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THE COLD ECONOMY

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Abstract

Lack of cooling and cold-chain access is a critical development challenge that has significant implications for people's livelihoods, productivity, health, food, and nutritional security. While business-as-usual demand projections suggest 19 new cooling appliances will be sold every second by 2050, universal access to cooling is expected not to be a reality even at this rate of growth, leaving poor and vulnerable populations to suffer the consequences. The global demand for cooling is already pressuring the energy system and the environment and given all the social and economic benefits of cooling and cold-chain but also the environmental risks, there is now a major opportunity for governments and the private sector to develop and deploy sustainable, affordable, and resilient cooling solutions, and contribute to three internationally agreed goals simultaneously: the Paris Agreement; Sustainable Development Goals (SDGs); and the Kigali Amendment to Montreal Protocol. Achieving this will require a radically different approach to cooling and cold-chain provision that starts by asking what energy services are needed and explores ways to meet them with minimum environmental impact and cost, taking into account available renewable, thermal, and waste energy resources, synergies between processes and systems, and aggregation opportunities, rather than defaulting to electricity to generate cooling. Such a system-level approach sits at the core of the Cold Economy.

Keywords: cold economy, cooling, cold-chain, energy demand mitigation, renewable energy, waste energy recovery, sustainable development, climate change

JEL Classification: Q01, Q42, Q43, Q48, Q55, Q56, Q58

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1. INTRODUCTION

Before the days of refrigerators and air-conditioners that most of us take for granted today, how did people preserve their food or cool their patients and medications at hospitals in the 1800s? Ice harvesting was a major industry during the 1800s and early 1900s. Entrepreneurs, such as the Boston “Ice King” Frederic Tudor, were harvesting ice with horses pulling ice cutters across frozen lakes, ponds, and rivers and shipping it around the world, as far as Europe, India, and even Hong Kong, China (Peavitt 2017). Despite the massive logistical challenges, there were 35 commercial ice plants in the US by 1879, and 2,000 by 1909 (IFCO 2017).

The ice harvesting industry slowly “melted” away with the advent of electric refrigerators and their continued rise in the 1930s, with ice harvesting companies’ mottoes like “A block of Ice never gets out of order” and “Those who really know prefer Ice” falling short in the face of the then-new technology (Bien 2014). From transporting blocks of ice across the world with ships, we have now arrived at a situation where projections suggesting 19 cooling appliances could be sold every second over the next 30 years (Peters 2018a). Today, we rely on cooling so much that cooling devices already account for more than 7% of all global greenhouse gas (GHG) emissions, significantly contributing to climate change, and hence to their own demand (K-CEP 2018). Space cooling alone was responsible for nearly 10% of the world’s total electricity consumption in 2016 with a 300% anticipated increase by 2050 without intervention (IEA 2018).

Despite its anticipated growth and the associated impacts on energy systems and the environment, cooling has so far been largely ignored in the energy debate, with the focus mainly remaining on greening electricity, transport, and heat. This is a major problem, which could lead to serious long-term environmental and socio-economic consequences. As conventional cooling technologies are energy-intensive and highly polluting due to the refrigerants with high global warming potential (GWP), how we meet the booming cooling demand and integrate it into the changing energy system will play a critical role in meeting the ambitions of the Paris Agreement and Sustainable Development Goals (SDGs).

The global challenge of meeting this cooling demand in line with our climate ambitions presents a fast-growing business opportunity for innovative and sustainable cooling technologies. These will be essential elements of the Cold Economy. However, they will not be enough to deliver cooling for all who need it sustainably nor will the high levels of investments in renewable energy we have been seeing over the last decade. Going back to the defensive mottoes of ice harvesting companies in the 1900s, they in fact inadvertently made an important point. Today, vast amounts of cold that is readily available often in our local natural environs (e.g., cold-water bodies), or is rejected by other processes (e.g., cold energy from liquified natural gas (LNG) regasification that is typically released into the sea), is wasted. This cold energy could be recovered to meet some of the cooling demand, but only if we stop assuming a singular path to make, produce, store, and transport cold, relying on electricity and chemical energy storage. Such a system-level approach sits at the core of the Cold Economy and starts by asking what energy services we need and exploring ways to deliver them with minimum environmental impact and cost, rather than defaulting to business-as-usual practices.

2. THE COOLING CHALLENGE

2.1 Socio-economic Dimension: The Need for Cooling

Cooling is vital to our ability to function in the modern world and improving human well-being, boosting economic growth, enabling sustainable urbanization, lifting hundreds of millions out of rural poverty, and delivering socio-economic development through the Sustainable Development Goals (SDGs). Without it, we would not have access to safe and nutritious food, the efficacy of medicines and vaccines would be compromised, workplaces and homes would be less comfortable for safe productive work, effective study, and pleasurable leisure, and the digital systems that underpin every aspect of contemporary life would be unable to operate.

In 2019, 1.7 million deaths globally were linked to extreme temperatures. While extreme heat was responsible for around 20% of those (356,000 deaths, which is still a staggering number) compared to extreme cold, this number is set to rise significantly as the climate warms unless the effects are countered with affordable, accessible, effective, and sustainable cooling strategies. Indeed, the historical trajectory shows that deaths due to extreme cold increased by 31% from 1990 to 2016, whereas deaths attributable to heat increased 74% (Burkart et al. 2021). The infamous record-breaking 2003 heatwave in Europe, for example, made the severity of the issue more apparent. Fifteen thousand heat-related deaths were recorded in France, and around 70,000 across Europe (Robine et al. 2008). According to the UK Met Office, the temperatures reached in Summer 2003 are in fact likely to become a norm in 2040, and as a result, heat-related deaths per year could triple in England and Wales (UKHSA, NHS, and DHSC 2022; Zero Carbon Hub 2015).

However, this is only a fraction of the picture, and what is often overlooked is that billions more deaths worldwide are in fact attributable to lack of access to cooling. Around 600 million people fall ill due to foodborne diseases, with around 420,000 of them dying annually, due in part to the lack of a food cold-chain that would ensure safety and quality of food consumed from farm to plate (Afshin et al. 2019; WHO 2022). Each day 25,000 people die from hunger, while the lack of effective refrigeration directly results in the loss of 526 million tons of food production annually (or 12% of the total food produced), which could feed an estimated 1 billion people (Holmes 2009, 25; IIF/IIR 2021). At the same time, more than 1.5 million people globally lose their lives due to vaccine-preventable diseases each year (The Children's Hospital of Philadelphia 2014), again due in part to the lack of a health cold-chain that would deliver life-saving vaccines and other temperature-sensitive medicines to those who need it without compromising their safety and effectiveness, jeopardizing the realization of universal health. Estimates suggest that 25% of vaccines reach their destination with degraded efficacy mainly due to failures within the cold-chains. Logistical issues alone are responsible for 30% of all scrapped pharmaceutical products, and 20% of temperature-sensitive products are damaged due to broken cold-chains (Barrowclough 2020). The importance of health cold-chains has become more pronounced with the COVID-19 pandemic. The world has faced the largest ever vaccination challenge with a high percentage of the population needing to be vaccinated in a short period of time. As of March 2022, 63.1% of the world's population has received at least one dose of a COVID-19 vaccine. Yet only 12.9% of people in low-income countries have received at least one dose (Ritchie et al. 2020), and one of the underlying problems is the lack of adequate cold-chain infrastructure in these countries to maintain the efficacy of the vaccines from manufacturer to arm.

Extreme heat also restricts physical functions and capabilities and reduces work capacity and productivity. It affects workers both in outdoor settings, such as the world's 1 billion agricultural workers who are regularly exposed to high temperatures, and those who work in hot indoor settings, such as the 66 million textile workers who work in manufacturing facilities and workshops without air conditioning. Research suggests that temperatures above 24–26°C are associated with reduced labor productivity and that temperatures of 33–34°C can reduce the work capacity of a worker operating at moderate work intensity by 50% (Kjellstrom and Maître 2019). 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 (Jadhav 2015). It can also result in productivity loss and reduced reproduction rates (Dash et al. 2016; Sejian et al. 2018). For example, multiple studies conducted in India suggest that heat stress can reduce milk production by between 5% and 50% (Belsare and Pandey 2008; Indian Dairy Association 2017).

All of these come at a significant cost to economies, businesses, and livelihoods. For example, according to the Food and Agriculture Organization (FAO), the total food produced for human consumption but lost and wasted along the supply chain cost the global economy an estimated \$936 billion a year¹ (FAO 2014). In 2018, Boston Consulting Group (BCG) estimated that annual food loss and waste may reach to 2.1 billion tons worth \$1.5 trillion by 2030 (Hegnsholt et al. 2018). Another estimate by the FAO suggests food loss reduces income by at least 15% for 470 million smallholder farmers across the world (Rockefeller Foundation 2013). Access to food cold-chains would reduce food losses, which would in turn raise incomes of farmers by increasing the quality and proportion of their produce that reaches market. Moreover, the global cost of vaccine wastage due to products being exposed to temperatures outside of their recommended range is estimated to be \$34.1 billion annually, not including the substantial physical burden and financial cost of illnesses that could be avoided with on-time delivery of effective and potent vaccines (Nagurney 2020). On the other hand, estimates suggest that every dollar spent on child immunization provides \$44 worth of economic benefits in low- and middle-income countries (Ozawa et al. 2016). Extreme heat is expected to reduce productivity by as much as 12% in South Asia and West Africa by 2050, which may potentially result in up to a 6% gross domestic product (GDP) loss annually (Monsalve and Watsa 2020). 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 (Kjellstrom and Maître 2019).

Furthermore, lack of cooling access also raises concerns about equity across and within countries. Unfortunately, the burden of lack of cooling access will fall disproportionately on poor, disadvantaged, and often marginalized individuals and communities in developing countries that tend to be situated in some of the hottest parts of the Earth. This is an undue burden to start with, as developing countries are the ones who are the least responsible for, and least able to respond to, impacts of climate change. Moreover, from a gender perspective, women and girls face significant challenges in accessing cooling services and the benefits they provide. Especially in developing countries, women and girls typically spend more time at home engaging in domestic activities compared to men and boys. Inadequate space cooling at home harms their health, and lack of refrigeration reduces women's ability to provide better quality food for the family. The lack of vaccine/health cold-chains also impedes access of women and their children to basic health services due to barriers, such as limited access to family income to pay for transportation to reach health services, constraints

¹ Based on the 2012 market value.

on leaving home without a male chaperone, and lack of time due to household chores. Furthermore, women comprise approximately half of the agricultural workforce in developing countries (FAO 2011). In sub-Saharan Africa, women are responsible for approximately 70% of the production, 90% of the processing and 80% of the storage of food (Vercillo 2016). Limited access to cooling and a food cold-chain can significantly reduce their yields and economic growth.

2.2 Environmental Dimension: The Vicious Cycle

If we rely only on the current climate commitments of the Paris Agreement, the global mean temperature is projected to be 3.4–3.9°C higher relative to pre-industrial times by the end of this century (UNEP 2019). In order to realize the ambitious 1.5°C target of the Paris Agreement, the Intergovernmental Panel on Climate Change (IPCC) recommends a target of net-zero CO₂ emissions globally by around the mid-century, accompanied by deep reductions in non-CO₂ emissions (such as hydrofluorocarbons (HFCs) from refrigerant leakage and/or spillage) (IPCC 2018). Conventional cooling technologies, such as refrigeration, air conditioning, and fans, already account for more than 10% of global fossil CO₂ emissions, or 7% of all global greenhouse gas (GHG) emissions,² further warming the planet, in other words, contributing to their own demand (K-CEP 2018). HFCs are in fact the fastest-growing source of GHG emissions in the world due to the increasing global demand for space cooling and refrigeration (Rand, Jaeger, and Gencsu 2015). To this end, how we approach cooling provision will play a critical role in making the 1.5°C target a reality.

Energy demand for space cooling is the fastest growing energy service in buildings worldwide. In 2016, more than 2,020 TWh of electricity was used for air conditioning. This was nearly 10% of the world's total electricity consumption, and almost 20% of all the electricity used in buildings. While today only less than a third of households around the world own an air conditioner,³ two in every three households around the world is expected to have one by 2050. Due to rising temperatures, increasing incomes and energy access 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. Left unchecked, the electricity demand for space cooling could reach 6,200 TWh in 2050, consuming as much electricity as all of the People's Republic of China and India today (IEA 2018). In some hotter regions of the world, share of space cooling in electricity consumption already reaches staggering numbers. For example, 70% of Saudi Arabia's electricity is used for air conditioning (Schlanger 2018). In India, the share of air conditioning in peak electricity load is projected to reach 45% in 2050 from 10% today in the absence of any intervention (IEA 2018). The projected increase in space cooling electricity consumption will consequently result in a substantial rise in GHG emissions associated with energy use. Without intervention, GHG emissions from space cooling energy consumption could almost double by 2050 from 2016 levels (IEA 2018).

² In total, around 80% of the GHG emissions from cooling technologies is associated with indirect emissions from energy use, whereas 20% is associated with direct emissions from refrigerant use (Peters 2018a).

³ 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% (IEA 2018).

At the same time, mobile air conditioning (such as space cooling in cars, vans, buses, and trucks) is responsible for 3–20% of annual vehicle fuel consumption, depending on the climate conditions they operate in. But this number can peak at over 40% in hot climates and congested traffic. Estimates suggest that mobile air conditioning-related GHG emissions were around 420 million tonnes of CO₂-equivalent in 2015 with approximately 70% of the total coming from fossil fuel combustion and 30% from refrigerants. These emissions are set to more than triple without further action, reaching to 1,300 million tons of CO₂-equivalent by 2050 (IEA 2019).

Another fast-growing sector that requires attention is data centers. The data centers are a part of the world's critical infrastructure today. Global electricity consumption of data centers in 2020 was 200–250 TWh (IEA 2021b), which is more than the total annual electricity consumption of some countries, and this number does not include the energy used for cryptocurrency mining, which was around 100 TWh in 2020 (IEA 2021b). Projections suggest that annual electricity demand from data centers could reach to as much as 8,000 TWh by 2030 under worst case scenarios (and as low as 1,100 TWh under the best-case scenarios with significant efficiency improvements) (Andrae and Edler 2015). Data centers generate a significant amount of heat, and cooling is essential to the operation of any data center. In fact, cooling can account for up to 40% of a data center's energy usage.

In terms of food cold-chains, according to the IIF/IIR, food cold-chain equipment contributed 261 million tons of CO₂-equivalent emissions globally in 2017. However, there are also food loss emissions due to lack of cold-chains. Emissions from food loss and waste due to lack of cold-chain are estimated to be 1 gigaton of CO₂-equivalent in 2017. Therefore, the food cold-chain is responsible for 1,265 million tons of CO₂-equivalent emissions globally or around 4% of total GHG emissions (IIF/IIR 2021). Moreover, food loss and waste have wider implications for the environment. According to the FAO, food loss and waste⁴ account for 250 km³ of the world's freshwater annually—three times the volume of Lake Geneva—and 1.4 billion hectares or 30% of the world's agricultural land area (FAO 2014). Looking further into the distribution stage, a transport refrigeration unit consumes up to 20% of a refrigerated vehicle's diesel, and emits high levels of airborne pollutants: 6 times as much nitrogen dioxide (NO_x) and 29 times as much particulate matter (PM) as a modern Euro VI truck propulsion engine (Dearman 2015). According to WHO, seven million people die prematurely each year due to air pollution, hence these hidden polluters cannot be ignored. In the next decades, the GHG emissions from food cold-chain equipment are expected to increase significantly as new cold-chain capacity comes online in developing countries. For example, projections suggest that food cold-chain emissions could double by 2027 in India in the absence of any intervention (Kumar et al. 2018). Furthermore, additional capacity will be sought to improve the health cold-chains, which has gained a greater significance with the COVID-19 pandemic. Continued expansion of cold-chains using conventional fossil fuel-based and high GWP technologies could result in significantly higher GHG emissions, detracting from the benefits gained from avoided emissions from food loss and waste.

Efforts to decarbonize economies majorly focus on replacing fossil fuels with renewable and low-carbon sources. While these efforts will help with cooling GHG emissions associated with energy use, they are falling short in the face of unprecedented cooling demand. For instance, more than 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 (Campbell, Kalanki, and

⁴ Including the loss and waste that is not related to lack of cold chain.

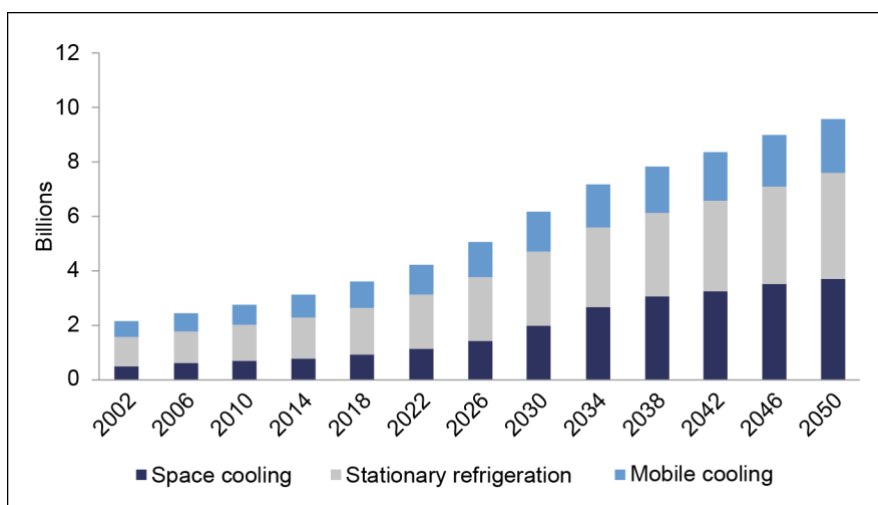
Sachar 2018). Similarly, 104 GW of solar power capacity was installed in 2018 while the energy demand resulting from new sales of room air-conditioner (AC) units only was 115 GW. In parallel, energy efficiency improvements are also falling short in meeting the cooling demand sustainably. For example, despite the efforts to improve energy efficiency, GHG 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 (IEA 2020).

Overall, the challenge we face is how to deliver cooling to everyone who needs it equitably, rather than just to those who are advantaged and can afford it, with minimum environmental impact and cost. The urgency of the challenge is now getting recognized globally with many governments developing and implementing National Cooling Actions Plans (NCAPs) and several international organizations developing tools, providing policy advice and funding, and raising awareness to support the transformation of the global cooling sector. These efforts are mainly concerned with equipment energy efficiency improvements in parallel with driving a phasing down of high-GWP refrigerants. For example, in responding to the threat posed by HFCs the Kigali Amendment to the Montreal Protocol was instigated in 2016 to phase down their production and use (UN 2016). The Kigali Amendment could help to “avoid up to 0.5°C of global temperature rise by 2100,” but there is much more to do beyond energy efficiency and refrigerants to address both climate change and SDGs simultaneously.

3. THE OPPORTUNITY

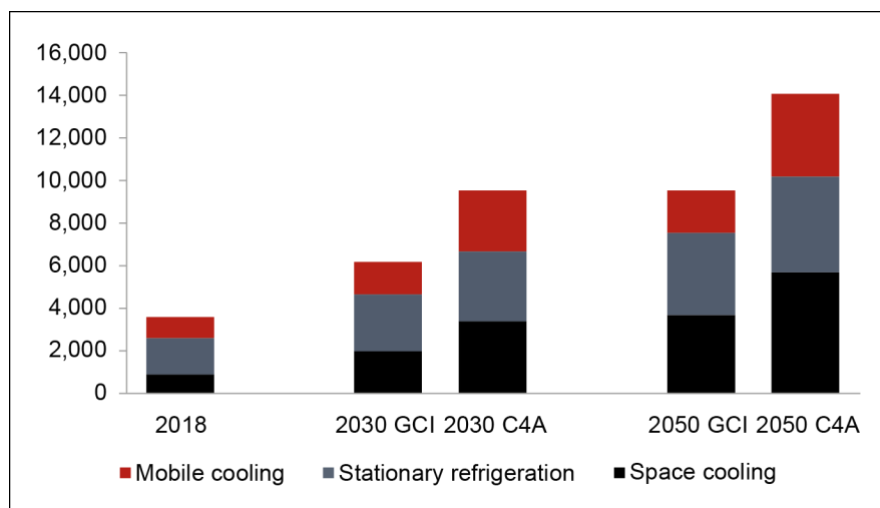
According to the Green Cooling Initiative (GCI), the number of cooling appliances could increase to 9.5 billion globally by 2050 from today’s 3.6 billion (Figure 1). To this end, the global annual sales of cooling equipment could grow to approximately \$270 billion by 2050 from \$140 billion in 2018 (Peters 2018b).

Figure 1: Number of Cooling Appliances in-use Globally, by Sector
(# of Units)



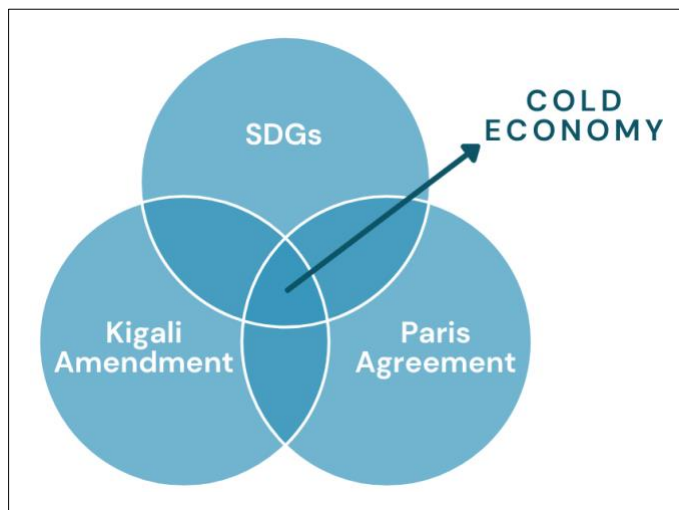
Despite the large-scale increase in cooling provision projected to take place by 2050, it is anticipated that access to cooling for all that need it to adapt to rising temperatures will still not be a reality at that time. In fact, providing cooling for all by 2050 would potentially require 14 billion active cooling appliances worldwide, which is 3.8 times as many appliances as are in use today (Figure 2). This is an important issue as providing access to cooling for all is critical to achieving many of the SDGs that the international community is currently off-track to deliver by 2030.

Figure 2: Total Cooling Equipment Stock by Sector (Million Appliances) – GCI versus C4A (Cooling for All) Projections



Assuming that appliance efficiency continues to improve as it has done historically, this would represent the consumption of more than 19,600 TWhs of energy per annum on cooling provision, which is more than three times the circa 6,300 TWhs energy budget allocated to cooling in the International Energy Agency (IEA) scenario for meeting even the less ambitious 2°C Paris Agreement target and 68%–101% of their projection for total supply from the world’s renewable energy infrastructure that year (Peters 2018a).

While cooling poses a massive environmental challenge, if its delivery is planned carefully it could contribute to three internationally agreed goals simultaneously: the Paris Agreement, SDGs and the Kigali Amendment, and this intersection is where we need to place the Cold Economy (Figure 3). The anticipated increase in cooling demand that the business-as-usual projections suggest combined with the unmet cooling needs that we must address—especially in the developing world where the cooling access gap is an endemic issue—represent a major opportunity for the private sector and governments to develop and deploy affordable cooling and cold-chain systems with minimum impact on environment and energy systems while strategically meeting climate and developmental targets. To underpin this opportunity, more detailed analyses are needed locally, nationally, and globally across multiple dimensions such as health, productivity, education, and income, taking into account equity issues to understand the real cost of lack of cooling to economies and societies. By doing so, we can better understand the economic, social, and environmental costs of failing to seize the opportunity that the surging cooling demand presents. This will facilitate investments in cooling technologies and systems, and the development of skills, business and finance models, and policy frameworks to support them.

Figure 3: Cold Economy and the Global Goals

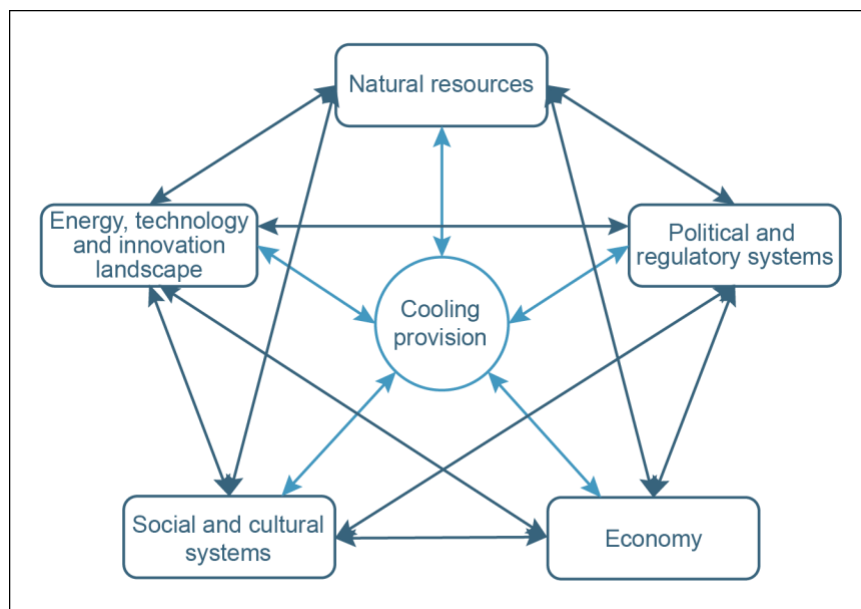
4. HOW DO WE DELIVER THE COLD ECONOMY?

Minimizing the GHG emissions from cooling and meeting the need simultaneously require delivering what Peters (2020, p. 2) has described as “clean cooling” provision:

Clean cooling provides resilient cooling for all who need it without environmental damage and climate impact. It incorporates smart thinking to mitigate demand or active cooling where possible, is minimised, and optimal use of natural resources, and a circular economy design that includes repurposing of waste heat and cold thermal symbiosis throughout the lifespan of the cooling system.

Clean cooling meets cooling needs while contributing towards achieving society’s greenhouse gas (GHG) emissions reduction, climate change mitigation, natural resource conservation and air quality improvement. It necessarily must be accessible, affordable, financially sustainable, scalable, safe, and reliable to help deliver societal, economic and health goals as defined by the United Nation’s sustainable development goals (SDGs). (Peters 2020)

To deliver cooling for all in a sustainable and resilient manner, there needs to be a paradigm shift to a different way of thinking that goes beyond simply taking business-as-normal action. To date, where there has been intervention to facilitate transition to more sustainable cooling provision, approaches have been inherently top-down, reductionist initiatives that typically focus solely on improving the energy efficiency of individual technologies or greening electricity. Such approaches are based on a linear logic and assume a singular path for sustainable cooling provision (i.e., thinking only in terms of electrons for cooling provision), ignore possibilities and alternatives as well as the potential impacts on other subsystems, and result in suboptimal outcomes and missed opportunities. This is because linear thinking by default disregards the interdependencies and feedback loops that exist amongst the cooling provision, natural resources, economy, energy, technology and innovation landscape, social, cultural, political, and regulatory systems (Figure 4).

Figure 4: System Linkages

By taking a holistic systems approach, we can better integrate our cooling service needs into the whole system. This would allow us to harness and leverage synergies between processes and other subsystems, but also to identify, plan for, and mitigate potential negative unintended consequences as well as to identify and reap potential indirect benefits that are often overlooked. For example, better connectivity to markets could allow farmers in developing economies to grow higher-value produce, which may in turn demand more water. This may have implications on water resources due to a move to potentially more water-demanding produce. A robust water framework will be needed to limit the extent of a shift to much more water-demanding agriculture. Similarly, availability of refrigeration at home can reduce the frequency of shopping, which can affect local marketplaces in developing countries. Understanding such consequences is important to meet cooling needs without affecting the overall sustainability of the whole system.

Equally, it is important to understand the wider benefits that sustainable and resilient cooling access would provide and integrate them into the decision-making processes. Approaches to cooling provision are often narrowly focused on simply measuring energy efficiency, 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. Examples of such an approach may include taking account of reduced food loss, reduced land-use change, healthier children, reduced visits to health centers and lower mortality from heat stress and air pollution, improved energy and community resilience, and increased sustainable job and investment opportunities, all of which can also provide additional economic benefits.

To summarize, to transition from an unsustainable into a sustainable state equitably, to ensure community and system resilience, and thereby to reach climate targets and help deliver the SDGs, it is critical to look at the dynamics between subsystems in the whole system.

4.1 The Cold Economy

We need a radically new needs-driven, systems-level vision to meet the current and constantly evolving future cooling needs with minimal climate and environmental impact and least cost. In physical reality the majority of the energy services required to support a modern society are thermal (i.e., for the provision of heating and cooling) and some predictions suggest that energy demand for space cooling globally could overtake heating by 2060 (Isaac and van Vuuren 2009). Yet vast amounts of cold that is already available are wasted, which could be recovered to meet some of the cooling demand by converting them into an energy vector to store and transport cold and start to mitigate cooling GHG emissions and to reduce pressure on the electricity grids. The mitigation potential of new energy-efficient cooling technologies and efforts to decarbonize electricity supply can only go so far, given the amount of projected cooling demand. The decarbonization of the wider energy system can be better supported by thermal-to-thermal solutions rather than electricity and chemical batteries. Such a system-level approach sits at the core of the Cold Economy. The key is that energy can be stored and moved to where the needs are in the form of cold rather than where the needs are than converted into electricity and then converted back again to cold. This will also support the wider energy system decarbonization by reducing the investment need for increased power grids 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 through thermal energy storage systems.

For instance, a massive amount of cold energy is wasted during the regasification process in the LNG regasification terminals, around 240 kWh per tonne of LNG. LNG is obtained by cooling natural gas down to the point of condensation, -162°C under atmospheric pressure, and regasified before supplying it to end-users. This untapped cold energy could be exploited at a certain stage of the LNG supply chain for multiple applications, providing an opportunity to recover part of the energy consumed at the liquefaction stage, improving energy efficiency and bringing considerable economic, environmental, and social benefits. Although there has been extensive research on LNG cold utilization technologies with various applications, the implementation level is still low. Globally, cold energy utilization currently represents <1% of the total potential (Agarwal et al. 2017).

In 2020, the global demand for LNG was estimated to have been 360 million tonnes, and it is expected to double to 700 million tonnes by 2040 (Shell 2021). That means, by recovering the waste cold energy from LNG regasification, we can theoretically supply 4,000 TWh high-grade cold from LNG regassification, which in turn can provide around 2.2 billion tonnes of CO₂eq emission savings (including the direct emissions) and more than \$440 billion worth of economic value by 2050. One barrier is that the majority of cooling demand is typically located far away from the LNG regasification plants, and this demand may be insufficient and unstable in many cases. Hence, the waste cold from LNG regasification is generally used for in-plant applications and/or sold to nearby industrial plants. Furthermore, without appropriate energy storage technologies, waste cold recovered can only be provided during the LNG regasification process. Hence, cooling demand needs to adapt to the LNG regasification schedule. These limitations

of time and place can be overcome by converting the waste cold into a vector or form that is storable and transportable, such as liquid air or nitrogen, allowing cold to be used at distant locations on demand.

For example, liquid air energy storage (LAES) is a long duration energy storage technology, which uses liquefied air as storage medium and can be integrated with the waste cold from industrial processes, such as LNG regasification. LAES uses off-peak or excess electricity to produce liquid air, which is then stored in pressurized above-ground tanks. Exposure to ambient temperatures results in rapid regasification and a 700-fold expansion in volume, which is then used to drive a turbine and create electricity without combustion. When the air liquefaction is integrated with cold sources, LAES can store waste cold in addition to electricity. Hence, LAES provides an opportunity to utilize both surplus electricity and waste cold energy. Such bulk energy storage technologies also play a critical role in facilitating renewable energy expansion. Wind and solar power are the fastest-growing sources of electricity globally. These sources are intermittent and uncertain, placing stress on the energy system operation. They are also connected to the grid without rotating mass. Instead, they are connected through inverters, which electrically decouple them from the grid, and hence they do not provide inertia, leading to weaker and more unstable grids compared to traditional grids. Long duration energy storage technologies can offer ancillary services that the grid needs, such as inertia, and also help in addressing the intermittency issue associated with renewables.

Developed by the University of Birmingham in 2015, the focus of the Cold Economy is on the efficient and effective integration of cooling with waste and renewable resources, and with the wider energy system, rather than individual technologies. The Cold Economy involves the development of integrated needs-driven—rather than demand-driven—resource-smart, system-level strategies first to mitigate the need for mechanical cooling, and second to understand and identify multiple cooling needs across buildings, food and vaccine/health cold-chains, transport and data centers, and explore aggregation opportunities, understand the renewable, thermal, and waste energy resources, and finally define the right portfolio of solutions that are fit for the economic, environmental, social, and cultural context, across behavioral changes, technology, skills, policy and regulations, finance, and business models to integrate those resources with service needs optimally and equitably.

Rather than presupposing cooling demand, the Cold Economy approach focuses on the services that are needed that depend on cooling. In other words, it is about asking “what are the energy services needed?,” rather than “how much electricity is required?” The first stage of such a needs-driven approach is going back to first principles and understanding at a macrolevel how much cooling would be required to provide comfortable environments for all to live, study, and work; to deliver food from farm to fork without any quantity and quality losses to feed the surging populations; to ensure universal health access and deliver life-saving vaccines and medicines from manufacturer to arm without compromising their safety and effectiveness; to ensure our digital infrastructure runs smoothly. Simultaneously, at a microlevel, we need to understand how people use cooling today; and how they seek to maintain or enhance this level of cooling, and how much cooling they need today, and will need in the future. Such an approach will enable effective minimization of the demand for mechanical cooling, hence the energy system demand, better integration of cooling needs with the wider energy system, and development of “fit for purpose” and “fit for market” cooling technologies and practices.

To summarize, realizing the Cold Economy requires:

- I. Minimizing the need for mechanical cooling through encouraging behavioral changes and passive technologies and approaches,
- II. Exploiting the opportunities for needs-based demand aggregation,
- III. Harnessing available renewable, thermal, and waste energy resources that are often readily available in the natural environs or are rejected by other processes,
- IV. Using thermal methods of storage rather than chemical-based batteries,
- V. Creating new finance and business models that create and share value equitably and lift financial barriers on clean cooling technologies and improve cooling access in urban as well as rural remote areas, rather than defaulting to extending grid electricity,
- VI. Creating skills and capacity in line with the technological progress to ensure adequate deployment, maintenance, and disposal,
- VII. Establishing an adequate policy and regulatory environment to bring clean cooling technologies and systems to market at scale (such as more stringent building codes and Minimum Energy Performance Standards (MEPS)).

4.2 Barriers to Transitioning to the Cold Economy

4.2.1 Equipment-based Projections, Rather Than Needs-based

Projection efforts on the scale of the cooling challenge are often based on historical equipment trends driven by socio-economic parameters such as gross domestic product GDP and population growth. The major issue is that these projections do not capture the unmet needs and consider how these needs will change (both in terms of size and nature) with often highly localized drivers, such as consumer preferences, local food production trends, new technologies, and modal shifts. Therefore, the current projections (1) have a high tendency to underestimate the actual size of the cooling provision that we need to accomplish to achieve our developmental targets, and (2) do not provide a clear understanding about what the cooling and cold-chain provision will look like in the future considering a wide range of drivers.

4.2.2 Lack of Credible Data

There is a lack of good-quality baseline data in many countries about equipment stocks, equipment sales, second-hand transfers of equipment, and refrigerant inventories as well as on the associated impact on the environment and energy systems. This is problematic as accurate baseline data are critical to understanding the real scale of the cooling challenge as well as to assess efficacy of any measures proposed.

4.2.3 Higher First Cost and Affordability

The high upfront costs associated with sustainable cooling technologies limit the uptake of such technologies, especially in the developing countries where many consumers who need cooling the most are under financial limitations. For example, most consumers purchase air conditioners that are two to three times less efficient than those available on the market, the major reason being the high upfront costs (IEA 2021a). Similarly, the vast majority of small-scale farmers in developing countries

cannot afford cooling technologies. For example, in sub-Saharan Africa (SSA), 62% of small-scale fresh produce farmers cannot afford cooling technology (Power for All 2021). To overcome this issue, financial incentives, such as subsidies for sustainable cooling technologies, can be effective in increasing the uptake. Microfinance institutions could enable vulnerable consumers to purchase new sustainable equipment technologies through mechanisms such as those that tie payment amounts to income generated. Equally, financial barriers and risk of investment could be addressed through business models such as pay-as-you-go (PAYG) and Cooling-as-a-Service (CaaS) that eliminate the need for customers to incur capital costs on asset ownership as well as maintenance costs.

4.2.4 Limited Financial Support for Research and Development

The development of sustainable cold-chain has been slow due to limited research funding. For example, the EU spent only 0.22% of its total engineering research budget on cooling research in 2018 (Peters 2018b). Investment in research and development (R&D) is not only critical to accelerate technological innovation, but also to make solutions more affordable and accessible to all.

4.2.5 Lack of Awareness Amongst Stakeholders

Consumers are often not fully aware of the emissions impact, energy consumption, maintenance requirements, and operating costs of cooling equipment they own. Equally, there is sometimes a lack of awareness about the availability and the lifecycle benefits of more sustainable equipment. This is also true for investors and donors, which poses the risk of the limited financial support available going to substandard interventions. This can potentially result in higher financial costs in the long run, with equipment and infrastructure needing to be replaced early or retrofitted to comply with new regulations and standards along with missed GHG mitigation opportunities.

4.2.6 Lack of Skills and Capacity in Developing Countries

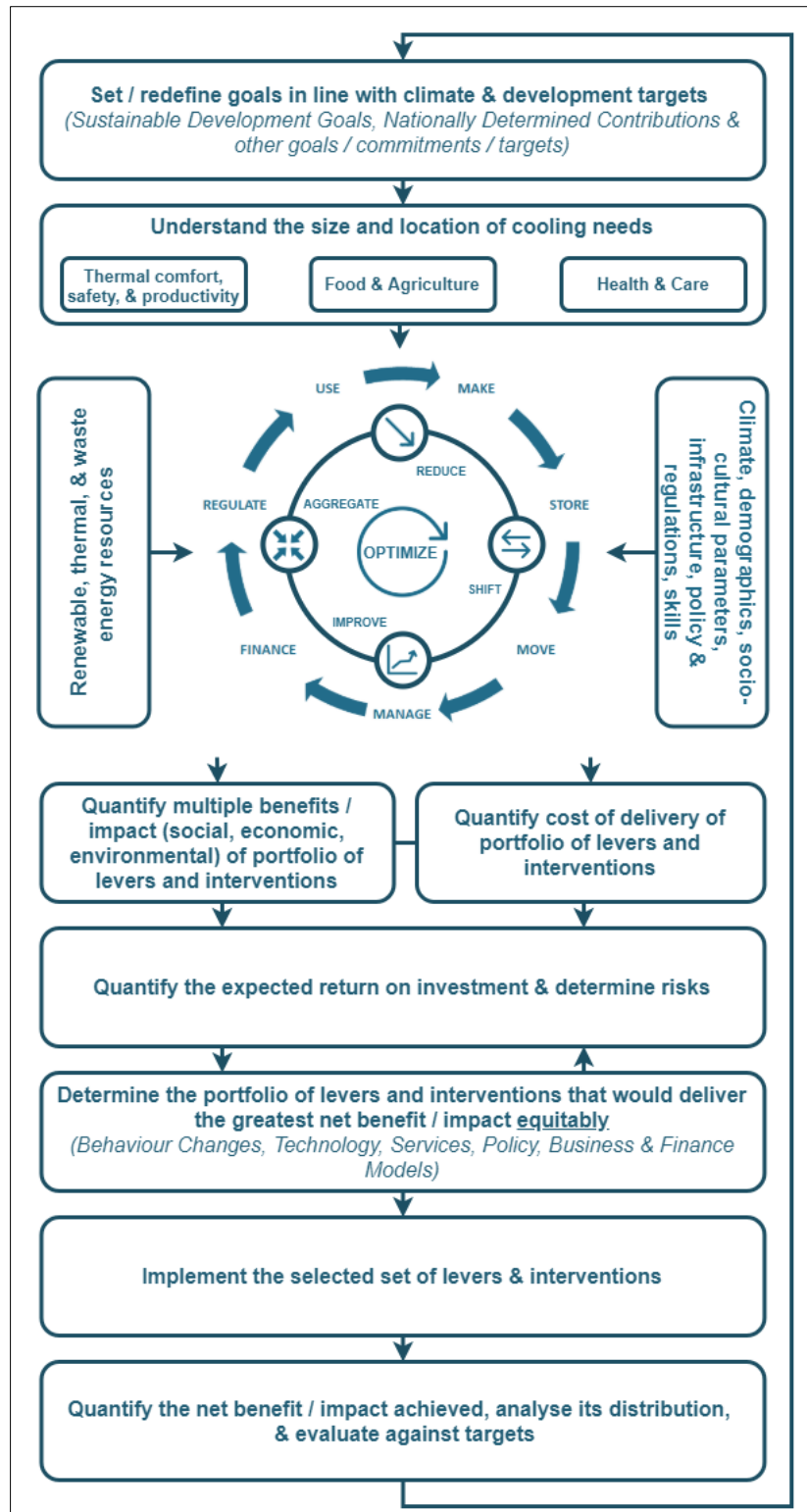
In many countries there are not sufficient numbers of trained technicians and engineers to deploy, operate, and maintain new technologies as well as safely decommission old systems, a problem compounded by new sustainable technologies that require an expansion in skills. Hence, there is a need for accreditation bodies and curriculum developers to be more agile in responding to trends in new cooling technologies and to modify and expand the curriculum accordingly. This is important in developing a cooling workforce with the right skill sets for the proper installation and maintenance of new technologies and innovative solutions, taking into consideration the digitalization of the sector and the rapid pace of advancements, demanding dynamic and continuous training.

4.2.7 Inadequate Legislation and Standards

Equipment-labeling programs and minimum energy performance standards (MEPS) are powerful tools for governments to raise consumer awareness about the impact of equipment and drive inefficient and polluting equipment out of markets. However, many governments have yet to adopt minimum energy performance standards, and other measures effective in promoting sustainable technologies, and where standards exist, they are typically not ambitious enough to bring best-performing available technologies to market at scale. Labels and standards should set targets to encourage equipment manufacturers to continually produce more energy-efficient and lower GWP equipment. As a best-practice example, Japan's Top Runner Program was designed to stimulate

continuous improvement by setting energy efficiency targets for appliances based on the most efficient model available on the market (Future Policy 2014).

Figure 5: Cold-chain System Design



Source: Authors.

Such lack of ambition in standards in developing countries along with a lack of robust monitoring and enforcement practices to prevent illegal imports also contribute to another problem: the dumping of substandard equipment to developing countries. This is because the developed countries impose typically higher equipment standards than the developing ones, and as a result the developing world faces the risk of becoming a dumping ground for equipment with low energy efficiencies and high GWP refrigerants. This can lock these countries into obsolete and substandard technologies for the next 15–20 years. For example, 75% of the refrigerators imported into Ghana from 2004 to 2014 were second-hand (GCI 2020).

Apart from labels and standards, wider legislation that could encourage transition is also often weak and/or poorly implemented. The UK government has only recently announced plans to remove subsidies for red diesel used in transport refrigeration units in 2022 to encourage cleaner transport (HMRC 2021). However, this also requires financial support to assist businesses in transition. According to the Cold-Chain Federation (CCF), this change will add £100 m in additional cost to the supply chain (Global Cold Chain News 2021). Equally, the cooling sector demands more clarity from governments about their decarbonization strategies to trial and adopt new technologies to reduce the risk of investment. For example, according to a survey conducted by the CCF, **“lack of clarity on what to invest in”** is the top barrier to achieving net-zero emissions in the cold-chain with 53%, followed by “lack of technology” with 24% (CCF 2021).

4.2.8 Lack of Reliable Energy Access in Developing Countries

In many communities in developing countries, electricity sources are unreliable or non-existent. Around 789 million people today still do not have access to electricity in their homes or communities (IEA et al. 2020). Due to a combination of high electricity tariffs and lack of access to electricity, many cooling services today typically rely on expensive fossil fuels with significant environmental impact in these countries. Unreliable energy access also limits the viability of some new technologies in these countries. For example, CO₂ refrigerant systems are significantly more susceptible to loss of full charge during power outages (Merrett 2020).

4.3 Designing the System

The key is, prior to undertaking system design work, to quantifiably set goals in terms of the benefits and impacts based on economic and social priorities, taking full account of the requirements of the Paris Agreement, the Kigali Amendment, and the SDGs. These goals should cover benefits that need to be achieved across social, economic, and environmental dimensions rather than solely focusing on energy efficiency gains and associated cost savings.

Second, it is essential to understand the size and location of the cooling needs to be addressed along with available renewable, thermal, and waste energy resources as well as climatic, demographic, socio-cultural parameters, existing infrastructure, policy and regulatory landscape, and available skills and technical expertise, which will inform the system design analysis to determine the optimal portfolio of levers and interventions (across behavior changes and passive solutions, technologies, services, policy and regulations, and finance and business models) that match the cooling needs and deliver the greatest net benefits equitably.

In the design stage, what is needed is to take a systematic approach to cooling provision, which defines the seven elements of a cooling system as use, make, store, move, manage, finance and regulate:

Make	Harness unused resources such as cold-water bodies (e.g., lakes, aquifers) and cool air, renewable energy (e.g., wind, solar), waste cold (e.g., cold energy from LNG regasification) and heat, or ambient heat sinks (e.g., ground source, sky cooling)
Store	Store energy thermally, in physical mass (e.g., thermal walls) or phase-change materials (e.g., ice) to make use of cyclical changes in ambient heat sinks and supply of (electric) energy at lower costs
Move	Use new energy vectors and materials to move thermal energy
Use	Reduce cold loads by lowering cooling demand (e.g., insulation, building aspect, shading, natural ventilation, white roofs), increasing equipment efficiency, and substituting refrigerants with high GWP. Highlight behavior change and demand mitigation strategies likely to be effective, whilst maintaining required service levels. Note that technology, services, policy, and financial solutions can all be used to help drive consumer behavior in the direction of efficiency, and shift meeting the cooling need towards more sustainable technologies. Behavioral change and the other four solution categories, as in addition, modal shifts can substitute for cooling solutions, with much lower energy use (e.g., transportation of vaccines by airborne drones in rough terrain)
Manage	Build skills and capacity in line with the technology development to ensure the correct installation, maintenance, and disposal. Make cooling systems smart for real-time monitoring of cooling needs and performance, load adjustments and integrated system management and storage
Finance	Develop new finance and business models to improve access to cooling and facilitate equitable distribution of costs and benefits (e.g., servitization models), taking into account marginalized individuals and communities, as well as women and girls
Regulate	Bring clean technologies and sustainable design approaches to the market through building codes, labeling programs and MEPs to incentivize building developers to adopt more sustainable design approaches and equipment manufacturers to produce more energy-efficient and lower-GWP equipment as well as to foster innovation, regulate consumer choice and raise consumer awareness about the impact of clean technologies. Implement robust monitoring and enforcement mechanisms to prevent illegal imports of equipment and non-quota/counterfeit refrigerants.

To deliver cooling with minimal climate and environmental impact, the strategy is to use a “reduce—shift—improve” approach, adding in the intervention of “aggregate.” These four interventions can simultaneously support cooling system transition, facilitating both early wins and the deep systemic changes to reduce both direct and indirect cooling GHG emissions through mitigation of cooling needs; move to highly energy-efficient mechanical technologies with the phase down of high GWP refrigerants; optimize the use of all available renewable, thermal, and waste energy sources, and by harnessing opportunities for demand aggregation. The resulting mix of technologies and design solutions will then need to be assessed with respect to barriers across policy and regulations, skills, affordability, as well as equity concerns. This will enable understanding where current policies and regulations perform well, and where they need to be redefined and/or enhanced, alongside the finance and business models that need to be developed, and the gaps that need to be closed in skills and capacity.

Through iteration, the mix of levers and interventions that will deliver the greatest net benefit equitably with minimum risk will be determined. The cost–benefit analyses should quantify and incorporate wider social and environmental benefits where possible, in addition to energy cost savings that the system will deliver to improve the scope of return on investment. Some of these benefits are the direct products of avoided GHG emissions, such as significant improvements of health or productivity increases through improved thermal comfort. While not always straightforward, quantifying these benefits will result in a more meaningful valuation process and reveal

the true value of levers and interventions. Even when the quantification is not possible, such as due to lack of data, it is important to at least identify these benefits to extract the strategic value of actions.

After implementation, the net benefit that has been achieved and its distribution across beneficiaries should be analyzed and evaluated against goals that were set in the first stage. This is a continuous and dynamic process that requires iteration due to the changes that are constantly emerging within the whole system. These include changing cooling needs due to many complex and often interconnected drivers, ranging from climate change, rising incomes, urbanization, changing consumer preferences to unexpected events (such as the rapid increase in cold-chain demand due to COVID-19), changing regulations, changing climate and developmental targets, changes and improvements in technologies, innovations, and the rapid pace of digitalization, among others. In short, the system requires constant monitoring of the impacts of implemented actions to see whether they are fostering the development of a sustainable and resilient cooling and energy system or whether some adjustments need to be made. Hence, it is crucial to measure the impact across social, economic, and environmental dimensions and to monitor the progress made towards sustainable development as well as the climate and environmental goals, targets, and commitments.

5. CONCLUSIONS AND RECOMMENDATIONS

Demand for cooling is on a rapid growth trajectory, with projections suggesting that the number of air conditioners and refrigerators could increase to 9.5 billion globally by 2050. But the one thing that is not clear to many is the difference between need and demand. The distinction is critical to understand in the context of cooling, with the latter incorporating an important dimension: delivering cooling for everyone who needs it, not just to those who can afford it. One of the main problems is that the current demand projections typically underestimate the scale of the challenge, which contributes to a lack of ambition in infrastructure and technology development, which ultimately could have far-reaching social, economic, and environmental consequences, preventing both SDGs and climate targets from being met. Therefore, firstly, the volume of cooling provision and cold-chain required to meet the cooling needs across food, health, and thermal comfort must be assessed and quantified, and the different ways the communities seek to maintain or enhance this cooling level to meet their health, economic, and comfort needs must be identified.

Second, rather than presupposing a top-down technical solution, possibilities of demand mitigation through the redesign of systems, the aggregation of demand, modal shifts, the use of waste or currently untapped resources, as well as support for existing cooling practices and behaviors must be explored. Understanding the challenges from a whole-system perspective is essential for identifying gaps and seizing the opportunities for mitigation and adaptation.

Such an approach will require consensus building and engagement of all stakeholders at all levels—industry, private sector, governments, academia, development institutions, and civil society, among others. Bringing together different sectors and parties is an immense challenge, but there is also a wide range of sources of knowledge, technical assistance, finance, policy initiatives, and political processes that already exist and offer routes that can help to drive cooperation in meeting the cooling challenge. There is now a great opportunity to get the cooling right both for the people and the planet. The ultimate and long-term objective is to maximize the sustainability of

the cooling and wider energy system globally, ensure system and community resilience, and enable an equitable and just transition, considering cooling needs ranging from thermal comfort to cold-chains. This can only be achieved by following the Cold Economy principles and driving a new systems-level thinking in key areas of make, store, move, use, manage, finance, and regulate cold; not by just deploying energy-efficient cooling technologies at every home, workplace, or farm gate.

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