermal energy storage. Achieving this requires taking a needs-driven, integrated system-level approach to cooling provision and driving a new thinking in key areas: How do we mitigate, make, store, move, manage, and finance/regulate cold? The holistic systems approach aims to minimize the demand for active cooling via integration of passive cooling techniques and approaches as well as behavioral changes (which is particularly important in regions where there is demand for cooling throughout the entire year), helps make sure individual cooling technologies are supported by the broader infrastructural landscape (e.g., energy and transport) in which they are embedded, and interdependencies between energy services are understood and managed, and ensures the whole system is supported by appropriate

skills, policies, regulations, and finance and business models. In this regard, it is important to take a future-oriented approach by understanding not only the current but also the future cooling energy service needs, by anticipating social, economic, environmental, technological, and regulatory changes over the long term, and by planning for unexpected/uncontrollable events and circumstances, such as natural disasters and pandemics, that could disrupt the cooling service or alter the demand profile.

Future-proofed design is critical to ensure future capability and capacity in a long life cycle. Buildings constructed today will still be in use for at least the next 50 years. For example, if new buildings are designed without considering the risk of overheating, the higher ambient temperatures and intense heatwaves that are expected to occur more often in coming decades will increase the reliance on air-conditioning systems, which are typically highly energy intensive and polluting. Furthermore, the need to comply with increasingly stringent building codes and standards will lead to unnecessary retrofitting costs. Similarly, electric-vehicle charging points will likely need to be integrated into buildings, consequently impacting the grid energy demand and peak loads, and this requires careful planning.²

With 80% of the buildings that will exist in 2050 in developing countries yet to be built [12], there is now a window of opportunity in these countries to significantly reduce space cooling energy demand and emissions in buildings, improve thermal comfort in outdoor urban environments, and maximize their life cycle value through future-oriented, needs-driven, and resource-smart design approaches. At the same time, we must recognize that addressing the cooling needs across other sectors requires equal attention. To this end, taking an extensive and comprehensive whole system-of-systems approach to cooling provision by identifying and leveraging interdependencies across cooling sectors and wider energy systems is key to ensuring current and future cooling needs are met for all efficiently, sustainably, and affordably, while building resilience.

2. THE DRIVERS FOR COOLING DEMAND GROWTH

Climate change: According to the IPCC's Sixth Assessment Report, "each of the last four decades has been successively warmer than any decade that preceded it since 1850." Since 1950, while hot extremes have become more frequent and more intense, cold extremes have become less frequent and less severe, and projections suggest future increases in the intensity and frequency of hot extremes, including heatwaves [13]. For example, in the tropical region, the temperatures increased by 0.7–0.8°C over the last century, with climate models predicting an increase of 1–2°C by 2050 and 1–4°C by 2100 [14]. Without any intervention, the average number of cooling degree days (CDDs), the number of degrees that a day's average temperature is above 18°C, at which a building must be cooled to achieve a comfortable indoor temperature, could increase globally by nearly 25% between 2016 and 2050, with the highest increases expected to occur in developing countries located in the hottest parts of the world [7]. For example, in India, the number of cooling degree days is already high with more than 3,000 per year, and this figure is expected to increase by 13% by 2050 [7]. Without any intervention, up to 3.5 billion people around the world could be exposed to

² From a systems perspective, electric vehicles will play a critical role in reducing the transport refrigeration and mobile space cooling emissions. For example, 40% of a bus's energy consumption in Asia can be air-conditioning load while a transport refrigeration unit consumes up to 20% of a refrigerated vehicle's diesel.

annual mean temperatures of 29°C, which are higher than nearly anywhere today, by 2070 [15]. Another research led by the UK's Met Office suggests that a billion people could suffer from extreme heat stress if global temperatures were to increase by 2°C [16].

Increasing population: The world's population is expected to increase by two billion by 2050, from 7.7 billion in 2019 to 9.7 billion, and may reach 10.9 billion in 2100 [17]. Much of this growth is expected to come primarily from developing nations in hotter parts of the world that are more vulnerable to climate change. For example, in 2019, 43% of the world's population, almost 3.8 billion people, were living in the tropical region, and this is expected to increase to 50% by 2050 [17].

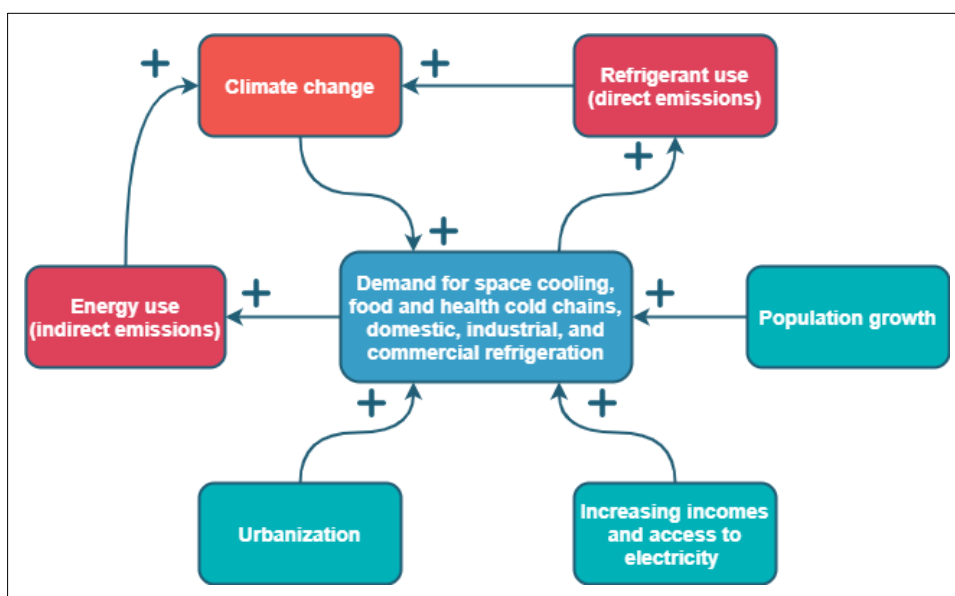
Urbanization: Over half of the world's population currently lives in urban areas, and this figure is expected to reach as much as 70% by 2050 [18]. A substantial proportion of this growth in human urbanization is projected to occur in the developing economies of the world and in locations that will experience significantly increased ambient temperatures and more frequent and intense extreme heat events. The impacts of these trends will be exacerbated by urban heat island effects that raise local temperatures in the centers of cities and urban conurbations to levels several degrees higher than simultaneously experienced in the surrounding suburbs or rural hinterland [19]. According to the Environmental Protection Agency (EPA), the annual mean air temperature of a city can be 1–3°C warmer on average – and as much as 12°C warmer in the evening than the surrounding areas [20]. Recent projections suggest that cities across the world could warm by more than 4°C on average by the end of the century [21]. The urban heat island effect is a complex phenomenon that depends on a multitude of factors. Buildings and other structures reflect less solar energy and absorb and emit more heat than natural surfaces. Displacing natural surfaces reduces the natural cooling effects of shading and evaporation of water from soil and leaves. Furthermore, the dimensions and spacing of buildings impact wind flow and the ability of urban surfaces to absorb and release heat. For example, narrow spaces between tall buildings (i.e., urban canyons) can block wind flow and trap heat. Moreover, waste heat from vehicles, factories, and air conditioners further exacerbates the heat island effect. For example, research suggests that heat exhausted from active cooling technologies alone can increase night-time temperatures in cities, where active cooling technologies are common, by 1 or 2°C (heat island effect) [22].

Increasing incomes and access to electricity in developing countries: In the last decade, air conditioner ownership has been rapidly increasing in emerging and developing economies, such as India, Indonesia, and the PRC, with 16, 13 and 8%, respectively [10]. While today, air conditioner ownership globally is mostly concentrated in the developed world, it is anticipated that 80% of the refrigeration and air-conditioning market will be located in developing countries by 2030, mainly due to increasing incomes and improved access to electricity [23]. Although 759 million people globally still lack access to electricity as of 2019, significant progress has been made, and this number has decreased from 1.2 billion in 2010 and is expected to further decrease [24]. Estimations suggest that 2.2 billion lower-middle-income people in developing countries newly entering the world's "middle classes" will soon be able to purchase the most affordable air conditioners [25]. However, these devices will likely be too inefficient and energy intensive in the absence of finance and business models to encourage best-in-class purchasing.

In addition to increasing demand for air conditioners in buildings, which is the largest energy consumer amongst the cooling sectors, accounting for 41% of global cooling energy consumption [11], the combination of these factors will drive the demand for cooling in other sectors. For example, rising temperatures will also consequently

increase the demand for space cooling in the transport environment, higher income levels will potentially result in higher food consumption levels, which will inevitably increase the demand for cooling in the food sector, both in the food production and cold chain, urbanization will increase demand for refrigeration at urban retail and hospitality outlets to meet the urban food demand, and food producers will be pushed farther from the demand due to urban expansion, resulting in greater demand for cold-chain logistics. The nature and size of the cooling demand across sectors will be impacted by other parameters specific to local circumstances, in addition to the ones mentioned, ranging from changing shopping preferences to increasing health, safety, and environmental concerns, and production patterns, among others.

Figure 1: Linkages between Demand Growth for Active Cooling, Climate Change, and Other Drivers



This demand will likely contribute to its own growth, as conventional active cooling devices are typically energy intensive and highly polluting due to the emissions from energy use (indirect emissions), especially if generated from carbon-intensive sources, and from refrigerant leakages during use and servicing as well as when the equipment is discarded at the end of life (direct emissions) (Figure 1). These devices contribute to more than 7% of global greenhouse gas (GHG) emissions today, and left unchecked, these emissions may double by 2030, and triple by 2100.

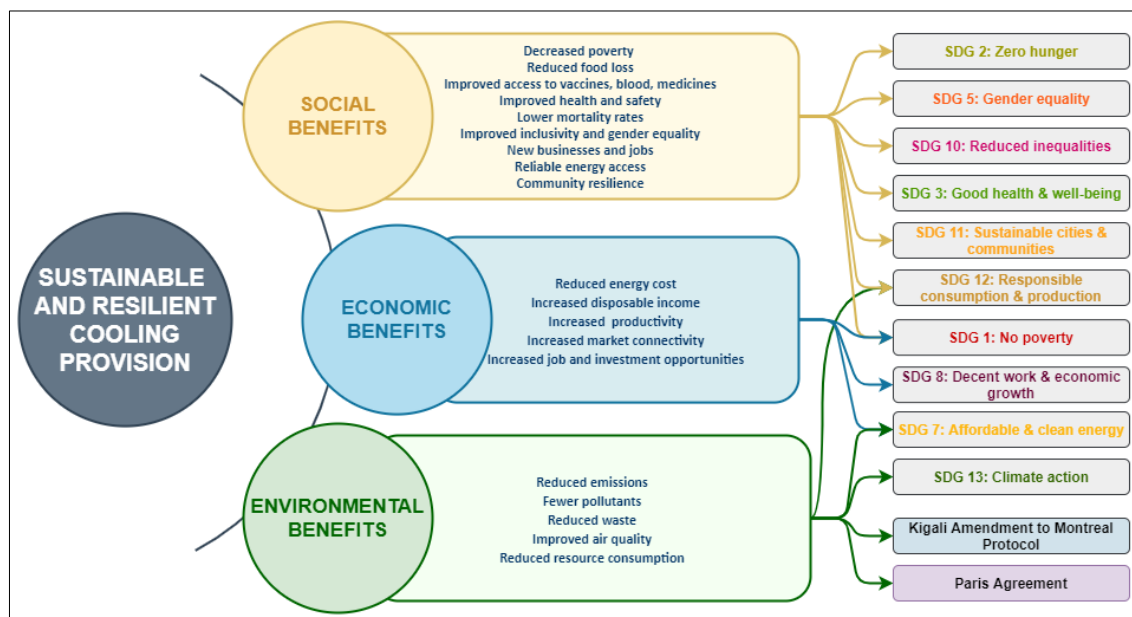
The critical importance of cooling in delivering climate and developmental targets has been getting recognized in recent years globally. In response, many countries have been developing and implementing national cooling plans with support from the cooling community. These plans involve roadmaps and timetables for achieving a sustainable cooling economy, involving short-term and long-term considerations on refrigerant transitions (HCFC phase-out and HFC phase-down), reducing the cooling demand, enhanced MEPS, building codes, and universal access to sustainable cooling. Moreover, currently 55 countries have committed to reducing their cooling emissions, either in their enhanced Nationally Determined Contributions (NDCs) or long-term climate plans [26]. Of these 55 countries, only six included cooling in their NDCs in 2015 [27]. In this regard, for example, Cambodia included space cooling of buildings as a priority GHG mitigation in 2020 in its revised NDC. The NDC includes passive cooling

strategies to reduce energy consumption in buildings and to reduce the urban heat island effect in cities. To this end, through the K-CEP NDC Support Facility, the Ministry of the Environment of Cambodia, the UN Economic and Social Commission for Asia and the Pacific (ESCAP), and the UN Environment Programme (UNEP) are planning to implement a technical assistance program on “Passive cooling strategies implementation in Cambodia” by the end of 2021 [10].

3. UNDERSTANDING THE REAL VALUE

In a warming world, cooling access is increasingly becoming a necessity for maintaining adequate human living standards. In countries with hotter climates, surging cooling demand is often coupled with the need for economic growth and development. Sustainable and resilient cooling access can provide many socioeconomic-societal-political benefits that are inherently aligned to, and critical for, achieving many of our SDG targets (Figure 2). This is particularly relevant in the context of inequalities. The social and economic costs of a lack of cooling access fall disproportionately on poor, disadvantaged, and often marginalized individuals and communities, as well as on women and girls, exacerbating inequalities and creating additional barriers to achieving the SDGs. More than one billion people face immediate risk from a lack of access to cooling, which includes 680 million slum dwellers living in hotter-climate urban environments [25]. These people are often not included in the climate planning processes, and some adaptation efforts may even exacerbate existing inequalities if not planned carefully [28]. For example, rapid urbanization and growth of large cities in developing countries have been accompanied by the rapid growth of highly vulnerable urban communities living in informal settlements. These communities are often located on land at high risk from extreme weather [29].

Figure 2: Multiple Benefits of Sustainable and Resilient Cooling Provision and its Linkages to SDGs



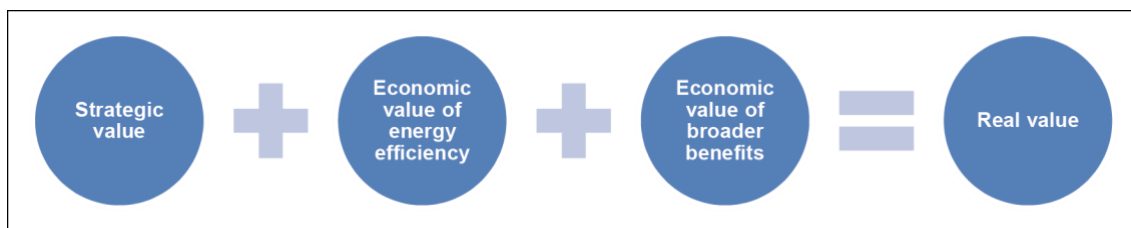
Source: Authors.

Despite the surging demand and central importance of cooling to a functioning modern society and the plethora of benefits it delivers, approaches to cooling provision today tend to be narrowly focused on simply measuring energy efficiency alone, quantifying savings on energy bills, and using these as the basis for the return on investment (ROI) calculations. The broader societal benefits of access to cooling are typically treated as a “soft win,” rather than the core driver for provision. Realizing a truly sustainable and resilient cooling system demands understanding, quantifying, and valuing the broader and potentially strategic impacts of cooling with their linkages to climate and developmental goals, targets, and commitments.

The key is to recognize that social and environmental benefits do have financial value – which often translates to reductions in other costs or lower economic losses – and the necessary data for their assessment are likely to be available once a requirement has been identified. For example:

- Higher ambient and extreme temperatures in a warmer world will negatively impact labor productivity by as much as 12% in South Asia and West Africa by 2050, which may potentially result in an annual GDP loss of up to 6% [30]. Increased heat stress is projected by the International Labour Organization (ILO) to reduce total working hours worldwide by 2.2% and global GDP by US\$2.4 trillion in 2030, affecting agricultural and construction workers particularly severely [31]. A recent study estimates that the labor productivity loss for low- and lower-middle-income countries due to high temperatures is approximately nine times more than that of high-income countries and that economic losses may already be as much as 2% of global GDP as a result [32]. In terms of strategic value, the provision of sustainable and resilient cooling is directly linked to SDG 8: Decent Work and Economic Growth.
- Women and girls are disproportionately affected by a lack of cooling, as they typically spend more time at home engaging in domestic activities than men and boys,³ especially in developing countries [34]. Ensuring equitable access to sustainable cooling can contribute to SDG 5: Gender Equality, and SDG 10: Reduced Inequalities.
- Climate change is estimated to be currently responsible for over 150,000 deaths annually, and between 2030 and 2050 it is expected to cause approximately 250,000 additional deaths per year, from malnutrition, malaria, diarrhea, and heat stress [35], [36]. For example, the estimated economic costs from the increase in heat-related mortality in the UK is estimated to have been £2.5 billion per year in 2020, and it is expected to rise to a staggering £9.9 billion per year by 2050 [37]. In terms of strategic value, this is directly linked to SDG 3: Good Health and Well-being.
- Increasing temperatures lead to high levels of discomfort and heat stress not only for humans but also for animals, which can result in increased morbidity and mortality levels. For example, more than 17 million chickens died in India during the 2015 heatwave [38]. Increasing temperatures can also result in productivity loss and reduced reproduction rates [39], [40]. For example, multiple studies conducted in India suggest that heat stress can reduce milk production by between 5 and 50% [41], [42]. All of these are directly linked to SDG 1: No Poverty, and SDG 2: Zero Hunger.

³ According to UNICEF, girls spend 160 million more hours a day than boys doing unpaid household chores [33].

Figure 3: Real Value of Sustainable and Resilient Cooling Provision

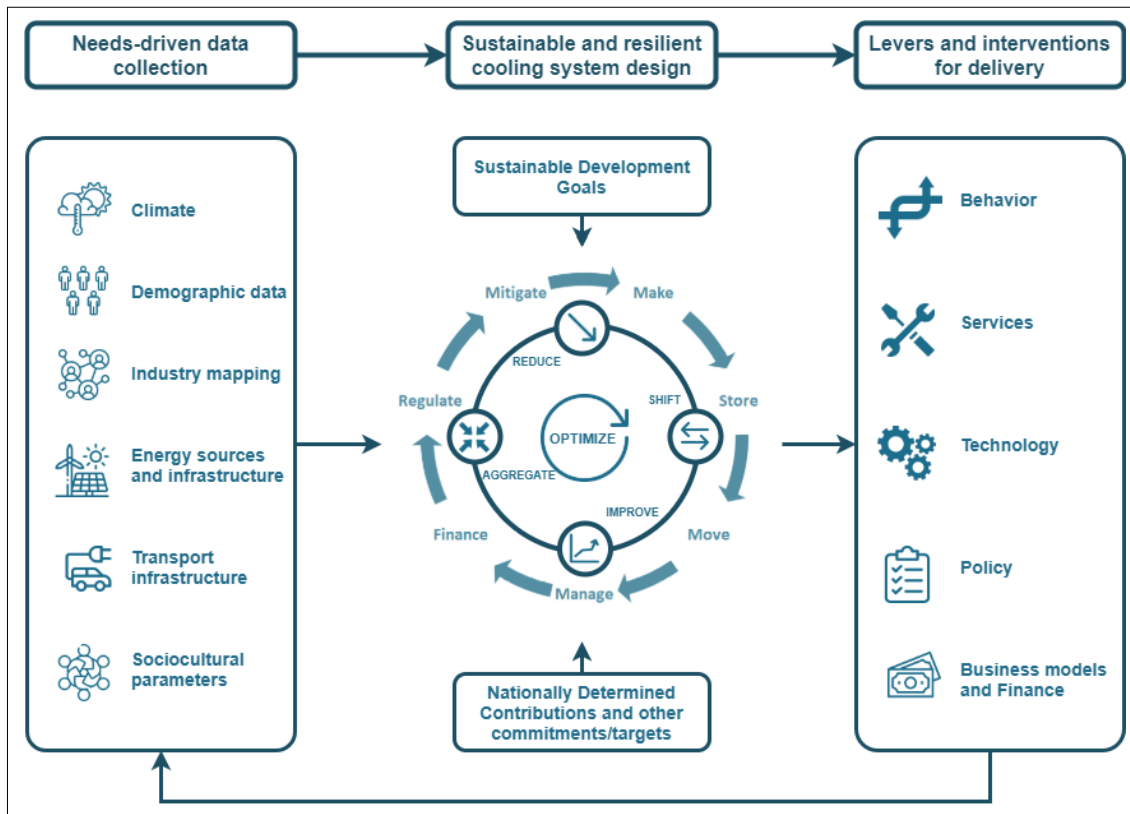
To summarize, the process for assessing the real value of delivering clean cooling involves the following steps (Figure 3):

1. Identify the social and environmental benefits and their impacts.
2. Create strategic value by linking benefits to a strategic direction, such as goals, targets, or commitments).
3. Quantify the economic value of social and environmental benefits.
4. Determine the energy cost savings through energy efficiency measures.
5. Aggregate all these values to establish the real value of delivering sustainable and resilient cooling.

4. THE SYSTEMS APPROACH

Governments' efforts to decarbonize economies today focus mainly on "greening the electricity supply" by replacing fossil fuels with renewable and low-carbon sources, such as solar, wind, hydro, and nuclear. In the cooling sectors, while these efforts will help with GHG emissions associated with energy use, they are falling short in the face of surging demand. For example, over 100 gigawatts (GW) of building space cooling capacity was added in 2017, outpacing the record 94 GW of solar power generation added to the world's renewable energy infrastructure that year [43]. Similarly, 2018 was again a record year for global deployment of solar power with 104 GW of installed capacity added, while simultaneously the energy demand resulting from new sales of room air conditioner (AC) units was 115 GW [44]. This excludes all existing cooling as well as new cooling equipment and appliances installed for other purposes. Even if we manage to fully decarbonize the electricity grid, we will still need to reduce refrigerant emissions. Note that achieving the 1.5°C target also requires deep reductions in non-CO₂ emissions such as hydrofluorocarbons (HFCs) from refrigerant leakage and/or spillage [45]. Emissions from refrigerants represent around one third of the total GHG cooling emissions, and HFCs are the fastest-growing source of GHG emissions globally due to the surging cooling demand [6], [46].

Similarly, we cannot rely on energy efficiency improvements in cooling technologies alone to meet the cooling needs sustainably in line with our emission targets. For example, after flattening between 2013 and 2016, emissions from energy use in buildings have increased in recent years as the increased demand for energy services, especially electricity for cooling appliances and connected devices, has outpaced energy efficiency and decarbonization efforts [47]. Within this, there needs to be a paradigm shift to a different way of thinking that goes beyond simply taking a business-as-usual approach focused on energy efficiency and greening electricity.

Figure 4: Systems Approach to Cooling Provision

Source: Authors.

Design and technical development approaches to cooling provision today typically focus on improving individual technologies viewed from a siloed perspective. While optimizing the components of the whole system is important, this reductionist approach neglects the interdependencies that exist between economic decisions, available energy resources, technology choices, climate change mitigation and adaptation strategies, and social, cultural, and political systems, and results in a suboptimal outcome. Solving the global cooling challenge and meeting the thermal comfort needs in buildings and urban environments while simultaneously delivering the targets of the Paris Agreement, the Kigali Amendment, and the SDGs simultaneously requires taking a systems approach to cooling provision. This requires assessing the current and future cooling needs in urban environments, and understanding the wide range of drivers and barriers that will shape the cooling system along with climatic, demographic, socioeconomic statistics, energy and transport infrastructure, and existing and emerging technologies, as well as policies, goals, targets, commitments, and initiatives, and a new thinking in the key areas of mitigating, making, storing, managing, financing, and regulating cold to meet the current and future demand sustainably while building resilience. The optimum mix of fit for market solutions across behavioral change, technology, services/skills, policy, business models, and finance solutions can be delivered through a “reduce-shift-improve” approach, adding in the intervention of “aggregate,” supporting both early wins and the deep systemic changes that are essential to achieve a sustainable and resilient cooling system in urban environments (Figure 4). Within this, the ultimate goal is to create an economically, environmentally, and socially sustainable integrated cooling system that:

- optimizes the sustainable use of all available natural, renewable, and waste resources;
- harnesses and leverages synergies between sectors and systems, to create symbiotic yet resilient relationships that account for unintended consequences and potential system vulnerabilities from integration and coupling;
- minimizes the need for energy-intensive active cooling devices through the use of passive approaches and techniques, behavioral change, demand reduction, and aggregation strategies;
- is regularly monitored, optimized, and adequately maintained;
- is supported by policy, regulation, and appropriately structured finance;
- enables safe decommissioning of component systems for reuse, remanufacture, and recycling in a circular economy model, with no unanticipated impacts on the overall sustainability of the system.

Mitigate

Mitigate refers to reducing the demand for active cooling in buildings and improving thermal comfort in residential and commercial buildings but also in outdoor urban environments through urban planning and infrastructure. Nature-based solutions (such as trees and plants), passive cooling techniques and approaches, and behavioral changes can be a partial or, in some cases, full substitute for energy-consuming mechanical cooling processes with chemical refrigerants (i.e., active cooling) in buildings and can improve thermal comfort in outdoor urban environments significantly by reducing the heat island effect. Integrating cooling demand mitigation through design and other means is especially important in countries/regions with high ambient temperatures and humidity levels all year long, such as tropical climates where monthly average temperatures are 18°C or higher all year round and there is no demand for heating.

Passive cooling techniques and approaches reduce the cooling energy consumption either by removing heat from buildings to a natural heat sink, such as ground, air, or water, or by preventing heat from entering buildings from external heat sources, such as through shading and thermal insulation or white roofs. At the city level, smart urban design and construction can significantly reduce the need for indoor and outdoor cooling by minimizing the heat island effect. Examples include building wind flow corridors and water bodies into city designs, replacing or coating heat-absorbing materials like asphalt and concrete with more reflective alternatives. Similarly, urban trees (and other plants) reduce urban air temperatures by providing shade and by releasing water vapor into the atmosphere from their leaves (i.e., transpiration). In the building sector, cool roofs are used to reduce solar radiation absorption, which can cut active cooling use by up to 20% [48]. Similarly, green roofs reduce the solar heat gain and also provide added insulation. Orientation is often used in building design to manage solar gain through alignment of surfaces, windows, and inner courtyards with areas of shading or lower solar gain. Natural ventilation is a method of supplying fresh air to buildings by means of passive forces, typically achieved through alignment of openings to predominant wind/breeze directions or through utilizing differences in air pressure internally and externally. A study conducted in southern Europe revealed that natural ventilation can provide a 13% annual saving in air-conditioning energy use [49]. The solution or combination of solutions should be carefully evaluated on a case-by-case basis taking into consideration parameters such as climatic conditions,

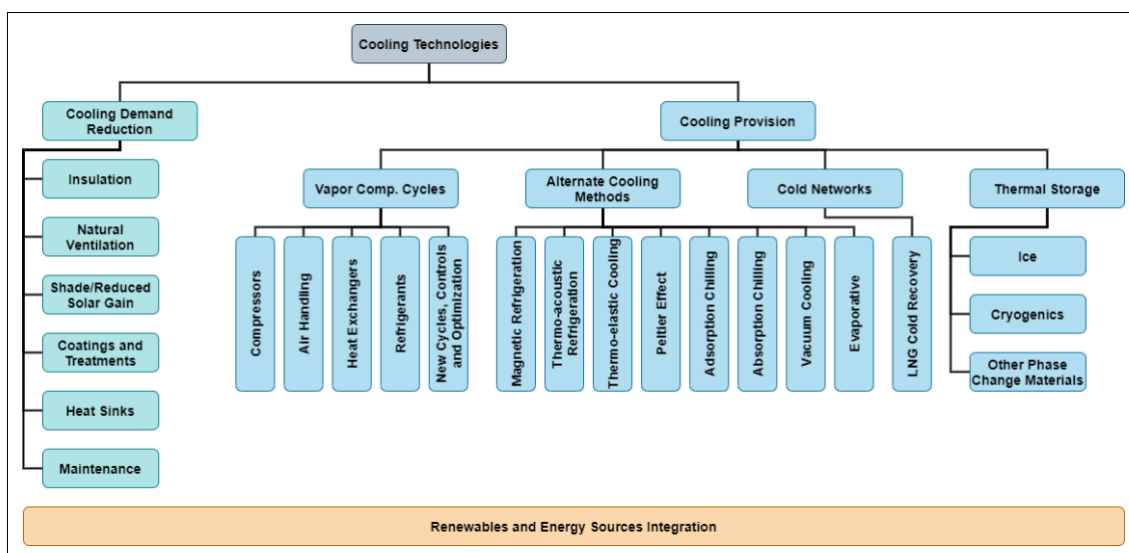
occupancy levels, building function, and time of use to decide which are most appropriate and effective.

User behavior has a significant influence on energy consumption. Behavioral changes that can reduce the need for active cooling include, among other things, increasing space cooling temperature set points, reducing the amount of cooled space, reducing lighting levels, switching to LED lighting (which emits less heat than conventional bulbs), optimizing thermostat settings, cooling only occupied rooms, and keeping windows and/or doors of the cooled space closed.

Make

Vapor compression-based air-conditioning systems are the most widely applied space cooling approach in buildings today and are expected to remain so in the foreseeable future due to their ease of use, scalability, and reliability [9]. Alternate cooling methods have been developed but remain for use in niche applications because they have not reached the scale needed to lower costs, such as magnetic refrigeration, thermo-acoustic cooling, and thermo-elastic cooling (Figure 5).

Figure 5: Cooling Technologies (from: [50])



While supporting the uptake of energy-efficient air conditioners is important, the key is to take a resource-focused approach and explore opportunities to harness free and waste energy resources. Space cooling needs can be effectively and efficiently met by making use of waste cooling resources that are highly localized, but also by harnessing and aggregating more remote waste cooling opportunities via a district cooling-type network infrastructure. For example, cold water from local rivers, lakes, or ocean sources can be circulated into a building to provide cooling. Similarly, industrial waste cold (e.g., waste cold from liquefied natural gas (LNG) regasification⁴) can be utilized to meet demands in an aggregated manner. In 2020, the global demand for LNG was

⁴ LNG is obtained by cooling natural gas down to the point of condensation, -162°C , under atmospheric pressure. The cooling process reduces the volume of the gas 600 times, which not only makes it easier and safer to store and transport but also expands its scope of application. LNG is regasified before supplying it to end users, such as industry clusters, electrical power plants, and buildings. The LNG regasification process releases a large amount of cold energy, around 240 kWh per tonne of LNG.

estimated to be 360 million tonnes, and it is expected to double to 700 million tonnes by 2040, with Asia set to drive approximately 75% of the new demand for LNG [51]. Globally, cold energy utilization from LNG regasification represents less than 1% of the total potential [52]. Given the expected increase in demand for LNG, the recovery of “coolth” from LNG regasification is clearly an opportunity that merits further investigation.

District cooling networks that exploit economies of scale to offer space cooling in industrial, commercial, and residential buildings as a service are in use in some countries. Aside from the economy of scale advantage, these networks offer the possibility of sharing the benefit of waste resources across multiple users. Research suggests that district cooling is five to ten times more energy efficient than conventional active air-conditioning systems, and it can provide savings on cooling energy consumption by up to 50% [53]. At the same time, rather than solely focusing on thermal comfort, the key is assessing how multiple cooling services could be integrated into a community-based thermal energy system using thermal networks for cooling.

Store

Space cooling represents almost 20% of all the electricity used in buildings and is projected to increase in the years ahead. Thermal energy storage (TES) can increase energy efficiency in buildings by reducing energy demand or peak loads for thermal energy needs (i.e., cooling and heating), and supports the wider energy system decarbonization by reducing the investment need for increased power grid and generation capacity, freeing up limited renewables capacity for other uses, reducing peak energy demand, and creating more room for intermittent renewable and waste thermal energy sources.

The variation in temperatures throughout the day can be exploited to provide cooling through the storage of cold energy at times when temperatures are low (typically during the night) and its subsequent use for absorbing heat when temperatures are high. Furthermore, for example, heat rejected from refrigeration systems can be used synergistically for heating, providing significant energy and emission savings, and leading to overall emission reductions. With the integration of thermal energy storage, heat can be stored when refrigeration loads and heating requirements are mismatched, and the stored heat can be made available for use later. One study of refrigeration system heat recovery for space heating provision in supermarkets found that through such an approach, thermal storage increases the potential of heat recovery by 11–12% [54].

Manage

Under the Montreal Protocol, it was recognized by TEAP that “the impact of proper installation, maintenance, and servicing on the efficiency of equipment and systems is considerable over the lifetime of these systems while the additional cost is minimal. The benefit of proper maintenance is considerable. Appropriate maintenance and servicing practice can curtail up to 50 per cent reduction in performance and maintain the related performance over the lifetime” [55]. Directly related to this, effective optimization, monitoring, and maintenance can, in fact, reduce total cooling GHG emissions by 13% and deliver substantial energy savings of up to 20% over the equipment life span [4]. Additionally, the lifetime of equipment can be improved, and the risk of breakdown can be reduced, through better design, installation, maintenance, and servicing practices, thereby preventing downtime and early replacement of

equipment. For example, the Indoor Air Quality Association estimates that regular maintenance of air conditioners can reduce the risk of breakdowns by as much as 95% [56]. To this end, it is important to develop a cooling workforce with the right skill sets for the proper installation and maintenance of existing equipment and innovative technologies, taking into consideration the digitalization of the sector and the rapid pace of advancements, requiring dynamic and continuous training.

Digitalization of cooling systems with smart controls and sensors can also improve the energy performance of buildings by eliminating the unnecessary use of cooling equipment. These systems can be as simple as a programmable thermostat, or they may be complex systems that can control various processes throughout a group of buildings [9]. According to the IEA, between 2017 and 2040, digitalization could reduce total energy use in residential and commercial buildings by up to 10%, and provide a cumulative energy saving of 65 PWh, which is equal to the total final energy consumed in non-OECD countries in 2015 [57].

Finance and Regulate

According to the IEA, most consumers purchase air conditioners that are two to three times less efficient than the ones available on the market, the major reason being the high upfront costs associated with sustainable cooling technologies that can deliver cooling with a significantly lower environmental impact [58]. Air conditioner manufacturers have been reluctant to risk large investments in R&D or commercialization of innovative technologies. Innovation prizes are effective tools to address this issue. For example, the Global Cooling Prize has recently shown what can be achieved with room air conditioners, and there are many emerging technologies that show great promise. In April 2021, Gree Electric Appliances, Inc. of Zhuhai with partner Tsinghua University, and Daikin with partner Nikken Sekkei Ltd., emerged as the two winners of the Global Cooling Prize among eight finalists by producing prototypes that exceed the Global Cooling Prize's five times lower climate impact criteria [59]. However, to bring these technologies to market, we need to align regulations and standards to the technological progress. However, most of the performance standards today are not ambitious enough to encourage the adoption of best-in-class technologies [60]. As a best-practice example, Japan's Top Runner program, introduced in 1999, was designed to stimulate continuous improvement by setting energy efficiency targets for appliances based on the most efficient model available on the market [61]. Financial incentives such as subsidies for sustainable equipment and passive design solutions – e.g., cool roofs – that reduce the upfront cost of sustainable solutions can also be effective in increasing uptake. Equally, financial barriers and risk of investment could be addressed through business models such as pay-as-you-go (PAYG), Cooling-as-a-Service (CaaS), Energy Efficiency as a Service (EEaaS), and Energy Savings Insurance (ESI) as well as bulk procurement programs. For example, 100,000 room air conditioners have been procured in India under the EESL Super-Efficient Air Conditioning Program (ESEAP), providing highly efficient equipment to consumers at a discounted price [62], [63]. Equally importantly, we need to develop the skills required to properly install, maintain, and operate these new technologies, especially in the developing countries where significant skill shortages exist. At the building level, building energy codes and standards are effective in bringing about energy efficiency gains and can address the issues around split incentives in the building sector arising from the fact that those responsible for paying energy bills are often not those making investment decisions. For example, in India, a 20% reduction in cooling loads can be achieved by 2037–38 in upcoming commercial buildings, through robust implementation of the building energy codes and climate-

appropriate building envelopes [64]. Furthermore, incentives can be provided to building developers, such as fast-track permit approvals, waiving permitting or planning fees, or allowing more buildable space, in exchange for integrating cooling load mitigation solutions in their projects [65]. For example, in Hong Kong, China, the government grants gross floor area (GFA) concession offers up to a 10% increase in allowable gross floor to developers that pursue certification under BEAM Plus [65], [66]. However, the unintended consequences of such incentives should be carefully planned for. Research suggests that an excessive GFA concession can increase the building bulk and height, leading to negative impacts, especially in dense cities, such as a lack of daylight and views, and air ventilation problems [67].

5. DISCUSSION

Energy use for space cooling has more than tripled since 1990, and rising temperatures, more frequent and extreme heatwaves, increasing incomes and access to electricity, population growth, and urbanization are expected to lead to an unprecedented cooling demand in buildings in the next decade. Furthermore, often not captured by projections, providing access to cooling for all that need it to adapt to rising temperatures will require significantly more investment in cooling provision than anticipated to ensure equitable access to cooling.

How the cooling demand is met in buildings and outdoor urban environments and integrated into the wider energy systems will have implications for our climate and environment globally, but also for our broader aspirations for a sustainable human future. To deliver cooling in a sustainable and resilient way, we need more than efficient air conditioners. What is required is a needs-driven, system-level approach, first to mitigate demand through passive approaches and behavioral changes, second to understand and identify multiple cooling needs, the thermal, waste, and wrong-time energy resources, and finally to define the right portfolio of solutions to integrate those resources with service needs optimally. This necessitates the integrated development of skills and capacity, the right policies and regulations, and finance and business models that are fit for purpose. It is important to recognize that the benefits of sustainable cooling provision go beyond reduced energy demand and costs, and emissions. Sustainable, resilient, and equitable access to cooling provides multiple benefits from productivity gains to health improvements, all of which do have financial value and should be quantified where possible to underpin and facilitate investments.

6. CONCLUSIONS AND POLICY RECOMMENDATIONS

With the emerging need to adapt to climate change, the demand for cooling is set to grow substantially. Indeed, predictions suggest that energy demand for space cooling globally could overtake that for heating by 2060 [68]. Today, more than one billion people already face immediate risk from a lack of access to cooling, including 680 million slum dwellers living in hotter-climate urban areas. Moreover, from a gender perspective, women and girls face significant challenges in accessing cooling services and the benefits they provide. Delivering sustainable and resilient cooling for all would provide a multitude of economic, social, and environmental benefits, and is key to achieving many of our SDG targets. Understanding, quantifying, and valuing the broader and potentially strategic impacts of sustainable and resilient cooling with their linkages to climate and developmental goals, targets, and commitments is key to attracting the necessary prioritization and investment by governments.

Business-as-usual approaches to cooling provision that primarily focus on piecemeal energy efficiency improvements and greening electricity will not be able to meet the surging cooling demand in buildings as well as other sectors. Achieving a truly sustainable and resilient cooling economy requires integrated system-level approaches to cooling provision, such as minimizing the demand for air conditioners in buildings through passive design techniques, looking for ways within the energy system to harness untapped thermal resources and make use of thermal energy storage to unlock otherwise redundant resources of renewable or waste energy, and aggregating demand through district cooling. It also requires integration and system management between built-environment and mobile cooling and energy demands.

As immediate wins, governments should (i) encourage the commercialization and uptake of ultra-high-efficiency sustainable air conditioners through more ambitious labeling and MEPS supported by innovative finance and business models for consumers to overcome first-cost barriers, and (ii) strengthen building codes and standards through the integration of passive cooling and energy efficiency requirements.

In parallel, there is a need to develop the skills and training required to deliver current sustainable technologies in the market, but also to scan the horizon by engaging with industry and technology developers to understand the potential future skill requirements to meet the technologies in development and manufacturing.

To summarize, while meeting the surging cooling demand for everyone poses a massive environmental challenge, it also represents an opportunity for governments to strategically meet targets of the Paris Agreement, Kigali Amendment, and SDGs simultaneously. We are seeing the development of more energy-efficient and less polluting cooling equipment. But these alone will not be sufficient to deliver cooling for all sustainably. Achieving this will require rethinking the way we deliver cooling: minimizing the need for active cooling in the first place, making best use of renewable, thermal, and waste resources available and the novel energy vectors, thermal stores, and sustainable cooling technologies appropriate for the societal, cultural, climate, and infrastructure context, and developing the appropriate skills, capacity, business and finance models, and policy frameworks to support them. In other words, it will require a transition from thinking at the technology level to the system level.

REFERENCES

- [1] U. N. Environment, Emissions Gap Report 2019. *UNEP – UN Environment Programme*, Nov. 19, 2019. <http://www.unep.org/resources/emissions-gap-report-2019> (accessed Mar. 24, 2021).
- [2] C. Mora *et al.* 2017. Global Risk of Deadly Heat, *Nature Climate Change* 7(7), Art. no. 7, Jul., doi: 10.1038/nclimate3322.
- [3] WHO 2014. Quantitative Risk Assessment of the Effects of Climate Change on Selected Causes of Death, 2030s and 2050s.
- [4] Kigali Cooling Efficiency Programme. 2018. Optimization, Monitoring, and Maintenance of Cooling Technology. [Online]. Available: <https://k-cep.org/wp-content/uploads/2018/03/Optimization-Monitoring-Maintenance-of-Cooling-Technology-v2-subhead....pdf>.
- [5] Four Things You Should Know About Sustainable Cooling. *World Bank*. <https://www.worldbank.org/en/news/feature/2019/05/23/four-things-you-should-know-about-sustainable-cooling> (accessed Mar. 24, 2021).
- [6] The HFC Problem. *North American Sustainable Refrigeration Council*. <https://nasrc.org/the-hfc-problem> (accessed Apr. 27, 2021).
- [7] The Future of Cooling – Analysis. *IEA*. <https://www.iea.org/reports/the-future-of-cooling> (accessed Mar. 24, 2021).
- [8] Z. Schlanger, 70% of Saudi Arabias electricity is used for air conditioning, *Quartz*. <https://qz.com/1284239/70-of-saudi-arabias-electricity-is-used-for-air-conditioning/> (accessed Nov. 02, 2021).
- [9] U. N. Environment, Beating the Heat: A Sustainable Cooling Handbook for Cities, *UNEP – UN Environment Programme*, Oct. 28, 2021. <http://www.unep.org/resources/report/beating-heat-sustainable-cooling-handbook-cities> (accessed Nov. 03, 2021).
- [10] GlobalABC. 2021. Global Status Report for Buildings and Construction, 2021. <https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction> (accessed Nov. 03, 2021).
- [11] T. Peters. 2018. A Cool World: Defining the Energy Conundrum of Cooling for All. University of Birmingham.
- [12] Climate: The Importance of the More Energy-efficient Buildings. *ID4D 07*, 2017. <https://ideas4development.org/en/buildings-climate-change/> (accessed Mar. 11, 2022).
- [13] MassonDelmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. and Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou.(Eds.). 2021. IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- [14] R. T. Corlett. 2014. Essay 2: The Impacts of Climate Change in the Tropics. James Cook University [Online]. Available: <https://www.jcu.edu.au/state-of-the-tropics/publications/2014-state-of-the-tropics-report/2014-essay-pdfs/Essay-2-Corlett.pdf>.

- [15] C. Xu, T. A. Kohler, T. M. Lenton, J.-C. Svenning, and M. Scheffer. 2020. Future of the Human Climate Niche. *PNAS* 117(21): 11350–11355. doi: 10.1073/pnas.1910114117.
- [16] Met Office. One Billion Face Heat-stress Risk from 2°C Rise. <https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2021/2c-rise-to-put-one-in-eight-of-global-population-at-heat-stress-risk> (accessed Nov. 09, 2021).
- [17] UN. 2019. World Population Prospects 2019. <https://population.un.org/wpp/> (accessed May 17, 2021).
- [18] World Cities Report. 2020. The Value of Sustainable Urbanization | UN-Habitat. <https://unhabitat.org/World%20Cities%20Report%202020> (accessed Mar. 25, 2021).
- [19] D. Li *et al.* 2019. Urban Heat Island: Aerodynamics or Imperviousness? *Science Advances* 5(4): eaau4299. doi: 10.1126/sciadv.aau4299.
- [20] O. US EPA. 2014. Heat Island Effect. <https://www.epa.gov/heatislands> (accessed Nov. 03, 2021).
- [21] E. S. Kravtsov *et al.* 2021. Cooling Hot Cities: A Systematic and Critical Review of the Numerical Modelling Literature. *Environ. Res. Lett.* 16(5): 053007. doi: 10.1088/1748-9326/abdcd1.
- [22] F. Salamanca, M. Georgescu, A. Mahalov, M. Moustauoui, and M. Wang. 2014. Anthropogenic Heating of the Urban Environment Due to Air Conditioning. *Journal of Geophysical Research: Atmospheres* 119(10): 5949–5965. doi: 10.1002/2013JD021225.
- [23] GLZ. 2018. Coordinating Finance for Sustainable Refrigeration and Air Conditioning.
- [24] Report: Universal Access to Sustainable Energy Will Remain Elusive Without Addressing Inequalities, *World Bank*. <https://www.worldbank.org/en/news/press-release/2021/06/07/report-universal-access-to-sustainable-energy-will-remain-elusive-without-addressing-inequalities> (accessed Nov. 03, 2021).
- [25] Chilling Prospects: Tracking Sustainable Cooling for All 2019, *Sustainable Energy for All | SEforALL*. <https://www.seforall.org/publications/chilling-prospects-2019> (accessed Mar. 24, 2021).
- [26] How Countries Can Enhance Nationally Determined Contributions in 2021 with Climate-Friendly Cooling. *Clean Cooling Collaborative*. <https://www.cleancoolingcollaborative.org/report/how-countries-can-enhance-nationally-determined-contributions-in-2021-with-climate-friendly-cooling/> (accessed Sep. 02, 2021).
- [27] Boosting Climate Ambition: Enhancing NDCs with Climate-Friendly Cooling. *Cool Coalition*, May 12, 2021. <https://coolcoalition.org/boosting-climate-ambition-enhancing-ndcs-with-climate-friendly-cooling/> (accessed Sep. 02, 2021).
- [28] M. Guardaro, M. Messerschmidt, D. M. Hondula, N. B. Grimm, and C. L. Redman. 2020. Building Community Heat Action Plans Story by Story: A Three Neighborhood Case Study. *Cities*. 107: 102886. doi: 10.1016/j.cities.2020.102886.

- [29] A. Revi *et al.* 2014. Urban Areas in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. pp. 535–612.
- [30] Human Capital and Climate Action: Outcomes that Deliver for People and Planet. <https://blogs.worldbank.org/climatechange/human-capital-and-climate-action-outcomes-deliver-people-and-planet> (accessed Mar. 24, 2021).
- [31] N. M. Tord Kjellstrom. 2019. Working on a Warmer Planet: The Effect of Heat Stress on Productivity and Decent Work, Report, Jul. Accessed: Mar. 25, 2021. [Online]. Available: http://www.ilo.org/global/publications/books/WCMS_711919/lang--en/index.htm.
- [32] Y. Chavaillaz *et al.* 2019., Exposure to Excessive Heat and Impacts on Labour Productivity Linked to Cumulative CO2 Emissions. *Scientific Reports* 9(1), Art. no. 1, Sep. doi: 10.1038/s41598-019-50047-w.
- [33] Girls Spend 160 Million More Hours than Boys Doing Household Chores Everyday. <https://www.unicef.org/press-releases/girls-spend-160-million-more-hours-boys-doing-household-chores-everyday> (accessed Jun. 04, 2021).
- [34] K. Lundgren-Kownacki, E. D. Hornyanszky, T. A. Chu, J. A. Olsson, and P. Becker. 2018. Challenges of Using Air Conditioning in an Increasingly Hot Climate. *Int J Biometeorol* 62(3): 401–412. doi: 10.1007/s00484-017-1493-z.
- [35] Climate Change and Health. <https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health> (accessed Apr. 28, 2021).
- [36] WHO | Climate Change, WHO. <https://www.who.int/heli/risks/climate/climatechange/en/> (accessed Apr. 28, 2021).
- [37] Impacts of Climate Change on Meeting Government Outcomes in England (Paul Watkiss Associates), *Climate Change Committee*. <https://www.theccc.org.uk/publication/impacts-of-climate-change-on-meeting-government-outcomes-in-england-paul-watkiss-associates/> (accessed Nov. 03, 2021).
- [38] R. Jadhav. 2015. Indian Chicken Prices Surge to Record as Heat Wave Kills Millions of Birds. *Reuters* (accessed: Jun. 02, 2021). [Online]. Available: <https://www.reuters.com/article/india-heatwave-chicken-idUSL3N0YM0B920150601>.
- [39] S. Dash, A. K. Chakravarty, A. Singh, A. Upadhyay, M. Singh, and S. Yousuf. (2016). Effect of Heat Stress on Reproductive Performances of Dairy Cattle and Buffaloes: A Review. *Vet World* 9(3): 235–244. doi: 10.14202/vetworld.2016.235-244.
- [40] V. Sejian, R. Bhatta, J. B. Gaughan, F. R. Dunshea, and N. Lacetera. 2018. Review: Adaptation of animals to heat stress. *Animal* 12: s431–s444. doi: 10.1017/S1751731118001945.
- [41] V. Belsare and V. Pandey. 2008. Management of Heat Stress in Dairy Cattle and Buffaloes for Optimum Productivity. *Journal of Agrometeorology* 10: 365–368.
- [42] Indian Dairy Association – 45th Dairy Industry Conference | nddb.coop. <https://www.nddb.coop/about/speech/dic> (accessed Jun. 02, 2021).
- [43] Rocky Mountain Institute (RMI) 2018. Solving the Global Cooling Challenge.

- [44] Professor Peters: We Need to Reinvent the Cold Chain. hydrocarbons21.com (accessed Apr. 28, 2021).
- [45] Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, and M. Tignor, and T. Waterfield (eds.). 2018. IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.
- [46] Country data – Green Cooling Initiative. <https://www.green-cooling-initiative.org/country-data/#!total-emissions/all-sectors/absolute> (accessed Feb. 14, 2021).
- [47] Tracking Buildings 2020 – Analysis. *IEA*. <https://www.iea.org/reports/tracking-buildings-2020> (accessed Mar. 25, 2021).
- [48] CLIMATE ACTION PATHWAY: Net-Zero Cooling – Executive Summary, *Cool Coalition*, Dec. 10, 2020. <https://coolcoalition.org/climate-action-pathway-net-zero-cooling-executive-summary/> (accessed Feb. 15, 2021).
- [49] R. Gonzalez-Lezcano and S. Hormigos-Jimenez. 2016. Energy Saving Due to Natural Ventilation in Housing Blocks in Madrid. *IOP Conference Series Materials Science and Engineering*, 138: 012002. doi: 10.1088/1757-899X/138/1/012002.
- [50] T. Peters, Clean Cooling Landscape Assessment. 2018. [Online]. Available: <https://www.clean-cooling.ac.uk/resources/CleanCoolingLandscapeAssessment%2012-18.pdf>.
- [51] Shell LNG Outlook 2021. <https://www.shell.com/energy-and-innovation/natural-gas/liquefied-natural-gas-lng/lng-outlook-2021.html> (accessed May 06, 2021).
- [52] R. Agarwal, T. J. Rainey, S. M. A. Rahman, T. Steinberg, R. K. Perrons, and R. J. Brown. 2017. LNG Regasification Terminals: The Role of Geography and Meteorology on Technology Choices. *Energies* 10(12) doi: 10.3390/en10122152.
- [53] District Cooling. <https://www.danfoss.com/en-gb/markets/district-energy/dhs/district-cooling/> (accessed Nov. 12, 2021).
- [54] G. Maouris, E. J. Sarabia Escriva, S. Acha, N. Shah, and C. N. Markides. 2020. CO2 Refrigeration system Heat Recovery and thermal Storage Modelling for Space Heating Provision in Supermarkets: An Integrated Approach. *Applied Energy* 264: 114722. doi: 10.1016/j.apenergy.2020.114722.
- [55] UNEP. 2018. TEAP Report, Volume 5: Decision XXIX/10 Task Force Report on Issues Related to Energy Efficiency While Phasing Down Hydrofluorocarbons September 2018 (updated final report).
- [56] HVAC Preventive Maintenance is Essential (6 Reasons Why) – Indoor Air Quality Association. <https://iaqa.org/consumer-resources/hvac-preventive-maintenance-is-essential/> (accessed Jul. 07, 2021).
- [57] Digitalization and Energy – Analysis. *IEA*. <https://www.iea.org/reports/digitalisation-and-energy> (accessed Nov. 12, 2021).
- [58] Cooling – Analysis, *IEA*. <https://www.iea.org/reports/cooling> (accessed Feb. 17, 2021).

- [59] Breakthrough, Climate-Friendly ACs: Winners of the Global Cooling Prize Announced. *Global Cooling Prize*, Apr. 28, 2021. <https://globalcoolingprize.org/grand-winners-press-release/> (accessed May 12, 2021).
- [60] World Bank. 2021. The Cold Road to Paris: Mapping Pathways Toward Sustainable Cooling for Resilient People and Economies by 2050. World Bank, Washington, DC. (accessed Nov. 04, 2021. [Online]). Available: <https://openknowledge.worldbank.org/handle/10986/36439>.
- [61] Japans Top Runner Programme. *futurepolicy.org*, Dec. 15, 2014. <https://www.futurepolicy.org/climate-stability/japans-top-runner-programme/> (accessed Nov. 04, 2021).
- [62] EESL Mart. <https://eeslmart.in/> (accessed Nov. 08, 2021).
- [63] M. Singh and G. Gurumurthy, Bulk Procurement in Room Air Conditioning: A Critical Analysis of the EESL Program, The Energy and Resources Institute (TERI) and Shakti Sustainable Energy Foundation, 2019.
- [64] Ministry of Environment, and Forest and Climate Change, India Cooling Action Plan, 2019.
- [65] E. S. M. A. Program. Primer for Cool Cities: Reducing Excessive Urban Heat – With a Focus on Passive Measures, World Bank, Washington, DC, Jul. 2020. doi: 10.1596/34218.
- [66] Notices and Reports – Buildings Department. <https://www.bd.gov.hk/en/resources/codes-and-references/notices-and-reports/GFA.html> (accessed Nov. 12, 2021).
- [67] Q. K. Qian, K. Fan, and E. H. W. Chan (2016) Regulatory Incentives for Green Buildings: Gross Floor Area Concessions. *Building Research & Information* 44(5–6): 675–693. doi: 10.1080/09613218.2016.1181874.
- [68] M. Isaac and D. P. van Vuuren 2009. Modeling Global Residential Sector Energy Demand for Heating and Air Conditioning in the Context of Climate Change. *Energy Policy* 37(2): 507–521. doi: 10.1016/j.enpol.2008.09.051.