The Hot Reality:
Living in a +50˚C World

Making the case for cooling as critical infrastructure

A COP28 Briefing Note

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Foreword

The provision of cooling[1] is not an optional extra or a lifestyle luxury. We argue that it is a critical service for a well-functioning, well adapted, resilient and healthy society and economy, enabling access to the basic essentials of life, such as food and health, and providing safe environments in which to live, work, learn and play. More broadly, cooling underpins modern communications, national and international trade and commerce, and individual as well as state-level economic well-being.

Cooling is already central to lifting hundreds of millions out of rural poverty and delivering socio-economic development in line with the Sustainable Development Goals (SDGs). Today, around a billion people would benefit from a reduction in the 12% of global food production lost due to a lack of refrigeration, and while 25% of vaccine doses are wasted globally because of failures within cold-chains, more than 1.5 million people worldwide die from vaccine-preventable diseases. As Rwanda's Honourable Minister for Environment, Dr Jeanne d'Arc Mujawamariya recently remarked: "Making cold-chain part of the critical infrastructure is key to breaking millions of rural and urban poor out of poverty and hunger, accelerating economic growth, and meeting our Vision 2050."[2]

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> ***Rwanda's Honourable Minister for Environment***

In recent years, record breaking summer temperatures in the high 40˚Cs and low 50˚Cs have been measured in places worldwide where their occurrence would previously be unimaginable. As the world continues to warm and humans seek to adapt to increasing seasonal ambient temperatures, as well as more frequent, prolonged, and intense heatwaves, the provision of cooling will become ever more critical. For example, with crop yields and livestock productivity projected to decline in the decades ahead due to near-term climate change, it will be vitally important that as much perishable food produce as possible is conveyed to its destination in cold-chains, so that it arrives fit for consumption in good nutritional condition. Similarly, the emergence of new disease vectors, as well as the spread of known diseases such as malaria and dengue fever into new territories, will also demand the expanding and reorganising of health-related cold-chains, to ensure that all who need vaccinations receive them in a timely manner and nations across the globe have the capacity to contain outbreaks.

In many countries, heat stress is expected to reduce economic productivity, for instance in South Asia and West Africa, it is anticipated to decline by as much as 12%, potentially resulting in up to a 6% GDP loss annually. In the absence of adequate cooling for worker comfort and relief from hot environments, such losses will not only put immense pressures on economies and health systems, but also exacerbate global disparities between Global North and South and worsen societal inequalities that

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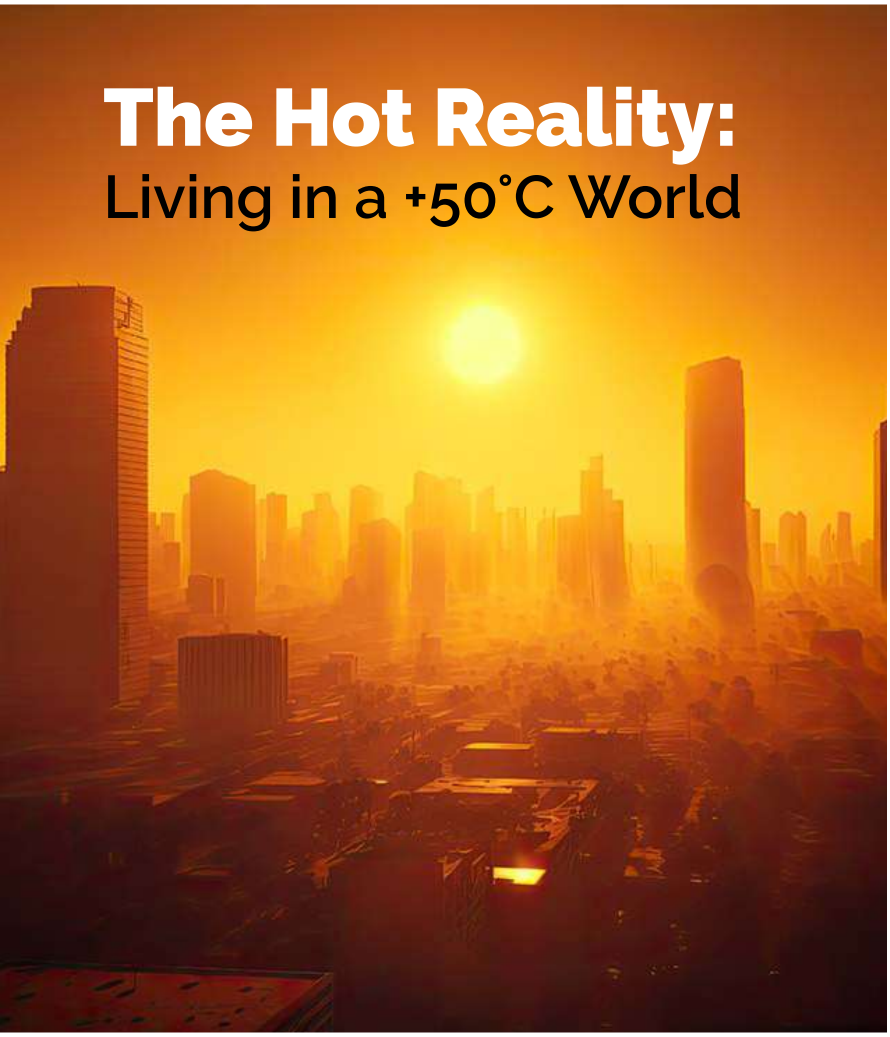
[1] Cooling includes thermal comfort and space cooling; industrial and commercial refrigeration, cold-chains for food and vaccines, domestic refrigeration

[2] See appendix 2 – Cold-chain and Rwanda Vision 2050



already run deep. Ensuring that the infrastructure systems that will deliver cooling in the future are designated as critical, well-adapted and climate change resilient, is therefore essential to all.

The equipment, assets, people, business and finance models and other non-physical components that form infrastructure systems delivering the critical service of cooling offer an adaptation strategy to help humanity survive and thrive in a +50˚C world. They are critical infrastructure, both at the national and global scale, and must be recognised as such by governments, international bodies and wider civil society. This Briefing Note makes the compelling case for the formal designation of cooling infrastructure systems as critical infrastructure, describes the benefits in doing so, and proposes important next steps that must now be taken towards this vital goal.

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Contents

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Introduction

In response to unprecedented heatwaves across the northern hemisphere in the summer of this year (2023) and record breaking global monthly mean temperatures, the UN's Secretary-General António Guterres announced in July that "the era of global warming has ended" and "the era of global boiling has arrived"[1]. That month saw the hottest three-week period ever recorded and the three hottest days experienced by humans on the planet since temperature measurement began. As the year has progressed monthly records have continued to be exceeded, both in the northern hemisphere's late summer-early autumn and the winter of the southern hemisphere. In addition to the all-time high in the low 50˚Cs measured in China (52.2˚C), summer temperatures in the upper 40˚Cs have been experienced for prolonged periods across the southern United States, northern Mexico, Europe, north Africa, southern Asia and Japan. Both South America and Australia have experienced warm winters[2], with the latter having its warmest on record[3], and southern Africa endured a prolonged heatwave that many described as effectively extending the summer into a year-round season[4]. Botswana, Namibia, Mozambique and South Africa all maintained winter temperatures in the high 30˚Cs and Malawi recorded values 20˚C above the seasonal average. Indeed, globally 2023 is anticipated to be the warmest year on record to date [5].

Climate change induced extreme heat is not a temporary or future issue. Urban environments in which temperatures above 50˚C are experienced is already a reality for many of the world's cities. In Pakistan, temperatures exceeded 50˚C in Jacobabad[6] and numerous locations across India recorded values between 45˚C and 50˚C in May of 2022. In the same year, June temperatures reached 52˚C in the Iranian city of Abadan[7] and in an earlier year Turbat in Pakistan measured the world's fourth highest temperature, 53.7˚C (2017)[6]. While the relatively temperate regions of North America and northern Europe have not yet experienced a temperature of +50˚C, the records are approaching this landmark figure, and it is anticipated that it will be exceeded soon. A 2021 summer temperature record of 49.6˚C was recorded in Lynton, British Columbia[8] and in the same year 48.8˚C was reached in Syracuse, Sicily[9]. This is happening in a world with 1.2˚C of global warming.

An even warmer world ahead

The hot reality is that in the absence of meaningful action on climate change mitigation through substantial greenhouse gas (GHG) emissions reductions, the world will become even warmer in the years and decades ahead. Indeed, based on current emissions reduction policies being pursued by governments worldwide, there is no credible pathway to achieving the 1.5˚C target of the Paris Agreement[10], which would limit changes in climates globally to levels that are considered safe by the scientific community. Without any further intervention, by 2070 up to 3.5 billion people around the world could be exposed to annual mean temperatures higher than nearly anywhere today[11]. It is therefore essential that humanity begins to prepare for a hotter world characterised by increased ambient seasonal temperatures and more frequent, prolonged, and extreme heatwaves. And to do so in an environment where climate induced extreme weather is simultaneously leading to more severe flooding and drought events, putting additional disruptive pressures on infrastructure for energy, transport, and water supply, as well as global supply chains delivering food, vaccines and medicines, fuels, raw materials and manufactured goods worldwide. A foretaste of the latter was experienced in this year's northern hemisphere summer when unprecedented drought conditions impacted the movement of shipping through the Panama Canal[12].

The Hot Reality: Living in a +50˚C World project, led by the Centre for Sustainable Cooling and the Africa Centre of Excellence for Sustainable Cooling and Cold-Chain (ACES) in Kigali, Rwanda, sets out to consider the impact of heat on humans and the broad range of essential cooling services upon which we rely to survive and thrive. In particular, the study focuses on food and nutritional security, health, buildings and the built environment, and the functioning of modern societies in terms of workplace output, economic productivity, digital

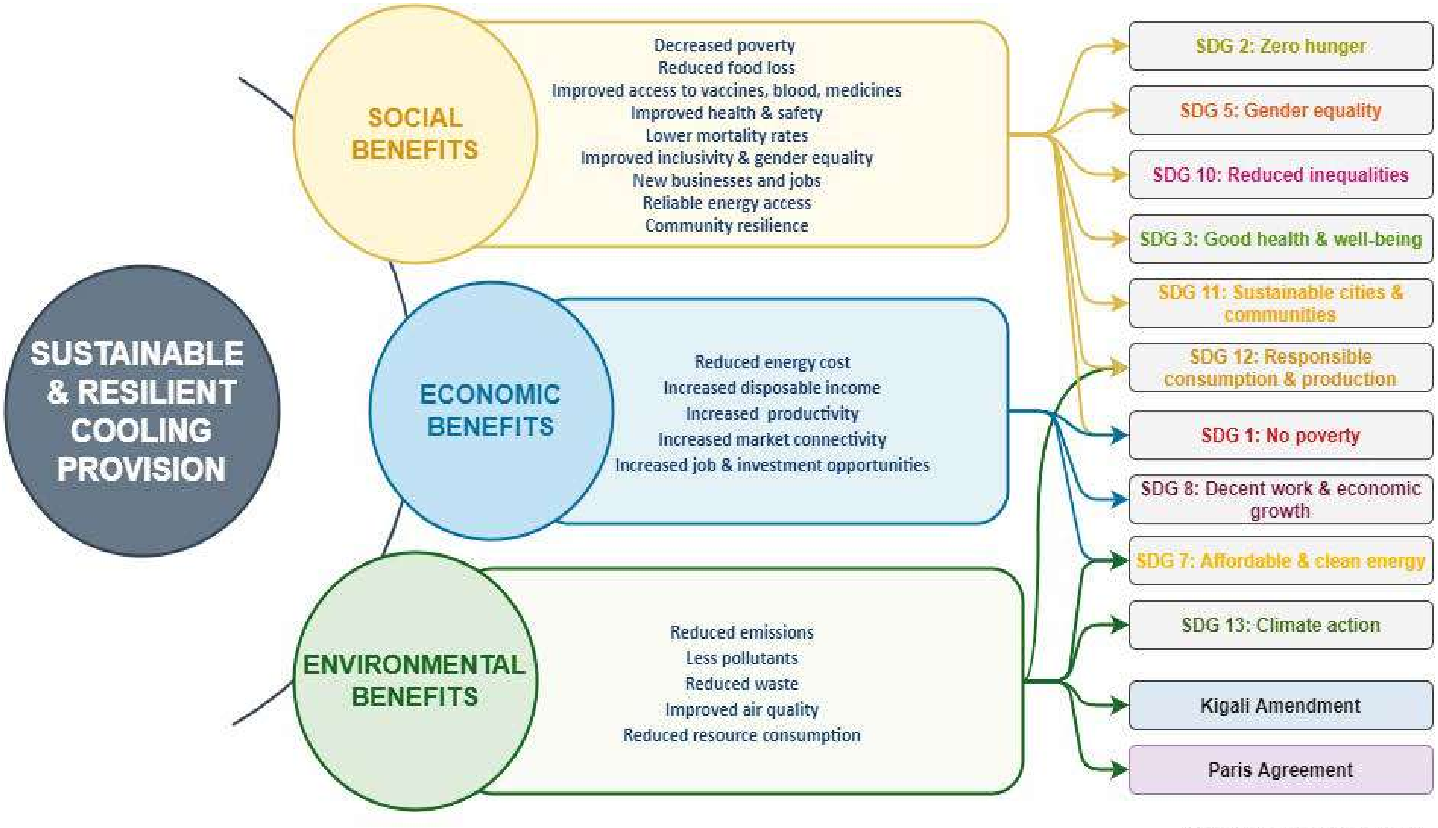

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Figure 1: *The relationship between sustainable cooling and the SDGs. Kigali Amendment to the Montral Protocol and Paris Climate Agreement.*

infrastructure, the movement of people in migration patterns, and the socio-economic disparities that lead to political and geopolitical tensions and instability.

Initial findings from the project show that sustainable cooling[3] is a core adaptation strategy for humanity to deal with higher ambient seasonal temperatures and more frequent, prolonged, and extreme heatwaves. Furthermore, the research undertaken in the study to-date has highlighted that cooling is a critical service, as important to our ability to function in the modern world as portable water or mobility, and that the infrastructure that delivers it, is critical infrastructure. Today, globally, 12% of food produced annually is lost[4] due to a lack of proper temperature management[13], 25% of vaccines degrade on the journey from manufacturer to recipient's arm[14], economies underachieve with US$ trillions wiped from productivity globally, and 1,000s of people die in heatwaves every year. In the hotter, +50˚C World of the near-term future, these statistics will become substantially worse unless action on adaptation to higher temperatures and capacity building for resilience to extreme heat impacts is urgently taken by international bodies, national governments, and society across the globe.

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[3] Delivering zero emissions cooling on a lifecycle basis, whilst in parallel balancing environmental, social and economic needs and benefits and leaving a positive lasting sustainable legacy for future generations.

[4] Across Sub-Saharan Africa small-holder farmers typically contribute about 80% of the food produced within their individual country (Business Call to Action 2021). However, about 37% of the region's produce is lost between production and consumption, including almost 50% of fruits and vegetables (World Bank 2020), resulting in lost income to these financially poor farmers upon whom the global food system relies for a substantial portion of its supply.

Adapting to higher temperatures and extreme heat through sustainable clean cooling

The impact of higher temperatures and heat extremes on people, places and the functioning of society will be both broad and deep, as described in detail in the Appendix 1 attached to this Briefing Note, with thermal comfort and safety, human health, mortality and food security, digital connectivity, workplace output, global supply chains and economic well-being all significantly affected. Already today, extreme heat leads to fatalities, for example 61,000 people lost their lives across Europe in a series of summer heatwaves between May and September 2022[15] and 37% of the warm-season heat-related deaths occurring in 43 countries from 1991 to 2018 have been attributed to climate change induced temperature rises[16]. As well as the direct impact on mortality, incidents of temporary and permanent illness, accidents and injury increase as a result of heat events, placing strain on health services and impacting workplace productivity. According to the UN International Labor Organization (ILO), assuming a 1.5°C rise in global mean temperature by the end of this century, an increase in work-related heat stress and loss of productivity equivalent to 2.2% of total global working hours is expected in 2030. This equates to 80 million full-time jobs and a cost of $2.4 trillion [17].

Growing concerns

There is growing concern that one of the most significant health impacts of climate change will be the emergence, re-emergence, and spread of infectious diseases. Evidence indicates a warmer environment changing the distribution of disease vectors, with many mosquito species, ticks, flies and other insects able to persist for longer, or inhabit places where they have not been recorded before[18]. This will have consequences for disease outbreaks in human populations unfamiliar with them and lacking the knowledge and health infrastructure to manage the outbreak.

Beyond human mortality, health, workplace output and economic productivity, higher temperatures are affecting the production of all food types by decreasing yields and impacting quality, with negative implications for food security worldwide. For example, it is estimated that there is a 6-7% loss in plant yield per 1°C increase in temperature above the meteorological season mean conditions[19] and milk production has been observed to reduce by up to 50% under some extreme conditions[20,21]. Overall, some projections suggest that crop yields and livestock productivity could decline by up to 30% by 2050[22]. Heat related reductions in the productivity of agriculture, horticulture, aquaculture and sea fishing worldwide, combined with decreased performance of refrigeration equipment (typically a 1.5-2.5% degradation per 1°C rise above the design temperature) and climate change related disruption to global supply chains[12],

Geothermal heat pump system, demonstrating the utilisation of natural underground heat for sustainable heating AND cooling.

already affect food availability, accessibility and affordability for millions of people across the globe, particularly those living in the Global South and the most vulnerable in all nations.

Sustainable cooling provision will be at the core of strategies to adapt to higher seasonal ambient temperatures and more frequent, prolonged, and intense heatwaves. Multiple sectors, governments, and publics in many nations worldwide, both developed and developing, will need to adjust comfort expectations and behavioural norms; reconfigure ways of living, operational practices, and economic, business and finance models; adjust policies, standards, and regulations; and create and refurbish cooling infrastructure. The task ahead is enormous and will need to be undertaken in such a way that it supports the transition to renewable energy, ensures GHG emissions are not increased further[5], adheres to the principles of economic, environmental and sustainability, and does not exacerbate existing injustices and inequalities or create new ones.

Sustainable cooling as an adaptation strategy

Applying sustainable cooling as an adaptation strategy will involve implementing change and new approaches across the built environment; food supply; vaccine and medicine distribution; digital infrastructure; and industrial production, supported by enabling governance frameworks; policy interventions; regulations; new and revised standards; and radical game-changing innovation in research; technology; funding; finance and business models; and training and skills development. Many specific individual adaptation solutions will necessarily be sector-based and place-based, but when spatially integrated will form complex national and international infrastructure system adaptations affecting billions of people across the globe. For example, place-based and sector-based adaptations to heat impacts on food production, storage and transportation in individual African nations will, in combination with multiple place-based and sector-based adaptations in international supply chains and their supporting sectors, effect food and nutritional security in many countries 1,000s of miles away.

Increasing injustice and inequality in access to cooling.

Sustainable Energy for All[23] has defined nine critical countries for the deployment of cooling technologies and within these the number of people at high risk (rural and urban poor) grew between 2021 and 2022 by an average of 7%. The organisation's annual Chilling Prospects reports have in recent years been extended to include forecasts for scenarios of populations at future risk, due to a lack of cooling provision, through to 2030. The forecasts published in 2022[24] show that across 54 high-impact countries, plus the high-temperature regions of an additional 22 countries, current trends would result in 1.22 billion people at high risk in 2030, compared to 1.2 billion in the 2022 analysis. This trend indicates that injustice in inequality in access to cooling is, in the context of current policies, interventions and actions, set to increase rather than decrease.

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[5] According to the IIR, cooling technologies, such as refrigeration, air conditioning and fans, currently account for about 20% of the overall electricity used worldwide and this figure is expected to double by 2050. Additionally, cooling is responsible for 7% of all GHG emissions[25] and it is estimated that by 2030 these emissions could be double the value, possibly triple by 2100[26]. Moreover, hydrofluorocarbons (HFCs) are the fastest-growing source of GHG emissions in the world because of the increasing global demand for space cooling and refrigeration[27].

Sector-based and Place-based Adaptations

Specific, individual, sector-based and place-based adaptations to heat impacts will encompass a large number of cooling technologies and approaches, ranging from changes in refrigeration, ventilation and air-conditioning system design and operation, the re-specification of refrigerants, improved cooling equipment maintenance and enhanced technical skills training:

- **in the built environment, adjustments to room temperature expectations and workplace practices, the adoption of passive and natural cooling techniques, deployment of district cooling networks, and establishing interconnected green spaces, cool refuge spaces and cooling hubs;**
- **in food production and supply, the development of heat and drought resistant plants, diversification of farm production, cooled indoor horticulture, farming and aquaculture, and reducing food losses by raising awareness of food preservation techniques and deploying sustainable cold-chains;**
- **in health, the use of ultra-fast delivery systems, such as flexible, reconfigurable drone-based infrastructure for highly temperature sensitive vaccines based on mRNA technology and rapid response to emerging diseases, study of serology and other markers for vaccine need in vulnerable populations to prioritise product use, and wastewater surveillance to witness and characterise the ever-changing repertoire of environmental pathogens and signals of sub-clinical-/mild human disease;**
- **in digital, the increased use of evaporative cooling and absorption chillers, utilisation of seawater, lake-water, grey and effluent water etc. for cooling, application of direct liquid cooling of core components in server racks, relocation of data centres to cooler climates nearer the poles;**
- **in industrial production, changes to plant equipment layouts, adjustments to chemical and physical processes, updating of safety procedures, co-design with employees of new working practices, rescheduling of manufacturing and production operations, refurbishment of factory buildings and revised design envelopes for new builds.**

Cooling infrastructure involves large-scale systems formed of many physical and non-physical sub-systems operating within larger complex physical and non-physical systems that impact upon them, and they, likewise, simultaneously impact. Taking a high level, holistic, whole systems thinking approach is therefore a prerequisite for an optimised outcome to planning, building, operating, maintaining, adapting, and decommissioning such infrastructure.

Systems thinking

In the application of sustainable cooling as an adaptation strategy for living in a warmer world, at its most basic minimal level, systems thinking should be applied to the physical assets that form cooling infrastructure. Extreme heat events, such as prolonged high temperature heatwaves, impact physical engineered infrastructure systems and the response of individual mechanical, electrical and structural sub-system components will be different depending on a range of factors, including location, age, design criteria, tolerance to heat, materials, and state of repair, amongst others. However, despite this being the case, there is limited understanding, both in the academic literature and professional practice, of the interdependencies between these sub-system components and the overall infrastructure system, as well as co-dependent linked systems, during extreme heat events. Although system-based approaches are known and readily applicable to climate-related contexts, their use in practice is not yet widespread.

However, although it is important at a minimum level to encourage wider analysis and understanding of the physical engineered system, to ensure the successful use of sustainable cooling as an adaptation strategy it will be necessary to look beyond it and take a holistic whole systems view. In this regard, consideration needs to be given to the non-physical sub-system components within the overall infrastructure system - such as the regulatory environment, societal norms of what is acceptable and expected and who provides it; the financing mechanisms, the motives of the actors involved, human capacity and skills requirements for resilient delivery, etc. - as well as the physical and non-physical interdependencies and feedback loops at the whole systems level as illustrated in Figure 2. In essence, the 'eco-system' within which the cooling infrastructure sits and operates must be considered in line with the core social goals cooling needs to deliver - i.e., safe environments to live and work, the provision of affordable and nutritious food year round, or the provision of universal healthcare.

Such an approach is essential to minimise the demand for active cooling equipment and ensure individual cooling technologies are supported by the broader system landscape in which they are embedded (such as manufacturing, energy, transport, waste management, etc.). It is also vital for a full understanding of the interdependencies and their management, as well as ensuring that all components work synergistically and efficiently together.

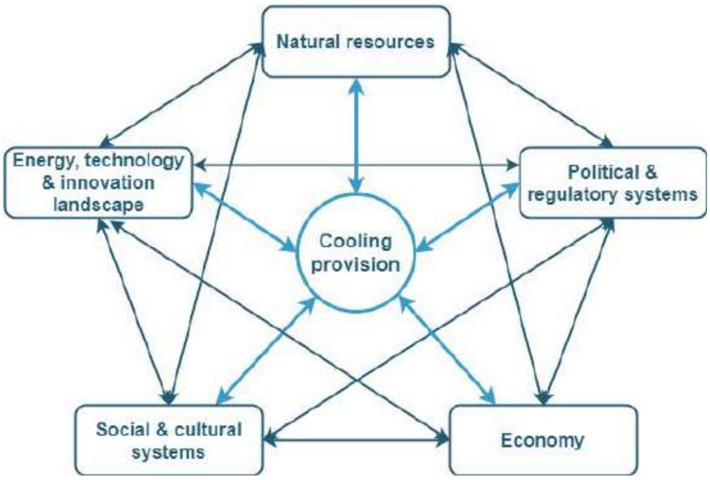


Figure 2: *Physical and non-physical interdependencies and feedback loops at the whole systems level that apply to the provision of cooling infrastructure (which itself is composed of physical and non-physical sub-system components).*

Needs and priorities

Opportunities and barriers

Behavioural change

Business Models

~Finance models

Social-economic environment

Cultural norms

Political and policy landscape

Development goals

Skills and capacity building

Thermal energy resources

Supporting infrastructure

Technology

IT and trading platforms

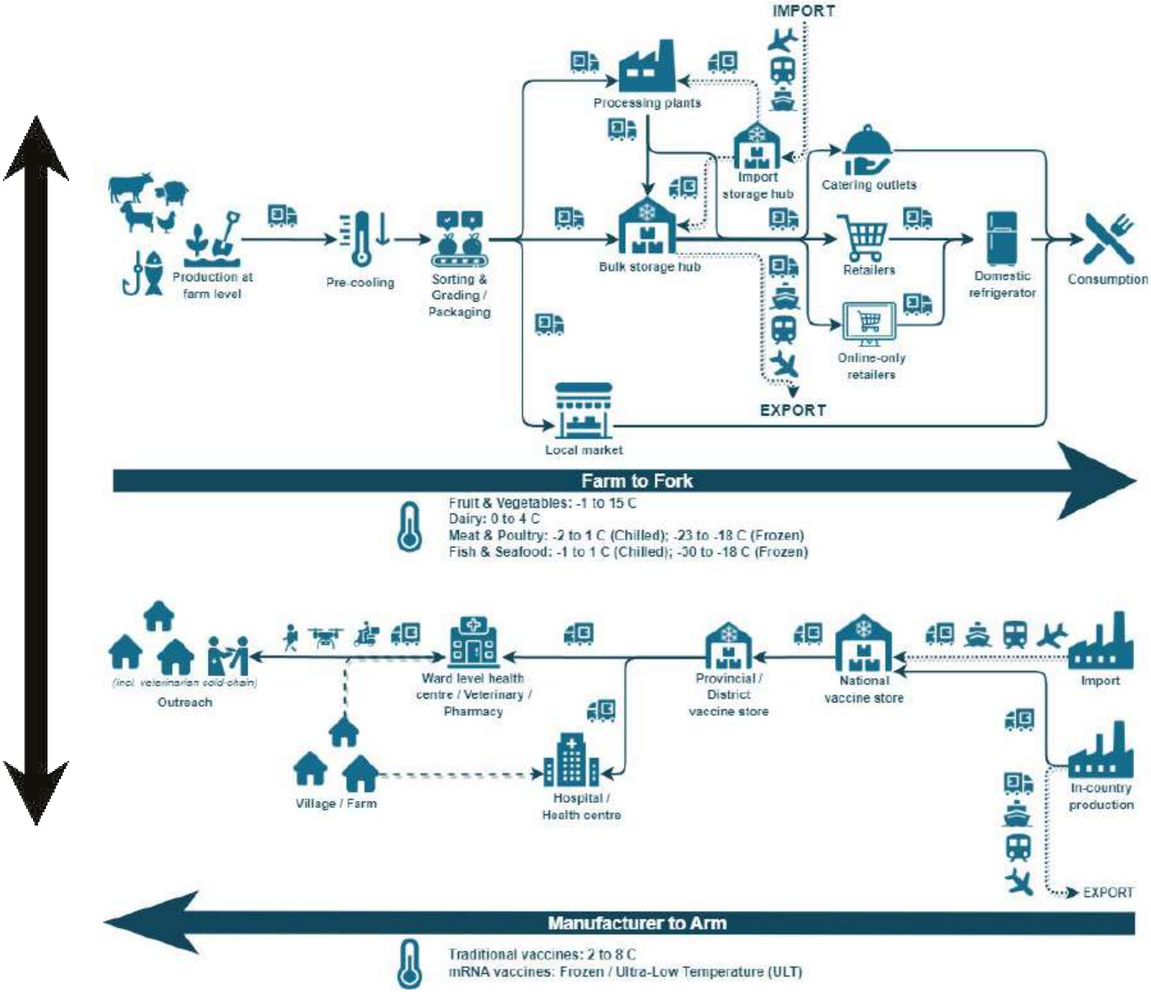


Figure 3: *Visualisation of a holistic whole systems approach for two cold-chain based cooling infrastructure 'eco-systems': 1) (upper diagram) 'farm to fork' perishable food produce supply chain and; 2) (lower diagram) 'manufacturer to arm' vaccine distribution chain.*

Figure 3 presents a visualisation of this approach for two cold-chain based cooling infrastructure systems: 1) 'farm to fork' perishable food produce supply chains (upper diagram) and; 2) 'manufacturer to arm' vaccine distribution chains (lower diagram). In this example, the physical engineered infrastructure system components are illustrated diagrammatically in the chain's process flow map visualisation, whilst the text on the left-hand side of the figure lists: (upper group) the non-physical infrastructure system components; (middle group) the non-physical interdependencies and feedback loops at the whole systems level; (lower group) the physical interdependencies and feedback loops at the whole systems level.

Holistic whole systems approach

By taking a holistic whole systems approach, the cooling service needs can be integrated more effectively, efficiently, and optimally into the infrastructure system. This allows not only the harnessing and leveraging of synergies between processes, energy resources (including waste heat and cold rejected from industrial and other processes) and other subsystems, but also the identification, planning for, and mitigation of possible negative unintended consequences, as well as the realisation of potential indirect benefits that are often overlooked.

Unlocking the multiple benefits

It is important to understand the wider benefits that access to sustainable cooling can provide and integrate them into decision-making processes. Current 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 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. Realising a truly sustainable cooling system demands understanding, quantifying, and valuing the broader and potentially strategic impacts of cooling along with their linkages to climate and developmental goals, targets, and commitments. The key is to recognise that social and environmental benefits do have financial value which often translate to reductions in other costs or lower economic losses. Examples of such an approach may include taking account of reduced food loss, decreases in land-use change, improvements to the health of children (for example, reduced stunting and malnutrition), reductions in visits to health centres and hospitals, lower short-term and long-term mortality, improved energy and community resilience, and increased sustainable job and investment opportunities, all of which can also be expressed as additional economic benefits.

Cooling is Critical Infrastructure

	Thermal comfort		Removing heat and maintaining stable temperatures for industrial and commercial purposes		Maintaining stable temperatures for food and medicine transport and preservation	
Application	**Mobile Air Conditioning**	**Space Cooling**	**Industrial Refrigeration**	**Commercial Refrigeration**	**Transport Refrigeration**	**Domestic Refrigeration**
	Cooling in passenger cars, commercial vehicles, buses, trains planes etc	Indirect district cooling and room air conditioning or fans for human comfort and safety in buildings	Used on farms, and in food processing (including marine) and pharmaceutical factories and product distribution centres	Used in supermarkets, restaurants and other retail premises, e.g. display cabinets and cold rooms	Movement of goods over land and sea, preserving their safety and quality, and extending shelf life	Safe storage of food and extension of its shelf life

Figure 4: *Cooling services*

When considering infrastructure systems, climate change resilience is a sub-set of systemic resilience, which is defined by the United Nations Office for Disaster Risk Reduction (UNDRR) as "a property of an infrastructure system that arises dynamically when the national infrastructure is organised in such a way that it can provide agreed critical services (power, heat, communications channels, mobility services, potable water, and wastewater and waste removal) despite endogenous and/or exogenous hazards, and despite the addition, modification and removal of infrastructure components"[28]. Logically, the infrastructure that delivers agreed critical services is 'critical infrastructure'.

As climates change across the globe in the years and decades ahead, some services that international bodies and governments do not currently regard as critical will emerge as vital and require identification as such. Although not widely recognised today, cooling is already a critical service, as vital as potable water and mobility to the ability of a modern society to function. Without it, we would not have access to safe and nutritious food; the efficacy of medicines and vaccines would be compromised; homes, workplaces and public spaces would be less comfortable for safe living, productive work, effective study, healthcare provision and pleasurable leisure; and the digital systems that underpin every aspect of contemporary life would be unable to operate. In the context of a hotter world, cooling provision will become even more critical.

The European Commission defines critical infrastructure as an asset or system which is essential for the maintenance of vital societal functions and states that damage to such infrastructure, its destruction or disruption, may have a significant negative impact for the security of the European Union (EU) and the well-being of its citizens[29]. In addition to being a critical service, cooling will become increasingly important to the food, health, digital, industrial and economic security of the EU and many nations worldwide, and be vital to the well-being of their citizens, as they seek to adapt the way humans live and function in response to climate change impacts. The infrastructure systems that provide cooling are critical infrastructure.

Before identifying what specific physical and non-physical components form a critical infrastructure system, and ensuring its systemic resilience, it is important to first understand the critical service need fully. For example, when considering non-fossil energy in terms of infrastructure, governments, academics and professional practitioners in the sector typically think immediately of electricity generators for renewable energy exploitation, associated changes in power grid configurations, and the use of batteries or pumped hydro as a storage technology, thereby jumping straight to the physical assets of the system and missing the first step of asking the critical service need question: how best to deliver the energy service both now and in the future? Asking the latter leads to a realisation that in fact most of the energy services needed to support a modern society are thermal in nature and delivering them through the use of electricity may not be the most sustainable, resilient infrastructure solution. Addressing the critical service need question is especially important in the context of a changing climate and the emergence of radical, disruptive and unforeseen innovations, both of which will affect fundamentally the way human society operates as it strives to transition economies away from fossil fuel dependency and unsustainable resource consumption.

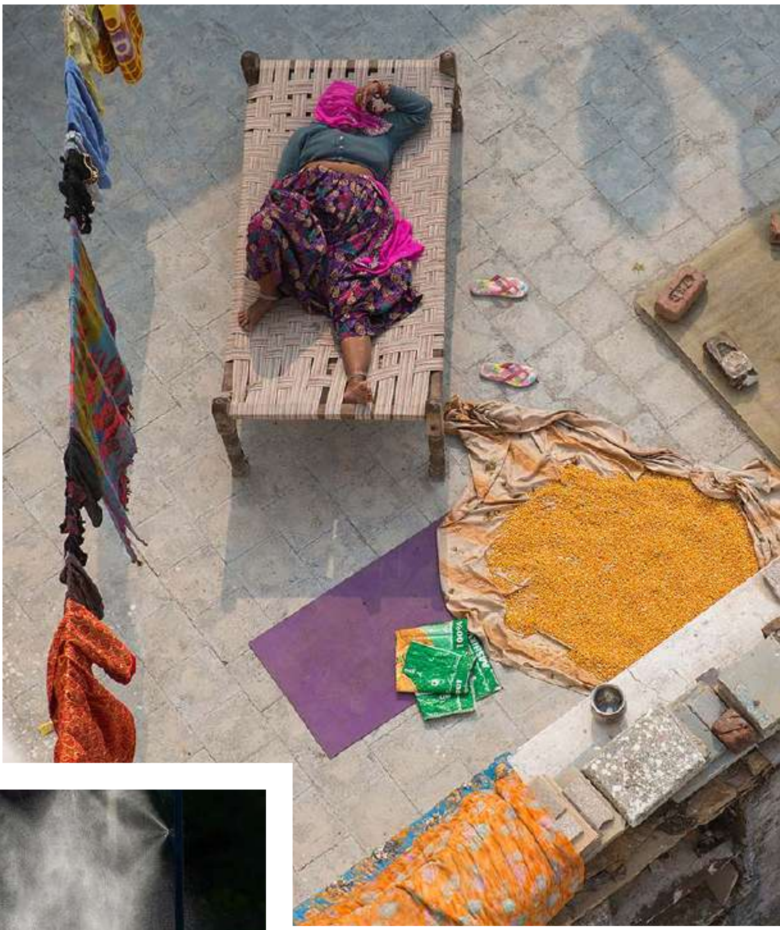
Asking the critical service need question

As nations transition to the supply and use of renewable energy, as well as adopting more sustainable resourcing solutions more broadly, if an element of the critical service need for cooling is to cool a city, should a business-as-usual approach be adopted of encouraging the autonomous uptake from the marketplace of individual air-conditioning (AC) units that consumers connect to an electricity grid? Or, instead, would the provision of district cooling infrastructure linked to a thermal heat sink, such as the sea, or river or underground aquifer, be a more sustainable, resilient solution? Likewise, if there is a need to take a supermarket's chiller cabinet off-grid at times of peak demand, or run a solar-powered vaccine fridge at night in a remote rural location, should the energy be stored in a lithium-ion battery or ice (or other phase change material)? Recognising that the majority of our energy services are in fact thermal, asking the critical service need question to determine what specific service is needed and how best to deliver it in a sustainable, resilient, future proofed way is key to ensuring the infrastructure system components are optimally identified.

Societal changes

Fully understanding the critical service need requires consideration of not only current societal requirements but also those that might emerge in the future. By mid-Century societal and demographic change, as well as changes in behavioural norms, cultural expectations and technology, may have driven widespread radical shifts in, for example, work-life balances, attitudes to commuting and working from home, dietary preferences and food procurement practices, and the acceptance of new drugs and vaccines. In the built environment, the adoption of artificial intelligence (AI) and a transformation to more flexible, fragmented, spatially and temporarily dispersed, formal and informal models of work could fundamentally change the use profile of domestic, commercial, and industrial buildings. Food procurement practices might shift in the next 30 years towards alternative proteins and local sourcing models, possibly in urban areas the latter being partially based on an increase in the vertical farming sector, dramatically altering supply chain needs. In parallel, a shift to a largely e-commerce rather than physical shopping retail model, driven by today's 'digital native' younger generations maturing into peak purchasing power, could become the societal norm, transforming 'last mile' delivery. In the medical domain, widespread acceptance of new vaccine technologies, along with the emergence of future pandemics based on yet unknown viruses, might drive radical changes in approaches to administering vaccines in delivery programmes, for example including the use of drones as a core element of the distribution logistics chain.

Such societal changes would have profound impacts on the cooling service need and thereby the physical and non-physical components of the critical infrastructure system that can most sustainably meet it and be resilient in a hotter world. To address this challenge, systems modelling is needed to rapidly conceptualise, build, test and deploy future proofed needs-driven cooling. The key to a successful outcome will be to avoid developing, deploying and supporting seemingly well adapted and systemically resilient infrastructure that may become redundant by mid-Century, because the sector, sub-sector, market or societal need disappears (after a substantial amount of human endeavour and physical resources have been invested unnecessarily).



Designing future-proofed sustainable, resilient and equitable cold-chains.

In a world of growing globalisation and uncertainty, both food and health security are threatened by many factors. Cold-chains are an integral part of the associated value chains and their dynamic capacity to continue to deliver against food and health security goals despite changes to the system, as well as disturbances and shocks, will be critical.

Designing a sustainable, resilient, and equitable cold-chain requires taking a responsive, future-oriented approach by understanding how the cold-chain needs, climate, technologies, policies and regulations, social norms, food, and health systems respond to innovations, such as alternative proteins, vertical farming and new vaccine technologies. The latter may include requirements for sub-zero cold-chains and future vaccine evolution for targeting new variants of disease and new populations. Consideration also needs to be given to opportunities for conflation of food and health products into a more synergistic strategy to develop both efficiency and resilience across the total cold-chain. But also, equally important, it requires understanding and minimising risks, and planning for future disruptions to the system, which are likely to happen more frequently.

However, both in the developing and developed world, there is limited understanding with regard to what an economically, environmentally, and socially sustainable and resilient cold-chain should look like in 10-20 years. Current models are often backwards-looking, based on historical equipment trends, failing to take changes to the system and future risks into account, and focus on short-term performance over long-term potential and value. Given the equipment and infrastructure we deploy during the rest of this decade will likely still be in operation in 10-15 years, this is problematic not only in terms of optimising investments and managing risks, including the impact on energy consumption from source to destination, transition to renewables, and GHG emissions, but also in terms of effectively addressing changing cold-chain needs over the long term and reaping opportunities.

Thinking thermally and cooling infrastructure

In physical reality, at the core of creating an optimised sustainable, resilient, outcome for the global energy system is seeking as close a balance as possible between thermal needs for a wide range of heating and cooling applications and available thermal resources. Yet, despite this obvious fundamental requirement, large numbers of available heat sinks and other natural and manmade thermal resources are unused or underutilised, whilst at the same time cooling demands are consistently met by using electricity resulting in energy inefficiency, unnecessary supply pressures on power grid infrastructure (including new peak demands), and avoidable GHG emissions. The mitigation potential of new energy-efficient electrically powered cooling technologies, along with efforts to decarbonise electricity supply can only go so far, given the amount of projected cooling need[30]. A radical rethink is therefore essential.

A holistic whole system level approach and 'thinking thermally' sit at the centre of the Cold Economy, a concept developed at the University of Birmingham which focusses on the efficient and effective integration of socio-economic cooling needs with available natural, waste, and renewable energy resources, thereby supporting the increased use of thermal-to-thermal solutions within the global energy system.

This alternative approach is a radical shift away from business-as-usual: improving the efficiency of individual electrically driven technologies, decarbonising electrical power, and using chemical batteries for energy storage. The key is that energy can be stored - and even moved - to where the cooling needs are in the thermal form of cold, rather than converting available renewable resources into electricity, transmitting the power to the location of the cooling demand, and then converting electric into cold. The Cold Economy thermal-to-thermal based perspective supports whole energy system decarbonisation by reducing the investment needs for increased capacity in power grid and generation

It is about asking "what are the energy services needed?", rather than "how much electricity is required?".

infrastructure, freeing up limited supplies of electricity generated from renewable energy for use in other applications, reducing peak energy demand, and creating opportunities for intermittent renewables and waste thermal energy resources through the provision of thermal energy storage systems.

Needs-driven

The starting point for a Cold Economy is the development of integrated needs-driven (rather than demand-driven) resource-smart, system-level strategies, firstly to mitigate the need for mechanical cooling; and secondly to identify and understand multiple cooling needs across the built environment, cold-chains for food supply and vaccine/health products distribution, transport and data centres, amongst others. Subsequent steps explore opportunities for aggregation of the needs; seek to understand the renewable, thermal, and waste energy resources available to meet them; and finally aim to define the optimum, most equitable portfolio of solutions that are fit for the economic, environmental, social, and cultural context (considering behavioural changes, technologies, skills, policy and regulations, finance, and business models).

Most importantly, rather than presupposing cooling demand, the Cold Economy approach focuses on the cooling service need. In other words, it is about asking "what are the energy services needed?", rather than "how much electricity is required?". This needs-driven approach requires a return to first principles and the development of an understanding at a macro-level of how much cooling would be required to provide comfortable and thermally safe environments in which to live, study, work and play; to deliver food from source to fork without any quantity and/or quality losses; to distribute life-saving vaccines and other temperature-sensitive health products, without compromising their safety and effectiveness, from manufacturer to individual recipient; and to ensure digital infrastructure runs smoothly. Simultaneously, at a micro-level, an understand is attained of how people currently use cooling; how they seek to maintain or enhance this level of cooling; and how much cooling they currently need and will need in the future. This approach enables effective minimisation of the demand for mechanical cooling, and hence the overall 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, infrastructure, and practices.

Prior to undertaking cooling infrastructure system design work, an important precursor is to quantifiably set goals in terms of the benefits and impacts to be achieved (see Figure 7 on page 20).

Economic and social priorities

These should be based on economic and social priorities, taking full account of the requirements of the Paris Agreement, the Kigali Amendment and the SDGs, and realised across social, economic, and environmental dimensions rather than solely focusing on energy efficiency gains and associated cost savings.

With these goals in mind, the design activity (Figure 7 on page 20) begins with fully understanding the size and location of the full range of cooling needs to be addressed in the community the infrastructure will serve (i.e., village, town, district, city, region, nation) along with the available renewable, thermal, and waste energy resources. At this stage, it is also essential that the demographics and socio-cultural parameters of the community; climate projections; existing relevant support infrastructure; policy and regulatory landscape; and available skills and technical expertise are scoped and understood. This place-based knowledge will inform the system design analysis to determine the optimal portfolio of levers and interventions (including behaviour changes and passive solutions, technologies, services, policy and regulations, and finance and business models) that can match the cooling needs and deliver the greatest net benefits equitably.

Delivering cooling for all

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 5).

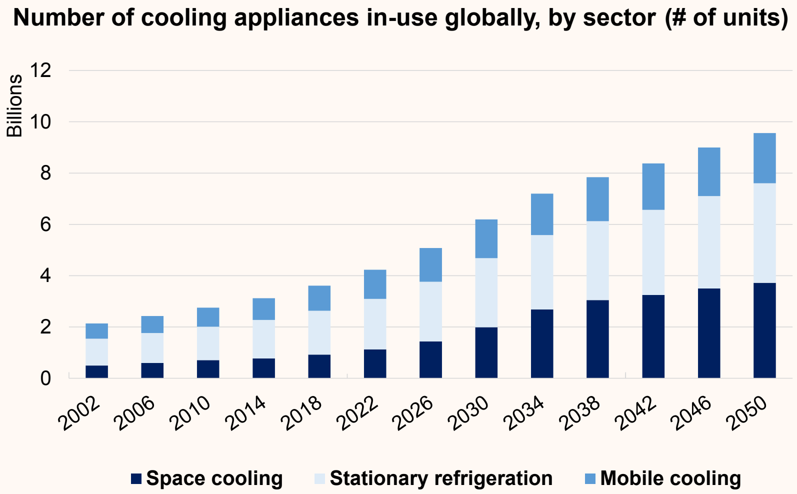


Figure 5: *Number of Cooling Appliances in-use Globally, by Sector (# of Units)*[30]

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 6). 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.

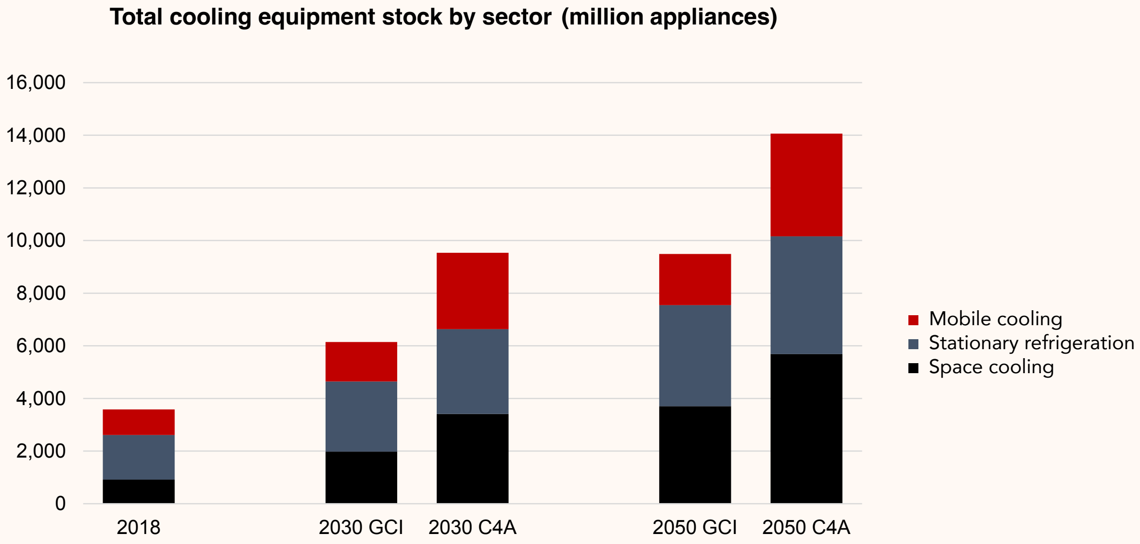


Figure 6: *Total Cooling Equipment Stock by Sector (Million Appliances) - GCI versus C4A (Cooling for All) Projections*[30]

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.

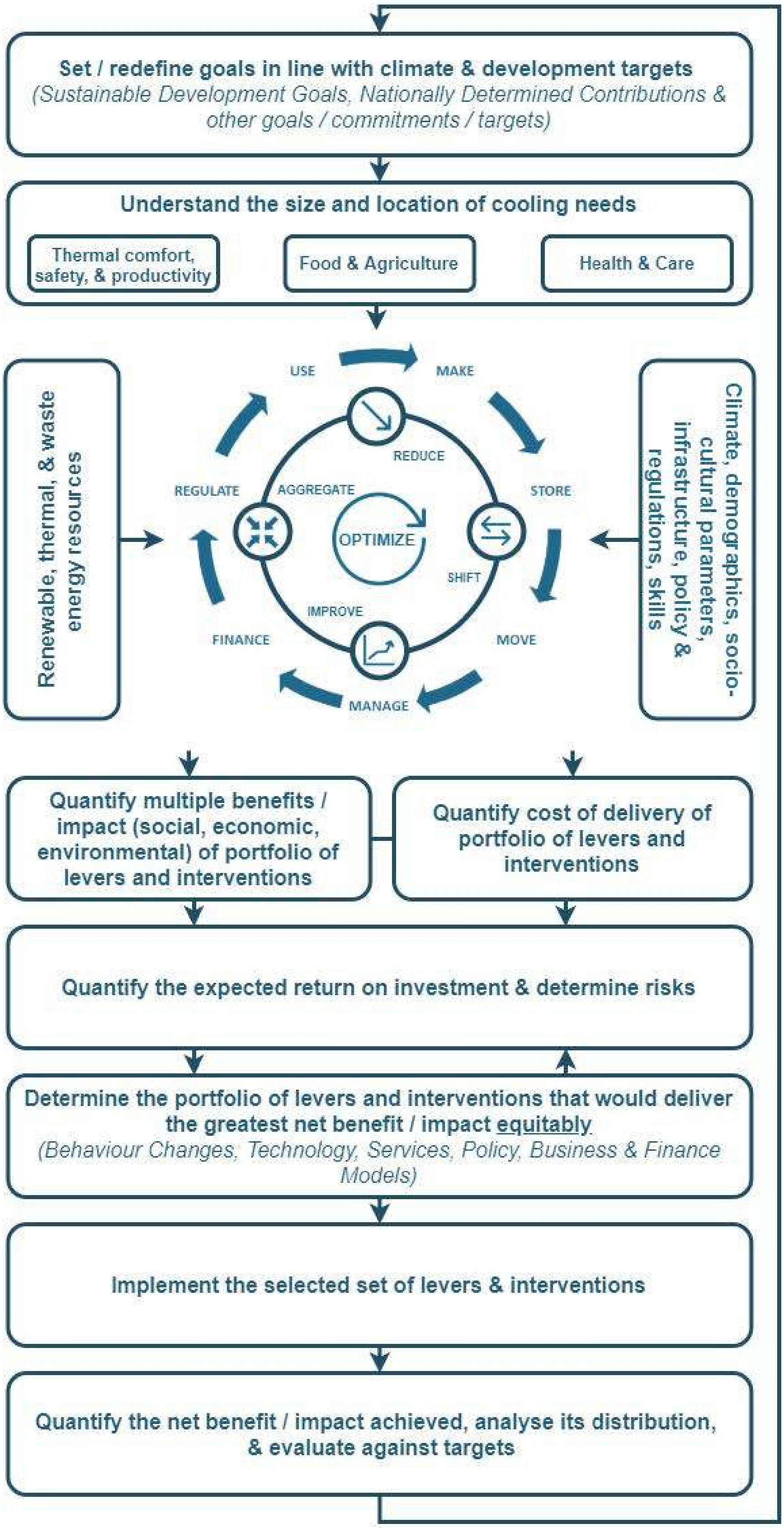


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Figure 7: *Cooling infrastructure system design process based on Cold Economy principles.*

In the detailed design stage itself, a systematic approach to cooling provision is needed which aligns with the seven defined elements of a cooling infrastructure system as presented in Figure 7 and Table 1: use; make; store; move; manage; finance and regulate. To deliver cooling with minimal impact on the climate and broader environment, the infrastructure design 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 early wins and the long-term systemic changes required to reduce both direct and indirect GHG emissions from cooling. The latter is achieved through mitigation of cooling needs; a shift to highly energy-efficient mechanical technologies combined with the phase down of high Global Warming Potential (GWP) refrigerants; optimisation of the use of all available renewable, thermal, and waste energy sources; and the harnessing of opportunities for demand aggregation. The resulting mix of physical technologies and non-physical solutions need to be assessed in the context of barriers across policy and regulation, skills, and affordability, as well as equity concerns. Such an assessment will enable an understanding to be gained of where current policies and regulations perform effectively, as well as where they need to be redefined and/or enhanced; what finance and business models need to be developed; and which gaps need to be closed in skills and technical capacity.

Make	Harness unused heat sinks and thermal resources[6] such as cold-water bodies (e.g., lakes, aquifers), ground soils, sky/space, cool air, renewable energy (e.g., wind, solar), waste cold (e.g., cold energy from LNG regasification) and heat.
Store	Store energy thermally, in physical mass (e.g., thermal walls) or phase-change materials (e.g., ice) to make use of diurnal/cyclical changes in ambient heat sinks2 and supply of (electric) energy at lower cost.
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 etc.), increasing equipment efficiency, and substituting high GWP refrigerants with lower value versions. Highlight behaviour change and demand mitigation strategies likely to be effective, whilst maintaining required service levels (technology, services, policy, and financial solutions can all be used to help drive consumer behaviour in the direction of efficiency, and shift meeting the cooling need towards more sustainable technologies).
Manage	Build skills and capacity in line with the technology development to ensure the correct installation, maintenance, decommissioning 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 sustainable cooling and facilitate equitable distribution of costs and benefits (e.g., servitisation models), taking into account Gender Equality and Social Inclusion needs
Regulate	Bring sustainable technologies and design approaches to market through building codes, design codes, labelling programmes and Minimum Energy Performance Standards (MEPS) that incentivise developers to adopt more sustainable approaches and manufacturers to produce more energy-efficient and lower-GWP equipment. Use of these policy and regulatory tools will also 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.

Table 1: *The seven defined elements of a cooling infrastructure system based on Cold Economy principles.*

Through iteration within the design process, the mix of levers and interventions that will result in the greatest net benefit equitably with minimum risk will be determined. In addition to energy cost savings that the system will deliver, to improve the scope of return on investment the cost–benefit analyses should quantify and incorporate wider social and environmental benefits where possible. Some of these benefits are the direct outcome 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 analysed 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

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[6] When considering the use of unused heat sinks and thermal resources it is important to consider future impacts on their ambient temperature as a result of climate change induced increases in seasonal ambient temperatures throughout the year and the occurrence of more frequent, prolonged and intense heatwave events.

drivers, ranging from climate change, rising incomes, urbanisation, consumer responses to unexpected events (such as the unforeseen rapid increase in cold-chain demand that emerged during the COVID-19 pandemic), changing regulations, climate change related and developmental targets, innovations and improvements in technologies, 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 sustainable and resilient cooling infrastructure, 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.

A system-based design tool-kit

In our work (including in Africa through the Africa Centre of Excellence in Sustainable Cooling and Cold-chain) at the Centre for Sustainable Cooling, we are developing tools to better design cooling systems, including understanding the impacts of key uncertainties and risks, such as geopolitics, macroeconomic developments, climate change impacts on food and health, as well as multiple socio-economic benefits.

Central to this activity is building virtual modelling tools to inform the design of national cold-chain infrastructure. Bespoke, robust modelling tools are being developed to measure the impact and holistic economic value of cooling and cold-chains, future emissions from different strategies, as well to support horizon-scanning and future demand/design, conduct a risk radar, and create a Cold-chain Security Index (Figure 8).

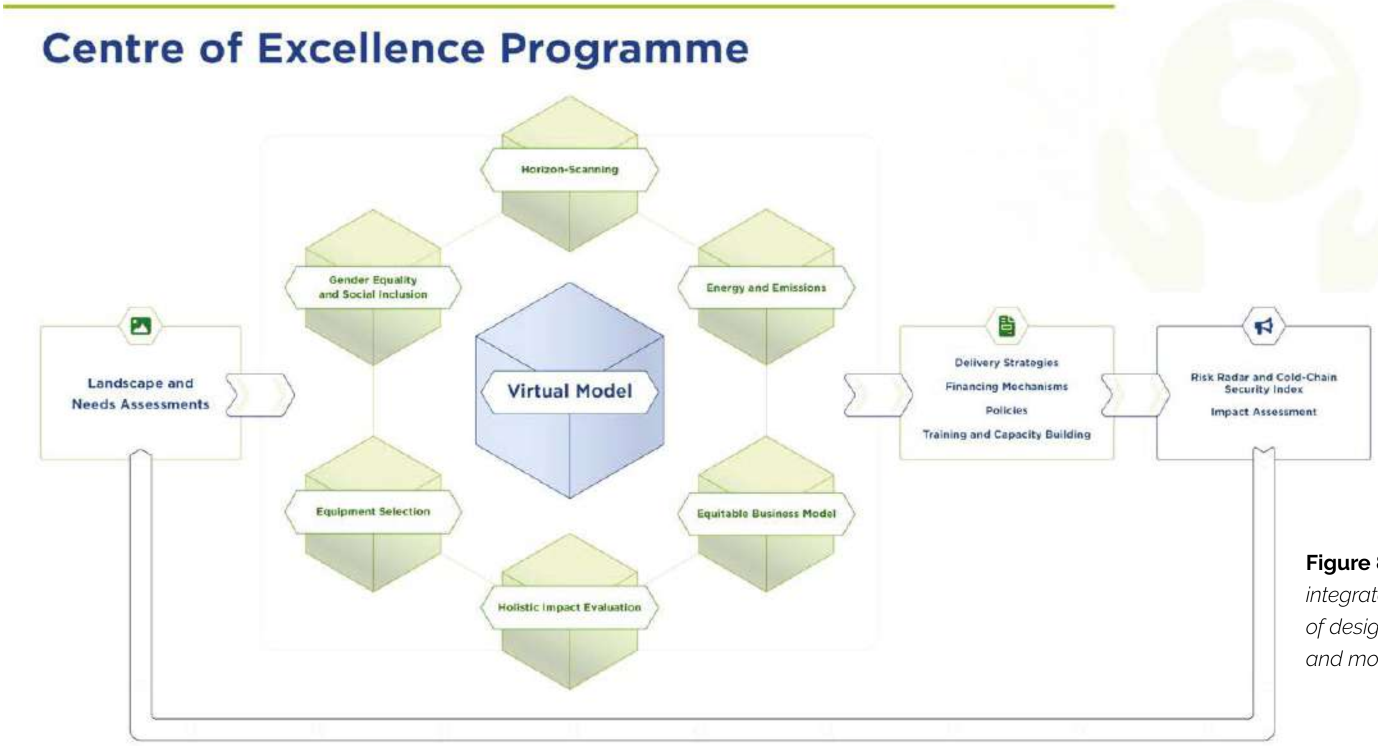

Figure 8: *An integrated set of design tools and models*

VACCINES - SYSTEM APPROACH: A CASE STUDY

The 'next-generation' vaccine cold-chain infrastructure and systems will need to accommodate the advent of lipid-enveloped mRNA vaccine technologies developed through the recent COVID-19 pandemic and now in development against a plethora of infectious diseases, many of which are endemic to the continent of Africa and identified by the World Health Organisation (WHO) as having high-priority for vaccine development. The mRNA vaccine platform offers major advantages in flexibility for re-design towards new threats and relative ease of large-scale manufacturing, and mRNA vaccine manufacturing capacity will soon become an in-country reality for several African nations. However, regardless of the disease target, mRNA vaccines require ultra-cold long-term storage (-20C or colder) that is simply unavailable to many African populations, plus matched to new ultra-fast fridge temperature deployment needs (28-days, comparted with 2yrs for 'standard' conjugate vaccines). Together with the uncertainties of climate change effects on the habitats of disease vectors and epidemiology of vector-borne diseases, and population movement that will stretch the fragile 'last mile' challenge further, we have recognised the need to review at a whole-systems level how vaccine cold-chains need to be configured and operate for reliable, resilient and sustainable vaccine security for Africa.

ACES health cold-chain work is underpinned by a core research programme that focus on optimising and designing the 'next-generation' vaccine cold-chain (VCC) systems for future resilience, sustainability, and value-for-money in low-income settings. A second programme has specific focus on integrating biomedical data (serology) into improved vaccine needs forecasting, and a third programme is looking to use bioinformatics to better understand the effects of climate change on future threats. Combined these will mitigate the immediate need for cold-chain, shift to zero-emission, efficient delivery strategies and build resilience.

The three programmes are as follows.

- **Real-world modelling and digital twin technology.** To 'de-risk' and best support the investment decisions that need to be made today for future needs and value-for-money in 10-20 years in Africa including:
  - Prospective, real-world studies that evaluate the full utility of modern operational technologies such as digital blockchain accountability to the level of a fraction of a vaccine vial (a dose) and the kinetics of vaccine stock movement and open/closed vaccine losses, plus the use of unmanned aerial vehicles (UAVs, or drones) for resilient vaccine supply and the minimsation of cold-chain equipment requirements.
  - Developing optimized standardised metrics for VCC performance and cold-chain security against indices of access/security/environmental impact/cost-effectiveness for within - and between - region optimised assessments of vaccine security, and readiness for new technologies and challenges.
  - Virtual evaluation of VCC threats and VCC innovations/solutions; stress-testing against the effects of climate change on vector/population movements, new antigens entering the schedule, mRNA cooling needs and 'black swan' events.
- **Integration of biomedical data for improved vaccine needs forecasting and safe demand reduction.**
  - Using novel point-of-care (POC) lateral flow tests (LFTs) for real-time (<15mins), in-theatre serological detection of antibody to inform vaccine needs at an individual level real-time decision making that will focus demand onto where it is needed most and optimise supply for greatest impact; starting with measles this approach might reduce measles vaccine volume by up to 80% in the WHO programme of measles eradication
  - Antibody microarray assays that use a single drop of blood to characterise the antibody profile across the whole range of childhood vaccines for the detection of population-level gaps in immunity in need of pre-emptive intervention.
- **Studying biological threats in the environment.**
  - Serial sampling of aircraft wastewater and the use of genomic analyses to understand potential known and unknown new and emerging public health threats (such as the evolution of vaccine-preventable pathogens), and a novel approach to global sampling and risks of air travel in the accelerated spread of infectious disease, antimicrobial resistance, and how climate change effects can be understood early.

ACES, with Rwanda Biomedical Centre, will also be a hub in Africa for clinical vaccine trials (new vaccines as well as delivery strategies) providing the robust data to drive the design of vaccine cold-chain to support vaccination strategies.[7]

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[7] ACES, Rwanda Biomedical Cwentre (RBC) and UoB are launching a first clinical trial to evaluate the safety and immunogenicity of concurrent dosing of viral-vectored Ebola vaccine with mRNA COVID-19 booster; to provide the scientific basis for minimizing clinic attendance and consolidation of resources for at-risk populations such as African healthcare workers.

What this means for Governments - policy interventions

Despite cooling being vital to the health, productivity, prosperity, economic well-being and security of most nations, it is typically absent from government lists of important national infrastructure or critical infrastructure. For example, in the UK, Government responsibility for critical infrastructure sits with the Cabinet Office[31] (which supports the Prime Minister and the Cabinet to ensure the effective running of government, as well as to strengthen and secure the country at home and abroad) and in this regard cooling does not form a discrete area of focus in their portfolio of sectors. Similarly, the National Infrastructure Commission (NIC)[32], an Executive Agency of the Treasury department that provides the UK Government with impartial, expert advice on major long-term challenges to the nation's "sectors of economic infrastructure", does not focus on cooling specifically. The sectors defined in the Commission's remit are energy, transport, water and wastewater (drainage and sewage), waste, flood risk management and digital communications. Although cooling might be considered tangentially as part of NIC advice given on transport, energy, and digital communications, its central role to the economic functioning of the UK society demands that it should be a distinct cross-cutting sector within the suite of "economic infrastructure" considered by the Commission, particularly in the context of future climate change and the impact of higher temperatures.

Further, in the UK, there is no specific mention of cooling in the list of national infrastructure sectors held by National Protective Security Authority (NPSA)[33], the government's National Technical Authority for physical and personnel protective security. The sectors listed are defined as "those facilities, systems, sites, information, people, networks and processes, necessary for a country to function and upon which daily life depends". The NPSA identifies 13 such sectors: Chemicals, Civil Nuclear, Communications, Defence, Emergency Services, Energy, Finance, Food, Government, Health, Space, Transport, and Water, and therefore, like the NIC, has no specific focus on cooling infrastructure despite it being essential to the functioning of the UK and the daily life of its citizens (for example for food, health, comfort, thermal safety and digital access etc.). Further, with regards specifically to "critical national infrastructure" (CNI), NPSA considers these to be a sub-set of the national infrastructure sectors list and identifies them in-line with the UK government's official definition of CNI:

"Those critical elements of infrastructure (namely assets, facilities, systems, networks or processes and the essential workers that operate and facilitate them), the loss or compromise of which could result in:

a) Major detrimental impact on the availability, integrity or delivery of essential services - including those services whose integrity, if compromised, could result in significant loss of life or casualties - taking into account significant economic or social impacts; and/or

b) Significant impact on national security, national defence, or the functioning of the state."

Cooling infrastructure meets that definition of CNI with regards to criteria (a), and potentially (b) depending on the level of "loss or compromise" (for example food supply, vaccine and other temperature sensitive medicine distribution, digital access etc.), and should therefore be included as such in the UK Government's considerations for protecting the most crucial elements of the nation's national infrastructure from internal and external threats, including climate change impacts. Adapting to a hotter world puts even more emphasis on that fact and a greater focus on the need to build capacity for resilience in cooling provision.

Critical infrastructure

Designation of infrastructure providing cooling as critical infrastructure creates a central high-level focus within the governance framework (for example at Cabinet Office level in the UK) that resolves a common policy related challenge for governments worldwide. In this regard, because of its importance to a broad range of sectors, policy on cooling within government is commonly the responsibility of multiple departments, for example energy; environment; agriculture and food; transport, business etc., each of which often takes a siloed perspective. This typically results in a fragmented, uncoordinated, sub-optimal approach to cooling policy which creates vulnerability and risk to services that are vital to the food, health, industrial, digital and economic security of a country and the well-being of its citizens.

The primary ask of this briefing paper is that national governments and international governance bodies worldwide recognise that cooling infrastructure is indeed critical infrastructure, designate it as such, and treat it as such in their assessments of national resilience; adaptation and resilience planning and implementation; and resilience capacity building activities.

Cooling as critical infrastructure - the precedent set by the UK Space Sector

The UK space sector provides a precedent for the recognition and subsequent designation of cooling as critical infrastructure. In this regard, prior to 2015 the sector was not considered by the UK Government as CNI, largely because at the time the consensus thinking amongst the relevant officials was that it was adequately covered through its support of a number of sectors already designated as critical national infrastructure, including telecoms, defence and transport (i.e. through GPS etc.). Given the close parallels between the distributed and fragmented nature of the space sector's physical and non-physical infrastructure assets and those of cooling, a similar view may emerge in the case of the latter. However, through work led by the UK Space Agency[34] to raise government awareness of the critical importance of these components to the functioning and security of the nation, this position amongst policymakers was subsequently changed and space sector infrastructure was recognised by Cabinet Office as CNI in its own right and to the NPSA maintained list. Its designation provides a clear precedent for cooling to be similarly recognised and designated by the UK Government, as well as other governments worldwide.

Paradigm shift

To deliver cooling infrastructure in a sustainable and climate-resilient manner, there needs to be a paradigm shift to a different way of thinking in policy that goes beyond simply regarding cooling as a set of services delivered by electricity and taking what has become a new business-as-usual approach. To date, where there has been intervention to facilitate transition to more sustainable cooling provision, initiatives have been inherently top-down and reductionist, typically focussing solely on improving the energy efficiency of individual technologies or decarbonising electricity supply. Such approaches are based on a linear logic and assume a singular path for sustainable cooling (i.e., thinking only in terms of using electricity as an energy vector for cooling infrastructure); ignore possibilities and alternatives as well as the potential impacts on other subsystems; result in suboptimal outcomes and missed opportunities; and potentially make the challenge of transitioning to net-zero and sustainability more difficult than necessary. This is because linear thinking by default disregards the non-physical interdependencies and feedback loops that exist within the whole system that delivers cooling. Specifically, policymakers need to recognise that the provision of cooling could often be better served through an integrated set of principles by:

- Minimising the need for active (mechanical) cooling in the first place, through encouraging behavioural change and deploying passive solutions.
- Aggregating multiple cooling needs for efficient use of supply, by for example using district cooling network infrastructure.
- Harnessing available thermal energy resources to meet thermal services, many of which are present in the local natural environs, such as water bodies and other heat sinks, and can often be sustainably utilised.
- Exploiting thermal energy resources rejected by other human processes and therefore currently regarded as 'waste', i.e. rejected thermal streams from one process can be used to provide valuable thermal services to another process (for example using the waste cold from LNG regasification), thereby replacing primary energy consumption.
- Using thermal methods of storage and the utilisation of thermal energy carriers instead of electricity and (chemical) batteries, thereby unlocking otherwise redundant resources of renewable or waste energy and boosting system flexibility by enabling cold and heat to be used where and when needed.
- Enabling new finance and business models that create and share value equitably, lift financial barriers on sustainable cooling technologies, and improve cooling access in urban as well as rural remote areas, rather than defaulting to extending electrical grid infrastructure.
- Developing skills and capacity in-line with the technological progress to ensure adequate deployment, maintenance, and disposal of cooling infrastructure.
- Establishing an adequate policy and regulatory environment to bring sustainable cooling technologies and systems to market at scale (such as more stringent building codes and MEPS).

Wider energy system decarbonisation

A holistic whole systems approach will support wider energy system decarbonisation 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 therefore preventing overloading of the power grid; creating more room for intermittent renewable and waste thermal energy sources through thermal energy storage systems. It also involves quantifying and valuing the economic, social and environmental benefits of sustainable cooling provision holistically against the socio-economic and environmental targets adopted by policy makers. By doing so it increases the scope of return on investment and improves the business case for sustainable cooling infrastructure, thereby allowing government interventions and investments to be considered more holistically against criteria that encompass impact-oriented policy and/or strategic targets, not simply financial goals.

Recommendations

The work described in this Briefing Note shows that sustainable cooling will be a core adaptation strategy for humanity to deal with higher ambient seasonal temperatures and more frequent, prolonged, and extreme heatwaves. It results in five key recommendations for Government policymakers, infrastructure designers, developers and operators, academia, and civil society, across the globe:

1. National Governments and international governance bodies worldwide should recognise that cooling is a critical service and that the infrastructure which delivers it is critical infrastructure, designate it as such, and treat it as such in their assessments of national resilience; adaptation and resilience planning and implementation; and resilience capacity building activities.

2 National Governments should develop integrated, future-proofed strategies for adaptation to climate change induced heat impacts that have the provision of sustainable cooling infrastructure at their core. These should include policies and interventions based on a comprehensive assessment of the food, health, digital, industrial and economic security implications of sustainable cooling provision (or absence thereof) for their citizens as well as the nation's ability to achieve its SDG objectives, goals and targets.

3. Governments, infrastructure designers, developers and operators, and academia should take a holistic, whole systems thinking approach to planning, building, operating, maintaining, adapting, and decommissioning cooling infrastructure. Such infrastructure involves large-scale systems formed of many physical and non-physical sub-systems operating within larger complex physical and non-physical systems that impact upon them, and they, likewise, simultaneously impact. Holistic, whole systems thinking is therefore a prerequisite for an optimised outcome to the application of sustainable cooling as an adaptation strategy for surviving and thriving in a +50°C World.

4. Governments, academia, infrastructure designers and civil society should recognise that in reality the majority of the energy services required to support a modern society are thermal and that at the core of creating an optimised sustainable and resilient outcome for the global energy system is seeking as close a balance as possible between thermal needs and available thermal resources. In doing so, they should better adopt a thermal thinking approach to energy system policy making, research and design worldwide.

5 Government need to quantify the wider social impact of cold-chains so as to understand their stakeholder role and justfy underpin investment in the development of the cooling and cold-chains as a part of country's critical infrastructure. This will unlock investments in acute areas that are often perceived as high risk by the private sector alone, but are key for the social, economic and environmental wins and to underpin a well-functioning society.

Appendix 1 - Impacts of heat on people, places and the functioning of society

Excessive heat and prolonged exposure to high temperatures can have a wide range of impacts on human health. Heat stress can occur when the mechanisms controlling the body's internal temperature fail and the excess heat cannot be shed. Under such conditions, the heart rate increases and the body's core temperature rises, the individual begins to find it difficult to concentrate, feels unwell, and may experience fatigue, nausea, dizziness, and fainting. Ultimately death can result if the body is not cooled down.

Heat-related deaths

Globally, 37% of warm-season heat-related deaths across 43 countries between 1991 and 2018 have been attributed to climate change induced temperature rises, indicating that increased mortality due to heat is occurring worldwide[16]. More specifically, heatwaves and extreme heat events have been linked to increased short-term mortality rates. For example, between May and September 2022 several heatwaves occurred across Europe and an estimated 61,000 people lost their lives[15]. In the same year, England and Wales experienced five heat-periods between June and August that led to the number of deaths being 6.2% higher than the five-year average[35]. Elderly individuals, women, those with pre-existing health conditions, and socio-economically disadvantaged populations are especially vulnerable. An analysis of the deaths in Europe found that more than half were in people over the age of 80 and 56% of heat-related deaths were women[36]. Similarly, in the heatwave of the 2021 Canadian Heat Dome event, 67% of recorded deaths were people 70 years of age or older and more than half lived alone[37].

Alongside the human tragedy of increased mortality, extreme heat degrades an individual's cognitive thinking, limits concentration, restricts physical functioning and increases risk taking, thereby increasing the likelihood of accidents. Prolonged exposure can result in chronic heat exhaustion, sleep deprivation and increased susceptibility to injury and illness, all of which reduce workplace output and negatively impact economic productivity. Personnel working in an overheating workspace can potentially suffer heat stress, dehydration, heat exhaustion, or heat stroke, with consequences for safety, work efficiency, operational downtime, healthcare costs, and sick leave[38]. For example, workplace injuries across various sectors in Canada surged during the 2021 Heat Dome and had economic implications for Canadian business with those that required compensation increasing by 180%, compared to the previous 3-year average, and a mean claim value of CA$2,800 per worker[39]. The direct impacts on production output can be significant, car manufacturing in the United States has been shown to be 8% lower in weeks with six days of temperatures at 32°C or above[40].

Economic losses

More broadly, recent research shows that the cumulative economic losses from climate change induced extreme heat between 1992 – 2013 likely fall in the range US$16 trillion to US$50 trillion globally[41]. However, the impact of these losses was not shared equally across nations, regions in the top and lower income deciles experiencing an impact of 3.5% and 8% of Gross Domestic Product (GDP) per capita per year respectively. Future heat stress impacts are expected to increase existing disparities

in productivity further, with reductions in workplace output being most severe in low-income tropical nations. For example, productivity is anticipated to decline by as much as 12% in South Asia and West Africa by 2050, which will not only put immense pressures on economies but also exacerbate divisions between the Global North and South.

Declines in productivity can result in lower wages for workers, with those in outdoor industries such as agriculture and construction reducing their hours by around 13% on the hottest days[42], due largely to increasing fatigue from exposure to the high temperatures. The decline in wages is not, however, confined to those working outside, industries including manufacturing, transport and retail often take place in non-climate-controlled environments where worker productivity can be severely impacted by heat extremes. Indeed, worker income losses in Canada of between CA$205 million and CA$328 million were identified across a wide range of sectors during the Heat Dome heatwave of 2021, with those working in food services, construction, agriculture and manufacturing most impacted[43]. Overall, a study by the UN International Labour Organization (ILO) projected that by 2030, assuming a 1.5°C rise in the global mean temperature by the end of the century, the equivalent of more than 2 per cent of total working hours worldwide would be lost every year, either because it is too hot to work or because workers have to work at a slower pace[17]. Agriculture and construction will be two of the sectors worst affected, with the former expected to account for 60% and the latter 19% of global working hours lost. This will not only affect the economic well-being of the individual worker and their immediate family, but also the wider community within which they participate.

Economic burdens

While climate change is a "global public bad", it is poor, vulnerable, disadvantaged, and marginalised individuals and communities who will face the greatest economic burden, not only in the less developed nations of the Global South but also in the North's advanced mature economies. In this regard, as an example of the latter, temperature projections for 2040–50 suggest that earnings impacts may be 95% smaller for US counties in the richest decile relative to the poorest[44]. Globally, the ILO estimates that in 2030 economic losses due to heat stress at work will be around US$2.4 trillion, disproportionately affecting lower-middle and low income workers[17]. The associated productivity loss is equivalent to 80 million full-time jobs and India alone accounts for 34 million job losses by 2030 due to heat stress related reductions in productivity, which in monetary terms would have an economic impact exceeding US$450 billion in losses[45].

Industrial impacts

In addition to the impacts on worker productivity, higher temperatures also affect the safety and performance of industrial processes, assets and buildings[46]. Indeed, exposure to heat levels beyond those for which designers have allowed can result in decreased industrial output through increased safety risks. These include the potential for spontaneous combustion of stored materials; overheating of mechanical equipment, electrical units, and monitoring and control systems leading to fire outbreaks in the facility as well as efficiency and performance reductions; and over pressurisation of vessels resulting in unexpected releases of hot gases and/or environmentally damaging pollution. Such impacts cause decreased production rates, temporary or partial operational shutdowns and, in extreme cases, longer term closures of facilities to undertake extensive repairs. Many industries that use temperature sensitive processes, materials, equipment and plant, are those that provide feedstocks or finished products which underpin the economic growth and well-being of developed and developing nations worldwide.

Food security

Beyond the impacts on mortality, workplace output and economic productivity, increased seasonal ambient temperatures and extreme heatwaves have wider, and equally important, implications for humanity. Changing climates are already affecting food and nutritional security as well as food safety worldwide, negatively impacting on human health and livelihoods. Higher temperatures can affect production of all food types by decreasing yields and impacting quality, but it is fruit and vegetables that experience the highest level of impact and where growers across the globe are

Climate change induced extreme weather events will also drive migration worldwide, both internally within nations and from nation to nation.

already suffering from the effects of heat stress on their products. For example, in Pakistan, 50% of exportable mango varieties and 30% of those destined for local consumption were lost due to the extreme heatwave experienced in 2022[47]. The Indian Institute of Horticulture Research (IIHR) has also reported a 10 to 30% loss of fruit and vegetables in 2023 due to a sudden increase in temperature[48]. Overall, globally, it is estimated that there is a 6-7% loss in yield per 1C increase in temperature above the meteorological season mean conditions[19] as a result of physiological factors, including compromised reproductive development and fruit and flower abortion linked to high energy demanding processes such as pollination; pollen maturation; and anthesis, which get the necessary drive from photosynthesis.

Rising temperatures and changing weather patterns can also shift traditional growing seasons, leading to altered planting and harvesting times that disrupt established production schedules and, in extreme cases, the ability to grow certain crops in specific regions. In the case of cereals, studies point to future reductions in crop productivity across Sub-Saharan Africa due to a combination of heat stress and decreased precipitation. For example, the mean decline in maize yield between the period 1971 – 2000 and 2041-2070 is projected to be approximately 85% in some areas of West Africa, 29% in Southern Africa and 32% in East Africa[49]. In the long-term, the impacts will affect a wide range of other cereals including sorghum, rice, and millet, resulting in declining yield and in some cases crop failure[50]. These outcomes will reduce food availability and nutritional value, as well as economic productivity from the agricultural and horticultural sectors in the region. Excessive heat in the Chilean Andes this year exacerbated drought in Argentina and Uruguay, resulting in an estimated loss of US$15 billion in agricultural exports and US$1.1 billion in local farming activity[51].

Furthermore, higher temperatures and reduced water availability can affect livestock health and productivity. Some projections suggest that crop yields and livestock productivity could decline by up to 30% by 2050[22]. Extreme heat can also lead to high levels of discomfort and stress for animals and, as a result, livestock morbidity and mortality levels can increase, for example more than 17 million chickens died during the 2015 heatwave in India[52]. Heat stress has been shown to reduced animal reproductive rates and productivity, as evident in milk production which can decrease by up to 50%[21] under some extreme conditions. In response, air-conditioning is already being used in the Gulf Cooperation Council (GCC) countries to maintain indoor temperatures at a comfortable level for dairy cows.

Cold-chain

In a +50˚C world, with crop yields and livestock productivity in decline[8], it will be vitally important that as much food as possible reaches its destination for consumption in good nutritional condition and food saved from wastage will be as important as food produced. However, it is currently estimated that about 12% of food produced globally is lost through spoilage within the food supply chain due to a lack of refrigeration[13]. This could feed approximately 1 billion people in a world where an estimated 811 million people are hungry[53]. Staggeringly, less than 50% of all perishable food that would benefit from refrigeration, such as fruit, vegetables, dairy, meat and fish, is refrigerated. This number is particularly low in the Global South, where only around 20% of perishable food produce is refrigerated compared with typically 60% in the Global North. As an example, only 5% of firms in the food and agriculture sector in Rwanda have refrigerated trucks and just 9% have a cold room to store fresh produce[54]. For small and marginal Rwandan farmers, where the majority of post-harvest food losses occur, functional cold-chains are completely absent (less than 1% of cold-chain capacity).

Addressing the lack of refrigeration in the Global South is vital to ensure not only the food and nutritional security of the region itself, but through complex global supply chains that also of the Global North. However, in doing so, the design, operation, maintenance and performance of both stationary and mobile refrigerated equipment in response to higher ambient temperatures and heat extremes will need to be considered. As the climate warms and the world becomes hotter, refrigeration systems will be increasingly stressed, more likely to fail, and exhibit degraded performance when in operation. Indeed, for every degree increase in ambient temperature, overall equipment performance typically decreases by approximately 1.5-2.5%, leading to higher energy (power) consumption and GHG emissions, increased operating costs, reduced cooling capacity and reliability, and shorter equipment lifespan. Systems that are not well maintained will be more vulnerable to failure, along with systems that have not been designed to cope with higher temperatures.

Large, centralised food distribution centres support vast networks of supermarket stores in most developed economies and depend on 100% reliability from their refrigeration systems with no scope for equipment downtime. A catastrophic failure of cooling in just one of these facilities supplying chilled and frozen food through a “just in time” business model to retailers can impact hundreds of stores across a nation and put US$ millions worth of stock at risk. At the retail end of the supply chain, the emptying of supermarket refrigerated display cabinets due to multiple failures of cooling systems is becoming more common place across Europe. Currently in the UK for instance, between 30-60 supermarkets per large retailer are typically closed due to refrigeration system failures when high temperature conditions prevail with a consequent loss of trade revenue as well as chilled and frozen product stocks. In a world characterised by summer temperatures in the high 40˚Cs and low 50˚Cs occurring for prolonged periods in locations where

[8] Ocean food sources are also threatened by CO2 emissions which result in acidification of sea water. The future availability of fish and seafood will diminish under such conditions, impacting the main source of protein for more than one billion of the most vulnerable people in the world.

today they are considered unprecedented, the risks for food and nutritional security, health, and consequential social and political stability, will increase substantially.

Infectious diseases

The performance and operation of refrigeration equipment in higher temperatures has wider health implications though beyond food and nutritional security. In this regard, there is growing concern that one of the most significant health impacts of climate change will be the emergence, re-emergence, and spread of infectious diseases. Evidence indicates a warmer environment changing the distribution of disease vectors, with many mosquito species, ticks, flies and other insects able to persist for longer, or inhabit places where they have not been recorded before[18], with consequences for disease outbreaks in human populations unfamiliar with them and lacking the knowledge and health infrastructure to manage the outbreak. This expansion of disease vectors is already observed in North America, where the range of ticks carrying Lyme disease is expanding and, this year, the US Centre for Disease Control and Prevention (CDC) notified two cases of malaria transmission, in Texas and Florida, which were the first transmission cases in over 20 years[55]. This pattern is set to repeat and likewise develop in other similar regions, such as southern Europe, and those on the 'climate frontier', for example in Central Africa where climate change creates favourable conditions for bats and other suspected hosts of Ebola[56].

Meeting this worldwide public health challenge will need a substantial deployment of vital cooling infrastructure for the timely distribution of vaccines and other temperature sensitive medical products. Yet even in today's climate, 25% of vaccine doses are wasted globally each year due to failures within cold-chains while at the same time over 1.5 million people worldwide die from vaccine-preventable diseases. In addition to this human tragedy, the global financial cost of vaccine wastage due to products being exposed to temperatures outside of their recommended range is estimated to be U$34.1 billion annually, not including the substantial physical and economic burden of illnesses that could be avoided with on-time delivery of effective and potent vaccines[57]. Given the future impacts of higher seasonal temperatures and heat extremes on disease vectors and the performance of refrigerated equipment, there is an urgent need to strengthen and expand health related cold-chains, as well as improve flexibility in deployment, to ensure that all who need vaccination receive it and nations across the globe have the capacity to contain outbreaks.

Climate driven migration

Climate change induced extreme weather events will also drive migration worldwide, both internally within nations and from nation to nation. Higher temperatures, more frequent droughts, and prolonged severe heatwaves with high humidity, will disproportionately impact the tropics and the affects will be particularly severe for many rural communities, especially those in Sub-Saharan Africa and Asia. The negative consequences for food security, livelihoods and disease will force households to move from their communities. Forecasts suggest up to 1 billion people will have to leave their homes by 2050 due to changing climate[58]. For those crossing borders with refugee status, they may face distinct climate change challenges in the camps in which they seek shelter. These settlements often lack a design foundation based on the principles of sustainability, adaptation and resilience, making them vulnerable to high temperature heatwaves and other climate change induced extreme weather events. For example, recent conflict in Syria has led to 100,000 Syrian refugees living under tents, or in makeshift shelters built from tarps and blankets, that offer little protection against high temperatures and heatwaves[59].

Deteriorating conditions in the rural landscape typically result in internal migration flows that orientate themselves in the direction of urban areas, as people shift in search of work and a better, more secure future. While cities in all countries are expected to be affected, those in the Global South are likely to experience the greatest impacts. By 2050, in the absence of a radical change in GHG reduction policies worldwide, climate change could lead to more than 216 million people in six regions (Eastern Europe and Central Asia; North Africa; Sub-Saharan Africa; South Asia; East Asia and the Pacific; and Latin America) migrating within their own borders[60]. These widespread population movements will put additional pressures on urban infrastructure and the built environment, including domestic dwellings; public buildings such as hospitals and other health care facilities, schools, and community centres; shops and other retail outlets; workplace buildings; and leisure, entertainment and hospitality venues, such as hotels, restaurants and sports stadiums, all of which will be affected by higher temperatures and heat extremes.

Building stock

Globally, much of the existing urban as well as rural building stock is not designed to cope with the higher temperatures already being experienced as a result of climate change and the building codes and regulations of many countries do not allow for anticipated future extreme heat events. For example, a recent report[61] for the UK's Climate Change Committee assessed the overheating risk of a range of existing residential buildings using CIBSE's TM59[62] methodology. It concluded that 55% failed to meet the bedroom overheating criteria when assessed against the current climate and 100% fail when a 2˚C warming scenario is considered for 2080. The bedroom overheating criteria is particularly important, as during heatwave conditions relief from excessive heat and a comfortable sleep environment are fundamental to the health of people who spend extended periods of time outdoors or work in a high temperature setting.

The poorest quality residential buildings that people live in globally are those of informal settlements and 'slums'. The UN estimates 1.1 billion people currently live in the latter and that this is expected to increase by an additional 2 billion people over the next 30 years[63]. Overcrowding, the poor-quality construction, and the urban heat island[9] effect, exacerbate heat stress for these residents. For example, temperatures measured

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[9] The urban heat island effect elevates daytime temperatures above those experienced at locations in the rural hinterland surrounding a city or urban conurbation. The tendency for urban materials to absorb heat, the heat generated by traffic, and transfer of heat into the outside environment by air-conditioning units, all contribute to the effect.

inside urban slum and rural village housing in India during the summer of 2019[64] concluded that "Most dwellings exhibited indoor conditions that were above those considered safe for occupants at some point during the day". It was also noted that many residents were working in hot conditions and as such were not provided with any respite from the heat.

Healthcare systems

High temperature heatwave events also put considerable strain on healthcare systems in both the Global North and South, with an increase in hospital admissions driven by normally healthy people seeking treatment for heat related issues[65]. The unhoused community are at particularly increased risks of being hospitalised as temperatures rise. Recent research has found that hospitalisation risk for London's unhoused was 35% more likely when temperatures exceed 25˚C compared with cooler conditions at 6˚C[66]. However, at the same time the overheating of overcrowded hospitals buildings and other health facilities impact personnel who work in the sector, leading to heat stress related staff shortages, and can compromise the safe storage of temperature sensitive vaccines, medicines and other vital supplies, such as blood. During the 2022 summer heatwave, one fifth of UK hospitals were forced to cancel operations (elective surgery) [67] and the primary contributing factors were identified as staff shortages (36%), unsafe theatre environments (31%), and a lack of available beds (22.1%)[68]. Overall, an estimated 90% of UK NHS hospital buildings are vulnerable to overheating even during moderately warm summers, with temperatures in some wards exceeding 30˚C when external temperatures are as low as 22˚C[69]. The ability of healthcare infrastructure to manage temperature risk is therefore of vital importance.

Similar overheating patterns and issues apply in other public buildings, such as schools, colleges, and government offices, as well as in leisure, entertainment, and hospitality facilities. For air-conditioned buildings, the elevated external temperatures in cities during a heatwave can exceed the temperature for which the equipment has been designed and under such conditions they fail to provide the desired cooling. Indeed, the capacity and efficiency of traditional ventilation and cooling systems significantly reduce (by more than 30% and higher) at 40˚C. These systems further reduce in efficiency with each degree of temperature rise beyond 40˚C, which is when they will be most required. Furthermore, many of the electronic components in cooling and ventilation systems, as well as laboratories where their integrity tests occur, are not designed to function at extreme temperature conditions. Current cooling and ventilation systems typically have a safety switch to shut down their operation beyond a high-temperature threshold to avoid damage to their equipment and the electronic components on which they rely. This threshold varies from 40˚C to 48˚C for different systems across the world.

A +50'C world

The reality will be that in a +50˚C world thermal comfort, human mortality, food and nutritional security, health, productivity, learning and economic well-being will all be seriously compromised by higher ambient seasonal temperatures throughout the year and more frequent, prolonged and extreme heatwaves. It is therefore a societal imperative to urgently develop adaptation strategies, as well as build capacity for heat impact related climate-resilience, so that humanity can not only survive, but also continue to thrive in this new environment.

Appendix 2 - Cold-chain and Rwanda Vision 2050

Rwanda is a small, landlocked country in Africa with a population of almost 13 million people[70], which is expected to double by 2050[71]. Since the end of the civil war in 1994, Rwanda has been undergoing substantial socioeconomic transformation with significant progress in poverty reduction, health, food production and access, women empowerment, and environmental sustainability. However, major challenges remain: 38% of the population still live under the poverty threshold of US$1.90 a day[72], almost 20% of households are food insecure[73], 33% of young children under 5 are stunted[74], and around half of the population do not have access to electricity[75].

The Rwandan economy is heavily dependent on agriculture with around 76% of the working population engaged in subsistence farming[76]. This sector contributes to almost 30% of the country's gross domestic product (GDP), and account for 31% of national exports[77]. Yet, the agricultural production volumes and yields remain low due to sub-optimal use of agricultural inputs (e.g., fertilisers), poor production techniques and farming practices; the country is densely populated; land is in shortage; agricultural production is vulnerable to climate change impacts and natural disasters such as warmer temperatures, prolonged droughts, changes in rainfall patterns and land-slides. According to the National Land-Use and Development Master Plan 2020-2050, yields will have to be improved 15 times compared to 2019 levels to ensure food security for all Rwandans by 2050[78].

However, we argue focusing on food saved is as important as food produced: 40% of food production in the country (around 3 million tons per year[10]) is lost or wasted along the supply chain[79], mainly due to poor post-harvest practices and lack of a robust cold-chain — a series of uninterrupted, temperature-controlled storage and transport from farm to fork. This means if the food loss were to be fully eliminated, yields would need to be improved 9 times instead of the current 15 to achieve food security in 2050. More broadly, developing a sustainable, resilient[11], inclusive and equitable cold-chain from farm to fork (and vaccine manufacturer to arm) will also be key to solving Rwanda's multiple developmental issues from malnourishment, hunger, access to healthcare, transition to clean and affordable energy, and thereby achieving objectives of the Government's Vision 2050 as well as UN Sustainable Development Goals (SDGs), and commitments on the Paris Agreement and the Kigali Amendment to Montreal Protocol.

Delivering the Vision 2050 and the role of clean cold-chain

Guided by Vision 2020 strategy launched in 2000, Rwanda has achieved an annual economic growth rate of 7.5% on average over the last two decades, which was the second fastest growth rate in Africa[83]. Following the Vision 2020, Vision 2050 national development strategy was launched in 2016, which seeks to transform Rwanda into an upper middle-income country by 2035 and a high-income country by 2050[12].

Rwanda's Vision 2050 sets ambitious goals for addressing multiple developmental challenges from food security, malnutrition, poverty reduction, and health to education and equality; all essential within a well-functioning society. Achieving these goals will however require developing an end-to-end, sustainable, resilient, inclusive, and equitable cold-chain for food and pharma.

It recognises the prominent role that the agriculture sector will play in economic growth and its links to poverty reduction, food and nutrition security[80]. In this

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[10] The total food loss in sub-Saharan Africa has been estimated to be 37% post-harvest, or 100 million metric tons annually.

[11] Both in terms of capacity and capability.

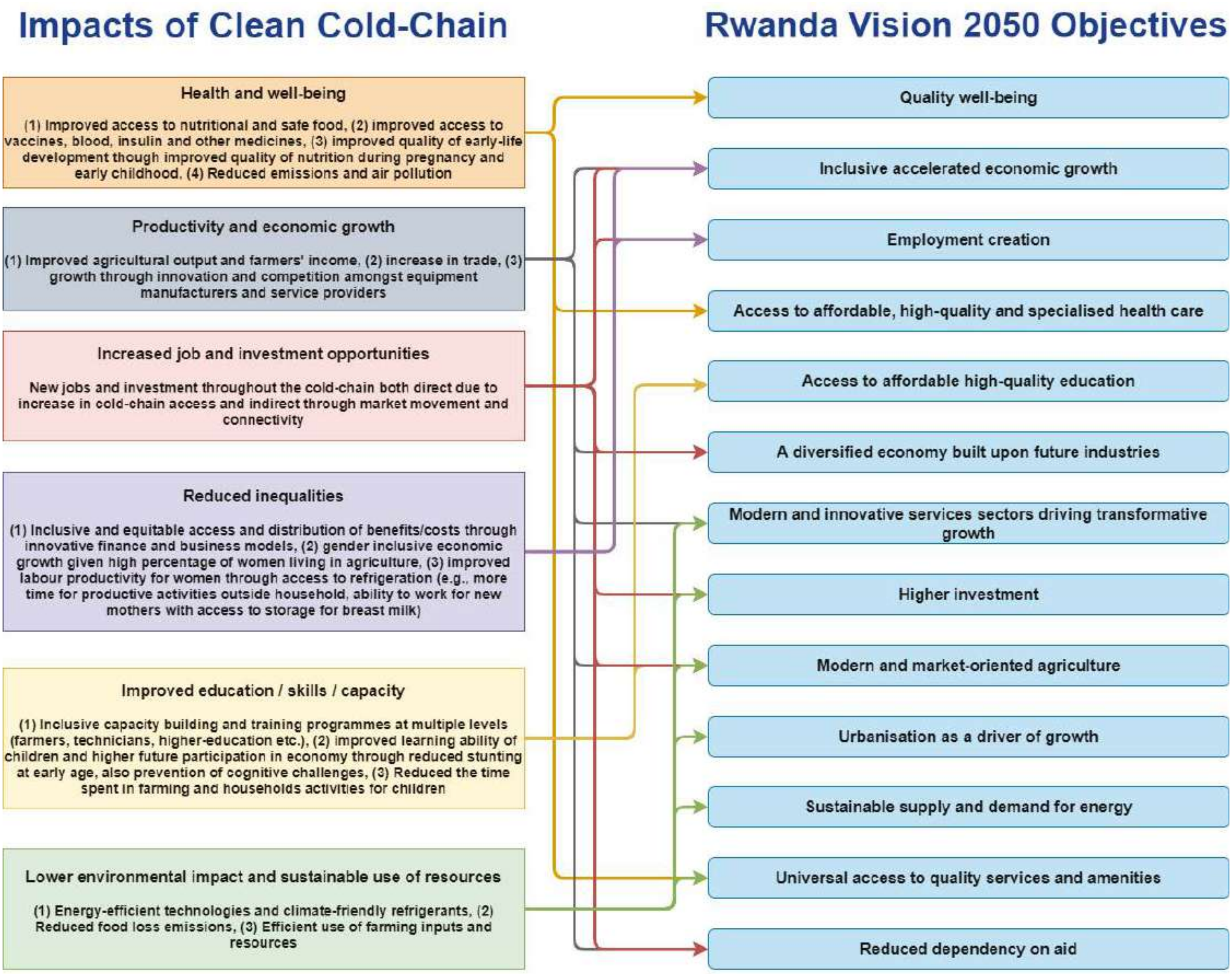
[12] Achieving this will require annual average GDP growth rates of 12% and 10% between 2018-2035 and 2036-2050 respectively.

regard, one of the most important tasks is to establish the cold-chain that the country is currently lacking.

A technology audit for fruits and vegetables value chain conducted by the National Industrial Research and Development Agency (NIRDA) in 2019 revealed that only 5% of firms in the food and agriculture sector have a refrigerated truck for transport and only 9% of firms have a cold room to store fresh produce[81]. Only 1% of the total cold storage capacity in Rwanda is used for fruit and vegetables[82]. Functional cold-chains are almost completely absent or unaffordable for small and marginal farmers, where the majority of food losses occur.

Establishing a clean cold-chain in Rwanda will provide multiple benefits from improving health and well-being, boosting productivity and economic growth, increasing job and investment opportunities, reduced inequalities to improved education, skills and capacity while ensuring environmental sustainability. Unlocking these benefits is an essential prerequisite to the delivery of the objectives of the Vision 2050 in which multiple SDGs are embedded into the promise of "leaving no one behind" along with aspirations to become a green and climate resilient economy by 2050 (Figure 9).

Click through to:
How cooling and cold-chain support Vision 2050



Health and well-being

(1) Improved access to nutritional and safe food, (2) improved access to vaccines, blood, insulin and other medicines, (3) improved quality of early-life development though improved quality of nutrition during pregnancy and early childhood, (4) Reduced emissions and air pollution

Productivity and economic growth

(1) Improved agricultural output and farmers' income, (2) increase in trade, (3) growth through innovation and competition amongst equipment manufacturers and service providers

Increased job and investment opportunities

New jobs and investment throughout the cold-chain both direct due to increase in cold-chain access and indirect through market movement and connectivity

Reduced inequalities

(1) Inclusive and equitable access and distribution of benefits/costs through innovative finance and business models, (2) gender inclusive economic growth given high percentage of women living in agriculture, (3) improved labour productivity for women through access to refrigeration (e.g., more time for productive activities outside household, ability to work for new mothers with access to storage for breast milk)

Improved education / skills / capacity

(1) Inclusive capacity building and training programmes at multiple levels (farmers, technicians, higher-education etc.), (2) improved learning ability of children and higher future participation in economy through reduced stunting at early age, also prevention of cognitive challenges, (3) Reduced the time spent in farming and households activities for children

Lower environmental impact and sustainable use of resources

(1) Energy-efficient technologies and climate-friendly refrigerants, (2) Reduced food loss emissions, (3) Efficient use of farming inputs and resources

Figure 9: *Impacts of clean cold-chain and links to the multiple objectives of Rwanda's Vision 2050*

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