Sustainable and Resilient Cold-Chains: The 2050 Imperative

The Local to Global Cold-Chain Summit:
Addressing Key Factors for Success

Conference Report

December 2022

Centre for Sustainable Cooling


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The Local to Global Cold-chain summit took place on the 29th September 2022 at the University of Birmingham, hosted by the Centre of Sustainable Cooling. The event brought together more than 50 research, industry and government partners from the UK, EU and Africa to share their knowledge and discuss research and innovation needs and collaboration opportunities to operationalise sustainable, equitable and resilient cold-chains for food and health globally. This report explores the outcomes of the summit.

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Foreword

Just like water from taps, electricity from wall sockets and the internet from the ether, most people in the economically developed nations of the world expect good quality, safe-to-eat food to emerge from restaurant kitchens, fast-food kiosks and supermarket shelves, without giving a second thought to the vast infrastructure network that enables it to happen. Likewise, with medicines, vaccines and other medical products, such as blood, they expect them to be available for safe use by their health practitioners where and when needed. Those in low- and middle-income countries are not so fortunate, but many want to be, and as their affluence increases with economic growth billions of people across the world will, rightly, demand to be. This demand will have profound implications for our ability to reduce human derived greenhouse gas emissions, and therefore mitigate the worst impacts of climate change, as well as live sustainably within the limits of our planet's natural resource boundaries.

Food production and supply already represents approximately a third of global greenhouse gas emissions, uses enormous amounts of land, energy and water, and is responsible for widespread environmental and ecological degradation globally, from deforestation and habitat destruction, through to air, soil, water and sea pollution. These impacts affect the health of millions of humans as well as of the ecosystems that support food production in first place. Without a radical change in the way we source, farm and supply food, they are set to increase dramatically in the decades ahead as demand soars. Cold-chains, particularly those based on the use of fossil fuels for their energy and out-dated environmentally unfriendly refrigerants for their cooling capability, are a significant component of what needs to change in food supply. Similarly, for health products, where the safe distribution of manufactured temperature-sensitive medicines and vaccines, as well as blood from storage, relies primarily on environmentally damaging fossil fuel based cold-chains, change is of vital importance.

Cold-chains create a seamless temperature-controlled environment for the distribution of chilled and frozen products between the point of production to point of consumption or use. They are composed of an unbroken series of stationary and mobile refrigeration equipment which consumes large amounts of energy in its operation and results in a broad range of environmental degradation, through the emission of greenhouse gases, air degrading particles and gases, and other pollutants and wastes. As discussed in this report, ensuring that the cold-chains of the future are sustainable by delivering a paradigm shift from today's 'business as usual' technologies and models is an imperative. But not only this, cold-chains are critical infrastructure to the functioning of a modern society, in the same way that water, electricity and internet networks are, and as such they must be resilient to shocks and extremes, particularly in a warming world, where ambient temperatures are increasing and heatwaves are becoming more frequent, severe and prolonged. Furthermore, ensuring equitable access to cold-chains to empower the half a billion small-scale farmers in low-income countries who are essential to current and future global food system is critical.

This report is the output of a Summit meeting held at the University of Birmingham in September 2022 which aimed to look beyond the immediate, and most obvious, responses to the challenge of delivering sustainable, resilient cold-chains. Rather than focussing on the important, but well understood and limited action of improving the energy efficiency of refrigeration equipment used in cold-chains, it sought to define a set of key factors that are essential to address to help ensure a successful outcome to meeting the challenge by 2050. Its findings and recommendations are intended to help shape research agendas, government policy making, and industrial operations, in effect to create an agenda of priorities for immediate action.

Dr Tim Fox and Professor Toby Peters
December 2022

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Executive Summary

Approximately 60% of the food we consume should be refrigerated at some point in the food supply chain and this number will only increase as we look to meet the Sustainable Development Goals (SDGs), feed a fast-growing population, and adapt to a warming world with a rapidly degrading environment. Lack of effective refrigeration results in the loss of 526 million tons of food produced (12% of the global total) with low- and middle-income countries refrigerating less than 20% of their production. These food losses account for an estimated 1 gigaton of CO_2 equivalent (CO_2e) emissions each year globally, as well as a substantial waste of agricultural inputs such as land, fertilizers, water and energy. Likewise, in the health sector, around 25% of vaccines reach their destination with degraded efficacy, mainly due to failures within the cold-chains deployed to deliver them, and more broadly about 20% of temperature-sensitive pharmaceutical products are damaged due to broken cold-chains.

In parallel with this unnecessary waste of food and health products, there is a disconnect between high-income and low-income countries in terms of cold-chain development and connectivity, as well as in policy and regulation across technologies and sectors, that needs to be addressed. For example, the UK is heavily reliant on overseas food sourcing with 84% of fruits and 47% of vegetables being imported in 2019. Food production worldwide will need to increase significantly in the coming decades if we are to feed the expected human population of 9.7 billion by 2050. This would require closing the 56% gap in the global food supply between what was produced in 2010 and what will be needed in 2050. With 60% of the world's uncultivated arable land laying in Africa, the continent will play a key role in feeding the surging global population. Hence, the development of food cold-chains in Africa to reduce food loss, maintain product quality and nutritional value, and ensure food safety is critical, not only to deliver food security for the continent's nations, but also for the high-income countries whose people depend on accessing the continent's production now and in the future.

At the same time, conventional cooling technologies are highly polluting due to the climate impact of the refrigerants that they use (hydrofluorocarbons, known as HFCs) and the indirect emissions accounted for in the energy they consume. Indeed, refrigeration is responsible for approximately 7% of all global greenhouse gas (GHG) emissions, and these emissions could double by 2030, and triple by 2100. Existing cold-chain technologies also represent 1/3 of HFC emissions and, given projected growth in demand, without urgent action this will increase proportionately by 2050.

Globally connected cold-chains

The imperative we face is how to provide the globally connected cold-chains for a well-functioning society in an efficient, affordable, equitable and sustainable manner that builds resilience while simultaneously delivering against the SDGs and meeting the commitments under the Paris Agreement, as well as Kigali Amendment to the Montreal Protocol. The key challenge in doing so is that temperature-controlled supply chain networks are complex, requiring coordination across multiple stakeholders collaborating both between sectors and between countries, and will often need to start within the 500 million smallholder farmers of the world who are each reliant on less than 5 acres of land.

As part of meeting this challenge we need to understand the interplay of cold-chain technology with renewable energy and climate friendly refrigerants, as well as the impact and opportunities of radical new innovations - refrigeration cycles, Drones, Blockchain, Internet-of-Things (IoT) and food innovations such as alternative proteins and vertical farming, which will dramatically change how we produce, distribute and consume food.

Food and health care resilience

Furthermore, as the impacts of the Covid-19 pandemic revealed, it is important for resilience, sustainability, and the efficient use of capital that we stop looking at cold-chains for food and health products in siloes. This is especially important for scenarios such as those involving messenger RNA (mRNA) vaccine technologies that need sub-zero temperature storage and transport, and may be deployed:

- against new pathogens responsible for a high burden to health service resources where no licensed vaccine is currently available, such as respiratory syncytial virus (or RSV, which accounts for admission burdens and mortality in the elderly comparable to seasonal influenza);

- in new populations, such as climate refugees, the frail elderly, and where the need is for indirect vaccine protection by targeting the interruption of transmission of pathogens (such as vaccinating healthcare workers and children);

- against new disease outbreaks, or where the need is for the use of reformulated vaccines against new variants of disease.

Multi-partner programmes

The Centre for Sustainable Cooling (CSC) is a lead co-investigator on a series of multinational and multi-partner cold-chain research programmes across the UK, EU and internationally, to (i) explore system approaches on how to use (and mitigate the need for), make, store, move, manage, finance and regulate “cold” to meet cold-chain needs; (ii) facilitate uptake of innovative systemic solutions at scale and (iii) increase awareness among policy makers about the importance of a sustainable, equitable and resilient cold-chain system globally and how to operationalise it. Active programmes include the Africa Centre of Excellence for Sustainable Cooling and Cold-chain (ACES); the Horizon 2022 ENOUGH programme, which brings together 30 partners from 12 European countries, and the UK’s four year Zero-Emissions Cold-chain (ZECC) study - a combined programme total value in excess of £25M, excluding infrastructure and industrial contributions in kind.

Local to Global cold-chain summit

On the 29th September 2022, more than 50 UK, EU and African research, industry and government partners from these programmes came together with a wider cohort of experts, industrial practitioners, academics and policymakers, including delegates from the State of Haryana in India, to share their knowledge and discuss research and innovation needs, along with collaboration opportunities to operationalise sustainable, equitable and resilient cold-chains for food and health globally. This report is a summary of the discussions and includes the identification of 7 key factors essential to address for a successful outcome to the 2050 imperative of delivering sustainable resilient cold-chains aligned with future needs; thoughts on what is required to close the research gaps identified, resolve the deployment issues raised, and meet the policy needs discerned; and the recommendations resulting for academia, industry, health sector organisations and government policymakers.

Introduction

Cold-chains are central to the functioning of a modern society and underpin food and nutritional security, as well as a broader range of human health needs including immunisation against diseases and infections, medicines, and the provision of blood products. However, set against these positive benefits is that the current technology suites and processes used to realise this critical infrastructure are energy intensive; often inefficient; highly polluting, both in terms of the emission of global warming GHGs and a range of other environmentally degrading pollutants; wasteful; and unsustainable.

The Centre for Sustainable Cooling (CSC), hosted by the University of Birmingham, is a lead co-investigator on a series of multinational and multi-partner cold-chain research programmes across the UK, EU and internationally, to (i) explore system approaches on how to use (and mitigate the need for), make, store, move, manage, finance and regulate “cold” to meet cold-chain needs; (ii) facilitate uptake of innovative systemic solutions at scale and (iii) increase awareness among policy makers about the importance of a sustainable, equitable and resilient cold-chain system globally and how to operationalise it. Active programmes, details of which are given below, include the Africa Centre of Excellence for Sustainable Cooling and Cold-chain (ACES); the Horizon 2022 ENOUGH programme; and the UK’s four year Zero-Emissions Cold-chain (ZECC) study. These programmes represent a combined total value in excess of £25M, excluding infrastructure and industrial contributions in kind. Additional initiatives being pursued for which advance discussions and planning are underway include establishing Centres of Excellence in India, to be located in the States of Telangana and Haryana.

AFRICA CENTRE OF EXCELLENCE FOR SUSTAINABLE COOLING AND COLD-CHAIN (ACES)

ACES is a first-of-kind Centre dedicated to sustainable cooling, cold-chain and postharvest management. It is hosted by the University of Rwanda in Kigali; SPOKEs are being rolled out throughout Africa to deploy ACES solutions in real-world settings; the first of these is in Kenya. The permanent Centre is developed by the Governments of Rwanda and the United Kingdom (UK), the United Nations Environment Programme (UNEP) and the UK's Centre for Sustainable Cooling leading a consortium of UK universities and industry partners. The work of ACES is to accelerate the uptake of sustainable cooling and cold-chain solutions in the agriculture and health sectors in Africa, improving livelihoods, health, food and nutritional security, bringing integrated environmental, social and economic development.

ENOUGH

The main scope of the ENOUGH programme, which brings together 30 partners from 12 European countries, is to support the EU farm to fork sustainable strategy by providing technical, financial, and political tools and solutions to reduce GHG emissions (by 2030) and achieve carbon neutrality (by 2050) in the food industry. The project will provide tools and methods to contribute to the EU Farm to Fork strategy to achieve climate neutral food businesses. It will Identify how to achieve climate neutrality for food businesses; Improve integrated sustainability and meet societal goals. The project will also aim to demonstrate promising technological solutions applied within the main sectors of the food chain from harvest to consumption (processing, transport, retail and domestic) for different products categories including meat, fish, fruits, vegetables and diary.

ZERO-EMISSION COLD-CHAIN (ZECC)

Bringing together academics and industry across the UK, the aim of this four-year project is to deliver an industry-led pathway to achieve the UK's net zero 2050 target whilst maintaining food security and affordability for UK consumers and economic opportunity for the UK food industry. It will also highlight opportunities and approaches that will enable the UK food industry to remain and become more competitive and provide potential new business opportunities to new actors in the food cold-chain. The project starts by evaluating future cold-chain and associated cooling energy consumption demands (from both a technical and non-technical perspective) and their impact on the

UK's energy consumption and peak electricity demand before going on to determine areas of intervention considering available energy and thermal resources, emission targets and other commitments as well as costs.

On September 29th 2022, more than 50 UK, EU and African research, industry and government partners from these programmes came together with a wider cohort of experts, industrial practitioners, academics and policymakers, including delegates from the State of Haryana[1] in India, to share their knowledge and discuss research and innovation needs, along with collaboration opportunities, to operationalise sustainable, equitable and resilient cold-chains for food and health globally. This report is a summary of the discussions and includes the identification of 7 key factors essential to address for a successful outcome to the 2050 imperative of delivering sustainable resilient cold-chains aligned with future needs; together with thoughts on what is required to close the research gaps identified, resolve the deployment issues raised and meet the policy challenges discerned; and recommendations for action by academia, industry, health sector organisations and government policymakers.

[1] A Memorandum of Understanding (MOU) to develop a Haryana Centre of Excellence on crop post-harvest management and sustainable cold-chain was signed between the University of Birmingham and the State of Haryana at the meeting,

The Cold-Chain and a Warming World

What are cold-chains and why do they matter?

A cold-chain is an integrated temperature-controlled distribution system that ensures temperature-sensitive products, such as perishable foods and vaccines, are kept at their optimum temperature, and in an optimum environment, from their source to destination. It is a complex system that has many static and moving physical elements and that requires accountability from multiple actors, including farmers, manufacturers, aggregators, processors, distributors, retailers and consumers. In a modern society, without cold-chain provision, populations would have limited access to safe and nutritious food and the efficacy of medicine and vaccines would be compromised or unattainable. Indeed, many aspects of a contemporary life in economically mature countries, which are often taken for granted by the majority of their citizens, are underpinned by cold-chains. Such is the central importance of this critical infrastructure to the foundations of what is considered essential in a developed economy, that it is at the core of successfully achieving many of the development goals of the UN's SDGs[1].

In the food sector, the term cold-chain is synonymous with the continuous process of producing, packaging and distributing temperature-sensitive primary products that are perishable, including fruit, vegetables, fish, meat and milk, as well as secondary processed products in a chilled or frozen state. These cold-chains can be separated into three principal components: precooling/chilling/freezing units; cold stores and stationary refrigerators; and refrigerated transport. Pre-cooling/chilling/freezing primary produce at source reduces the energy demand in subsequent stages of the cold-chain, retains more original nutrients, and can add many days to the 'shelf life' of a product, thereby substantially reducing subsequent food losses, boosting food safety, improving product quality, and increasing incomes for producers[2].Beyond this first stage, produce is placed in a cold store until it is transported onwards in refrigerated containers to food processing businesses or direct to markets, or to intermediate cold stores for onward distribution to markets, where it is displayed for sale in chillers or temperature-controlled shelving or delivered direct to homes or food service businesses and stored in fridges. Products derived from primary produce delivered to food processing businesses are subsequently chilled or frozen and transported in refrigerated containers direct to markets, or intermediate cold stores, to complete the final stages of the chain in the same way as primary produce.

Impact of ineffective cold-chains

A lack of effective refrigeration and cold-chain currently results in annual food losses estimated to be around 526 million tonnes, or 12%, of total global production, with a market value of circa $379bn. This is enough food to feed approximately 1 billion people in a world where as many as 828 million people suffer from hunger[3,4]. In addition, it is estimated that 600 million people worldwide fall ill, and 420,000 lose their lives, from contaminated food, in part due to a lack of refrigeration[5,6]. Furthermore, 736 million people today still live in extreme poverty, with about 79% residing in rural communities[7] where they are primarily dependent on agricultural production derived from farms based on small land holdings. These farmers do not have the financial capacity to own and operate cooling technologies[8] or access to adequate cold-chains that connect them to markets, resulting in missed income opportunities due to food loss and distress sales. Integrated cold-chains could increase the incomes of poor rural farmers 4-5 times, through a combination of reduced food losses and the facilitation of a switch to higher value produce as well as value-added food processing[9]. Alongside the social and economic impacts, the production of food which does not reach the marketplace due to inefficient or missing cold-chains accounts for ~1GT CO_2e GHG emissions[10] and represents an unnecessary waste of agricultural inputs required for cultivation, such as energy, land, irrigation water and fertilisers, as well as an unsustainable drain on the world's natural resources.

Cold-chains in the health sector

The utilisation of cold-chains in the health sector for temperature-sensitive products, such as vaccines and medicines, involves a similar set of components to those utilised in food supply arranged in a continuous seamless system, from manufacture through to delivery to the immunisation candidate or patient. In this case, chilling or freezing takes place at the production facility with subsequent cold storage, followed by transport in refrigerated containers to cold stores in distribution centres for onward refrigerated transport to fridges in hospitals, health care facilities and pharmacies. Certain medicines may also include a final stage of domestic refrigeration. Maintaining the end-to-end integrity of the cold-chains used in both the food and health sectors is vital - any break in the seamless fully integrated infrastructure of the cold-chain compromise the entire system.

The importance of cold-chains has gained more attention in the public sphere recently throughout the world with the need to vaccinate a large proportion of the global population to achieve immunity against COVID-19. Many low- and middle-income countries lack the infrastructure and resources needed to deliver vaccines in an equitable and safe manner even at conventional temperatures. Therefore, some of the COVID-19 vaccines requiring sub-zero temperatures create extra logistical challenges that for many such nations appear insurmountable. A lack of adequate cold storage and refrigerated transport vehicles to support medical supply chains in low- and middle-income economies currently contributes to over 1.5 million vaccine preventable deaths each year[11]. Apart from resulting in this tragic loss of human life, these infrastructure deficits are a major impediment to achieving universal vaccine access - the global financial cost of vaccine wastage due to exposure of vaccines to temperatures outside of their recommended range is estimated to be $34.1billion annually, not including the substantial physical burden and economic cost of illnesses that could be avoided by ensuring on-time delivery of effective vaccines[12]. Estimates suggest that every dollar spent on child immunization provides around $44 worth of economic benefits in low- and middle-income countries[13].

Ultimately, cold-chains enhance economic wealth and improve the quality, safety and nutritional value of food supplied to customers as well as maintain the integrity and efficacy of vaccines, medicines and other health sector products. As the world becomes increasingly warmer and climates change, seasonal temperatures rise, and extreme heat events become more frequent, intense and of longer duration, farming in many countries will become more challenging and the impacts on human health from diseases and infections more acute. For example, in the case of the latter, climate change is estimated to be currently responsible for over 150,000 deaths annually, and between 2030 and 2050 is expected to cause approximately 250,000 additional deaths per year, from malnutrition, malaria, diarrhoea and heat stress[14,15]. It will therefore become increasingly important to ensure that as much perishable food produce as possible reaches consumers in a healthy, nutritious condition and that health-related products are not degraded by heat on their journey from their production line to recipient - making this critical infrastructure even more critical.

Future scale of global cold-chain infrastructure

The atmosphere of planet Earth is warming and with the GHG emissions reduction targets and associated policies currently committed to by governments around the world it is anticipated that the 1.5°C target of the UNFCCC Paris Agreement will not be achieved[2][16]. Indeed, the recently published IPCC 6th Assessment Report[17] noted that the global mean temperature is projected to rise above 1.5°C by 2030 in all the emissions scenarios that they considered, from the lowest to the highest, and the value to which it would eventually return if emissions reach net-zero is uncertain. In response to an increase of such magnitude, as humanity attempts to adapt to higher ambient temperatures and more frequent

[2] On the basis of an analysis of current policies and pledges at the time of writing UNEP estimate a 2.8°C increase by 2100[16].

and extreme high temperature excursions, the global demand for cold-chain provision will grow substantially. This growth will be superimposed on a set of demographic characteristics, including population growth; urbanisation; increasing affluence; higher health expectations; shifting dietary; and evolving purchasing preferences, that are anticipated to drive increased demand for food and health sector cold-chains in the future regardless of the need to adapt to higher heat levels.

For example, the world's human population is expected to increase by 2 billion from 7.7 billion today to 9.7 billion in 2050[18]. Associated projections of the food requirements for such a population suggest that adequately feeding 9.7 billion people would necessitate closing a gap of 56% between the amount of food available in 2010 and that required by 2050[19]. Tackling the issue of the more than 12% of food produced globally that is lost due to lack of adequate refrigeration and cold-chains, with 63% of the losses arising in low- and middle-income countries[20], would help to close that gap, contribute to attaining zero hunger, and create a more sustainable food global system. However, while modern cold-chain infrastructure for food supply is the ‘norm’ in the mature developed economies of the world, it is currently at best patchy and fragmented in low- and middle-income countries, or in the worst cases non-existent.

Global growth of cold-chain

Overall, growth in the global deployment of cold-chains in the food sector has in recent decades been positive with, for example, refrigerated warehouse capacity in the two years between 2018-2020 estimated[21] to have increased across the world to approximately 719 m^3, a rise of around 16.7%. However, this additional build has been confined largely to North America and China, the latter of which is an advanced developing economy and should not be considered an indicator of growth in developing and least developed economies. A better indicator of the capacity gap and potential for future growth is that in the low- and middle-income countries of the world cold storage average capacity is typically about 20 cubic metres per 1,000 inhabitants, whereas the figure is 10 times more for North America, Western Europe and Oceania at 200 cubic metres per 1,000 inhabitants[3]. Small-scale and marginal farmers in low-income countries simply do not have access to cold storage facilities and end-to-end cold-chains with robust connectivity are almost completely absent or unaffordable for this potential group of users.

A recent technology audit of Rwanda’s fruits and vegetables value chain, conducted by the National Industrial Research and Development Agency (NIRDA) in 2019, revealed that only 5% of businesses in the food and agriculture sector have a refrigerated truck for transport and just 9% of firms have a cold room to store fresh produce[22]. Indeed, only 1% of the nation’s total cold storage capacity was being used for fruit and vegetables with around 72% allocated to flowers[23]. For small and marginal farmers, where the majority of post-harvest food losses occur, functional cold-chains were found to be almost completely absent. Refrigerated transport, in addition to cold storage capacity, is essential for establishing fully integrated cold-chains and in an earlier study conducted in India, the world’s largest producer of perishable food produce, the country’s National Centre for Cold Chain Development (NCCD) found that in 2015 only 15% of the refrigerated vehicle capacity needed to adequately service the market was in place and a deficit of around 53,000 units existed[24]. Globally, less than 50% of all food that would benefit from refrigeration is refrigerated. This number is particularly low in the developing world where only around 20% of the produced perishable food is refrigerated (compared with 60% in developed countries).

Given the substantial cold-chain infrastructure deficits that exist in low- and middle-economies, in response to demands from their increasingly affluent populations for more and better-quality perishable food, it is anticipated that capacity will grow significantly in the decades ahead, even without accounting for climate change induced impacts. Indeed, the Economist Intelligence Unit estimates a 4.8% annual growth rate for refrigerated transport vehicles between now and 2030[25] to service food and health-related temperature-sensitive product demand. The University of Birmingham estimates that, overall, 4.5 billion new units of equipment, including static domestic, commercial and industrial refrigerators as well as transport vehicles with refrigeration, will be needed for the equitable deployment of cold-chains in the food supply sector alone by 2050[26].

Implications for climate, the environment and sustainability

The growth of cold-chain infrastructure globally for food and health related products has significant implications for global warming, climate change and the broader environment. At the core of these implications is the fact that fossil fuels are the primary source of energy for today's cold-chains and that they are intensive users of such energy. Future deployment based on this 'business-as-usual' model will contribute substantially to further raising atmospheric GHG concentrations, be unsustainable, and significantly impact society's ability to achieve a range of economic, environmental, social, and political goals, including the SDGs, Paris Agreement targets and Kigali Amendment to the Montreal Protocol commitments.

Fossil based energy use in cold-chains takes two forms: direct consumption of fuels such as diesel and petrol in the main and auxiliary (refrigeration units) of refrigerated transport vehicles; and the use of electricity generated from burning coal, gas or oil in power stations or standalone generator sets (gen-sets). In the case of the former, these often-unregulated auxiliary engines not only produce GHG emissions that contribute to global warming, but also substantial amounts of other air degrading pollutants including nitrogen oxides (NOx) and particulate matter (PM) that can exceed World Health Organization (WHO) set limits[27].

The 'indirect' emissions of the cooling technologies which arise from the use of fossil fuel-based energy represent around 75-80% of the overall total, the remaining balance of 20-25% is accounted for by the 'direct' emissions that result from leakage of refrigerant gases into the atmosphere[26]. The latter can occur during all stages of the equipment lifecycle, from initial filling with refrigerant, through the operation and maintenance phases, and finally at decommissioning and end of life disposal. Although often small in volume, the impact of these leakages is significant because many of today's widely used refrigerants (HFCs) have high global warming potential (GWP), making them far more impactful than CO_2 on the atmosphere in terms of climate change[28]. It should be noted that according to the North American Sustainable Refrigeration Council, as a result of growing demand across all cooling and refrigeration sectors, HFCs are one of the most rapidly increasing sources of GHG emissions[29].

In addition, ozone depletion can result from the leakage of some refrigerants still in use despite substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) have been largely phased out globally. For example, HCFCs were phased out in developed countries in 2020, but until 2030 as much as 0.5% of base-level consumption can be used for maintenance purposes in already installed refrigeration and air-conditioning equipment. In the case of low- and middle-income countries, the figure increases to 2.5% until 2040 against a phase-out date of 2030[30].

Cold-chain emissions

The cold-chains currently installed in the global food supply system alone were estimated to be responsible in 2017 for total CO_2e emissions of approximately 261 million tons[3], or around 0.5% of global GHG emissions that year. However, GHG emissions from cold-chain equipment are anticipated to rise substantially during the decades to 2050 as developing economies rapidly increase their installed capacity, particularly if the business-as-usual deployment model is followed. A doubling of emissions from cold-chains deployed in the food system by 2027 is anticipated in India, for example, as the infrastructure deficits highlighted earlier begin to be addressed[31].

Cold-chains create broader environmental impacts beyond GHG emissions and airborne pollutants, both in terms of individual pieces of equipment (for instance, such as oil spills during maintenance etc.) and their mode of use. In the case of the latter for example, the food, vaccine, and medicine packaging materials required to perform without degradation in the low temperatures that are characteristic of a cold-chain typically become waste and, as such, end life in a landfill or incinerator. These items include cartons, boxes, crates, pallets, airbags, vials, temperature-sensitive ink labels etc, made from cardboard, plastic, glass, glass ceramics, foils, wood and thermo-chromatic chemicals. Additionally, the thermocouples and other temperature logging equipment used to monitor a products journey through the chain are often discarded, contributing the world's electronic waste challenge. The preparation of perishable produce prior to entering a food cold-chain, in process such as cleaning, trimming, and washing, can also result in waste organic material, effluents, chemical residues and fertilisers entering the environment in the form of land contamination and watercourse pollution.


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The 2050 Imperative

A sustainable, resilient and equitable cold-chain aligned with future needs.

It is clear, within the context of the anticipated future growth in the deployment of cold-chains in both the food and heath-products sectors, that a business-as-usual approach is simply not tenable. Without a significant change in the suite of technologies and operational processes utilised by the cold-chain industry, climate change and environmental degradation will be significantly exacerbated, and a wide range of society's global sustainability goals will be severely compromised. What is required is the development and deployment of sustainable resilient and equitable cold-chains aligned with the food security, energy security, nutritional and health needs of developed, middle- and low-income nations alike. Indeed, this is a 2050 imperative for the industry if it is to make its rightful contribution to helping humanity avoid the looming existential catastrophe.

Key factors essential to address for a successful outcome.

Delegates to the workshop identified 7 key factors that it is essential to address for a successful outcome to this 2050 Imperative:

1. Future proofing cold-chain decision making.

One of the most difficult success factors to address in the journey to 2050 is that of future proofing research, development, policy, investment, and deployment decisions. The scale of the sustainable, resilient and equitable cold-chain challenge, both in terms of what needs to be done and the timescale in which to do it, is such that policy makers and the sector cannot afford the luxury of wasting time, money and brainpower on initiatives that will not contribute significantly to achieving the required goals and targets. In this regard, although 2050 is less than 30 years away, the characteristics of the food and vaccine sectors could be significantly different by mid-Century, requiring a suite of technologies, finance, business models, policies and regulations as yet unknown.

For example, societal and demographic change may drive changes in food procurement practices to more local sourcing models, in urban areas possibly based on an increase in the vertical farming sector. In parallel, a shift to a largely e-commerce rather than physical shopping retail model, driven by today's 'digital native' generation maturing into peak purchasing power, might become the societal norm. Similarly, a demographic change to a more environmental and animal welfare focussed consumer may also result in a move away from meat consumption towards diets characterised by vegetarianism, veganism and flexitarianism. In the medical domain, widespread acceptance of new vaccine technologies, along with the emergence of future pandemics based on as-yet-unknown viruses, might drive radical changes in approaches to administering vaccines in delivery programmes. Such societal changes would have profound impacts on the requirements for cold-chain infrastructure in terms of the technologies, financing and business models needed. In parallel, many technologies and infrastructure that are available and in-use today may struggle to operate, or would not operate at all, in a future world characterised by higher ambient temperatures and more frequent, intense and prolonged heatwaves. Extreme temperatures could push materials and equipment beyond their operational ranges, leading to supply chain disruptions, damaged roads, prolonged blackouts, among others. Hence, technological innovations and new system designs will be required to address this issue. For example, during the 2022 heatwave, supermarkets across the UK had to empty their shelves as fridges, freezers and chillers failed due to prolonged high temperatures.

To meet this challenge, deep innovative thinking supported by wide ranging and rapid research programmes is urgently needed, to conceptualise, build, test and deploy methodologies that will identify high impact roadmaps for future proofed cold-chain related research, development, and deployment. One initiative that is beginning to consider these issues is the ENOUGH project[32], which brings together 29 partners from 11 European Union nations and the United Kingdom all with in-depth expertise across the entire food system. The aim of this collaboration is to help build robust, resilient, clean and efficient food supply chains for the future. In doing so, rather than focussing on specific technology suites for individual sectors, the team will take a system-based approach to cold-chain research design and roadmap development, with an objective of quantifying and benchmarking energy use to identify opportunities for substantial emissions reductions by 2050. During the work, they will implement innovative concepts and techniques, create digital tools and smart data analysis methods to quantify and benchmark energy use and emissions, generate new information on emissions from the food supply chain, and develop strategic roadmaps (technical, political and financial), as well as demonstrate high impact future proofed technologies that are at a high technology readiness level. Areas to be covered include: minimization of energy use and maximization of energy efficiency of cooling; freezing and heating processes; encouraging the widespread introduction of natural refrigerants; thermal storage techniques; energy demand/supply strategies, smart integration of cooling and heating, high-temperature heat pumps, adsorption/absorption cooling, heat-driven energy generation cycles, greater use of zero-carbon energy sources (including hydrogen, solar power and geothermal energy), efficient transport and packaging, alternative food supply chains and smart fridges.

In short, the key to a successful outcome will be to avoid developing, deploying and supporting solutions that may become redundant on the journey to 2050, because the sector/sub-sector/market disappears after a substantial amount of resource has been invested.

2. Continuous training and skills.

A critical success factor for a sustainable, resilient and equitable cold-chain, which is significantly underappreciated, is the need to develop a well-trained and appropriately skilled industry to support technology development, deployment, operation, maintenance and decommissioning. Without making adequate provision for this success factor, progress towards the sectors 2050 goals will be significantly hindered and ultimately there will be the potential for a high risk of failure in meeting targets for emissions reductions, increased sustainability and resilience building.

For example, as early as 2012 – as the European Commission worked on an HFC phase-down in the context of revising the European Union’s 2006 F-Gas Regulation – the Air Conditioning and Refrigeration European Association (AREA) warned of the risk of shortage of contractors trained in the use of low-GWP refrigerants (which have different characteristics relative to traditional high-GWP refrigerants in terms of flammability, toxicity, system pressure requirements etc), against the estimated demand. A decade later, the situation has actually worsened: training rates have remained largely stable, whereas demand for low-GWP alternatives has increased substantially. The issue is widely acknowledged and is considered to be a major obstacle to stronger market uptake of alternative refrigerant solutions. As these alternative solutions become available for a growing number of applications, additional certified contractors are needed to safely work on them.

While most established equipment providers set up service centres to warrant the equipment upkeep in the initial year of ownership and offer training to their customers, this is not always sufficient and comprehensive. To this end, there is a need to quickly assess and strengthen the skills and training required to deliver, operate, use, and maintain current sustainable technologies in the market, as well as to scan the horizon by engaging with industry and technology developers to understand the potential future skill requirements to meet the needs of technologies in development. During maintenance, refrigerant gases must be properly recovered and there is a potential for their further recycling and reclamation to avoid the production of new virgin gases. However, this has had a limited application, especially in the context of low- and middle-income countries, due to lack of incentive and needed scale to run self-sufficient business models.

Specifically, in low- and middle-income countries the deployment and implementation of best cooling practices will require particular attention to skills and capacity building for design, installation, commissioning, operation, use, inspection, maintenance and disposal of cold-chain equipment, as well as enabling, coordination, implementation, financing, enforcement and evaluation of policies and programmes. Alongside demonstrating and proving refrigeration and cold-chain technology in-market, a key objective of the ACES initiative is to help build after-sales capability and develop capacity through teaching and training programmes. In this regard, the centre is planning to focus on the delivery of basic training programmes aimed at understanding the fundamental physics and engineering of refrigeration so that individuals operating in the field can use acquired knowledge to solve problems from first principles, rather than relying on detailed information on the specifics of proprietary systems. This is important in an operating environment where equipment is often repaired using cannibalised or none-standard parts and helps to safeguard against knowledge becoming irrelevant as sectors or sub-sectors disappear or technologies become redundant.

Technical training across all levels should lead to better outcomes in the management of cooling loads, improved operation and maintenance of equipment to maintain optimum system performance, and accurate verification of the performance of installed cold-chain assets. However, in addition to closing the skill gaps at all technical levels and attracting new engineers and technicians into the industry, continuous professional development rather than well-meaning one-off interventions is required to avoid the issue of 'rusty skills'. Broader training is also needed, to raise awareness and create a better prepared market for absorbing and using new technologies and ensuring the associated economic, social, and environmental benefits are realised. In this regard, continuous education and training provision is essential for all stakeholders, including project developers, contractors, and end-users, such as smallholder farmers and medical outreach practitioners, to raise awareness of the benefits of sustainable and resilient cooling access, facilitate behavioural change and increase the uptake of systems thinking, best-in-class technologies and best professional practice.

If not underpinned by appropriate skills and trained capacity, attempts to achieve sustainable and resilient cold-chains will be subject to significant social, economic, and environmental risks; missed opportunities; and ultimately failure.

3. Resetting temperature set-points for frozen foods.

With the anticipated growth in the future demand for frozen foods[33] comes a significant energy and GHG emissions challenge to the success of a transition to sustainable and resilient cold-chains. At the core of this challenge is the temperature at which stationary and mobile refrigeration systems are set (the 'set-point') for handling frozen products. Currently, the industry standard set-point is -18°C, a temperature established in the mid-20th Century[34] and arguably not relevant in the context of today's food products and real time monitoring technologies.

The set-point challenge is that reducing refrigeration temperatures to below those that are required to maintain product safety and quality leads to unnecessary energy consumption and thereby results in avoidable GHG emissions. This outcome is exacerbated by the 'oversetting' of equipment to temperatures much lower than the industry standard by individual companies (for example in the -20s), through conservative risk averse corporate policies and/or to position themselves as 'gold standard' operators, and poor engineering design of refrigeration systems leading to highly inefficient thermal characteristics[34].

To tackle this challenge there is a need to undertake a thorough review of the set-point standard for refrigeration of frozen foods. In this regard, since the mid-20th Century food products have changed significantly, both in terms of type and composition, and affordable 'real-time' monitoring technology has emerged that has the potential to alleviate concerns leading to conservative risk averse oversetting. Some in the industry think that these two factors could potentially mean that a standard set-point of -15°C would be more appropriate and that a requirement to not over-cool could be introduced. This, without any negative impacts on food safety or quality. Further, they consider it an absolute imperative in the context of controlling the growth of GHG emissions from the sector and that it would deliver a substantial commercial benefit to cold-chain operators through energy bill savings.

In order to build industry and consumer consensus for the development of a new standard and catalyse such a change, a comprehensive programme of scientific and engineering research focussed on creating an evidence base for the choice of a new set-point is urgently required. This work would consider the food safety and quality aspects, as well as develop an understanding of the implications for energy systems (including temperature-controlled EV logistics charging infrastructure); cold-chain economics; food supply chain resilience; GHG emissions; and broader sustainability issues, in a warming world with an increasing population characterised by rapidly shifting demographics. The starting point for this journey is to undertake an initial scoping study to:

- estimate the ‘size of the prize’ in terms of current and future energy and GHG emissions savings;
- determine issues and barriers to implementation;
- consider the implications for low- and middle-income economies;
- determine what a roadmap to making such a change might look like;
- define the next steps.

This work needs to be undertaken in the sector as a collaborative pre-competitive activity leading to an internationally accepted standard as no country, trading block or individual private company is likely to unilateral raise the frozen food set-point temperature for fear of food safety/quality issues (even if only a public perception of a problem and not scientifically true/real) and/or tarnishing of a brand.

4. Conflation of energy for tackling energy inflation.

The current global energy crisis has significantly impacted countries worldwide, both mature developed economies and low- and middle-income nations alike. In the UK for example, it is estimated that 14.5 million people are now in fuel poverty, due largely to the dramatic rise of wholesale gas prices in the country driven by supply constraints resulting from the geopolitics of the war in Ukraine. Gas is used predominantly for domestic, commercial and industrial heating in the UK, but it is also the energy source for around 40% of the nation’s electricity generation and sets the market price for power. In low- and middle-income economies, such as those of sub-Saharan Africa and Southern Asia, the situation is exacerbated by a parallel crisis in global food supply, particularly a shortage of wheat from Eastern Europe; a breakdown in global supply chains impacting on exports of commodities and manufactured goods; and the escalating cost of national debt repayments. This global economic impact of constrained oil and gas supply has focussed the attention of governments worldwide on the urgent need to improve their national energy security, particularly as demand for energy is projected to increase substantially in the decades ahead. Given that cold-chains are highly dependent on secure and affordable energy supplies for their operations, these issues are critical to their broader, and equitable, deployment and use.

As national energy systems are decarbonised, opportunities will arise for the conflation of energy sources, greater flexibility in supply, and building resilience, thereby improving energy security and overcoming energy inflation. By conflating energy demands and energy sources, that is bringing them together, there are opportunities for end users and suppliers to share infrastructure, benefit from energy that would otherwise be wasted, and utilise locally sourced energy which would not otherwise be exploited. A simple example of this approach is where the heat expelled in cooling a data centre is used locally to provide domestic heating via a district heating system. By using a conflated energy system, significant savings can be achieved in costs and GHG emissions, whilst simultaneously helping to deliver other national and international policy targets for energy, economic growth, and sustainability more broadly.

As a sectoral example, in low- and middle-income economies agricultural policymaking for the incentivisation of cold-chain provision is often reduced to a focus on simply establishing a single component of the overall system – typically cold-storage facilities. Such action disregards the essential connectivity of the cold-chain, that necessarily must include multiple static and mobile elements of cooling, as well as the underpinning energy system. Likewise, attempts to establish vaccine cold-chains are often focused on the individual fridge to be located in a health centre, rather than the management of the entire chain of cooling required from point of manufacture through to dose recipient (which can often necessitate outreach provision to a remote, difficult to access rural community). At the systems level, multi-sectoral synergies can be exploited by creating cold-chains that would provide integrated services, for example, across food supply and agriculture as well as health, especially where geographical reach overlaps[3]. Similarly, when district cooling is considered in urban environments, the focus is typically only on delivering district air-conditioning for thermal comfort, rather than assessing how multiple cooling services could be integrated into a community-based thermal energy system using thermal networks for cooling.

Aggregating cooling demands within and/or across sectors can enable optimisation of system performance, as well as resource use, and can facilitate bundling of multiple revenues across sectors and end-user applications to increase socio-economic benefits. As an example, the Community Cooling Hubs (CCHs) concept[36,37] is an innovative, communitarian and integrated systems approach to meeting the broad portfolio of a rural community's cooling needs in developing markets in a highly accessible, efficient, affordable, resilient, and sustainable manner. CCHs supported by appropriate technology and business models can meet diverse local cooling needs ranging from agriculture and health to thermal comfort in an aggregated manner, as illustrated in Figure 1, and reduce both the economic and environmental cost of cooling. The first such CCH will be implemented in Kenya as a component in the ACES SPOKE programme.

[3] Recognising the need to protect against cross-contamination and meet safety regulations.

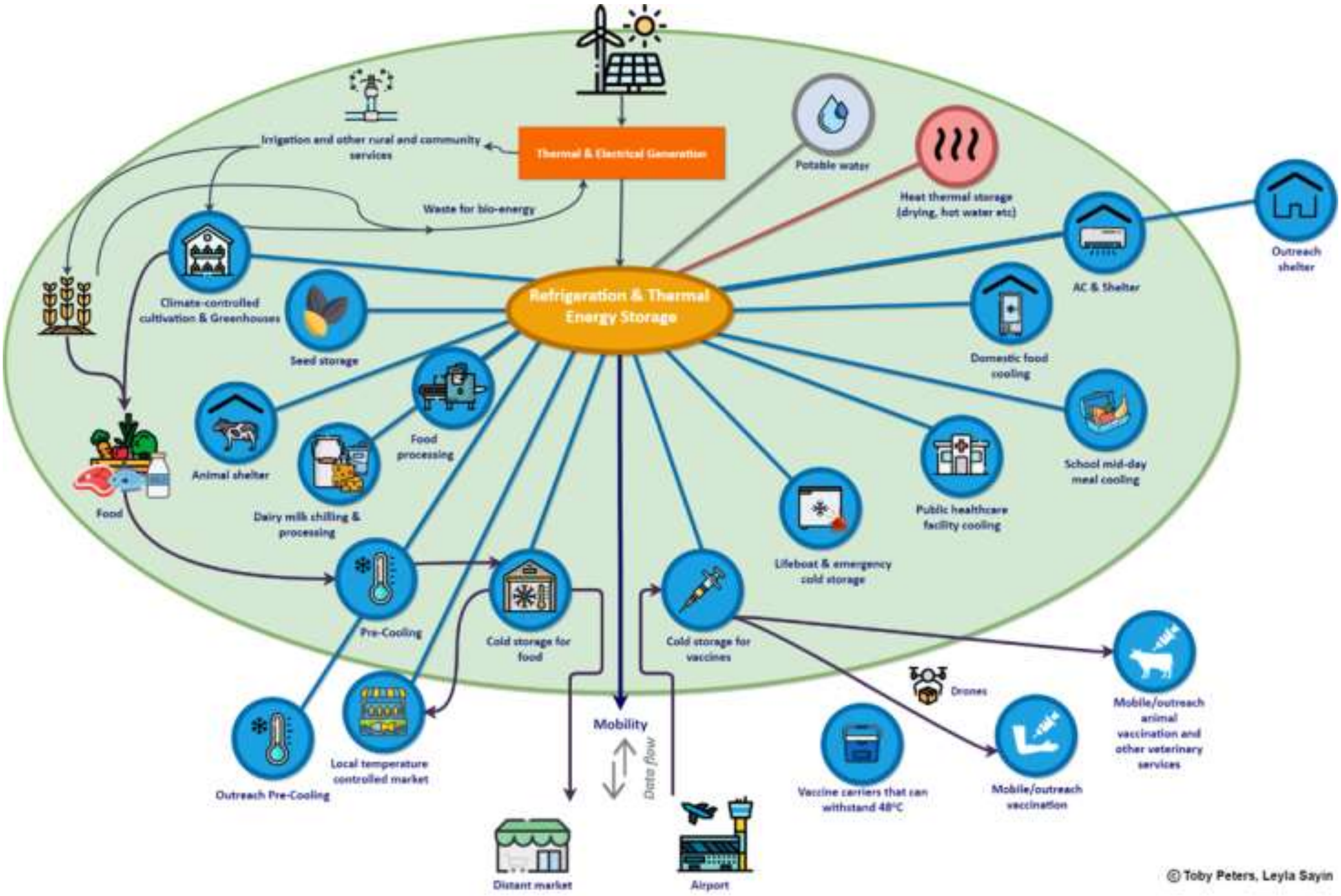

Figure 1: Community Cooling Hubs – Providing integrated cooling services

Most farming communities need temperature-controlled pack-houses / aggregation hubs which will, as the first stage of the cold-chain[4], typically include energy-intensive cooling systems to pre-cool and store the aggregated perishable produce. By designing the cooling system from a broader set of community needs, aggregating cooling demand to create system efficiencies and bundling multiple revenues streams, CCHs can meet a portfolio of a rural community's societal needs with economic accessibility and resilience. Specifically, they can support farmers and fishers with reducing post-harvest food losses, increasing productivity through animal shelter and access to veterinary vaccines, protecting quality and value and providing new distant market connectivity, whilst ensuring that the wider community has continuing access to life-saving vaccines, domestic refrigeration, and properly cooled health facilities and community services.

Critically, and central to the opportunity presented by CCHs, these additional community supporting functions do not require a significantly larger energy load than that which is typical of a modern pack-house. Through aggregation in design, the energy requirements of such added services could be met efficiently and sustainably using energy strategies that build on this core load, including for example:

- capturing excess cold produced by the use of thermal storage when the pack-house is not required to operate at full demand;
- recovering waste heat from cooling equipment into co-located services, such as food drying; cooking and processing to hot water for cleaning and washing applications in pack-houses;

[4] Today, nearly 45% of the world's population live in rural areas[35] and providing access to cold-chains is critical to their economic development (through underpinning agriculture based livelihoods), health, food and nutritional security.

- rerouting excess thermal energy to an off-grid energy supply mechanism for community cooling or hot water provision.

Creating an environment that drives conflation is a key success factor in delivering sustainable and resilient cold-chains and needs to be an urgent policy issue for national governments globally. However, local ambition and drive is essential to making conflation work, particularly as national energy systems transition to a decentralised and decarbonised model in which a myriad of local facilities integrate smartly into a more resilient overall system. Without local drive, conflation is unlikely to be implemented and, in this regard, a key question is whether it should be encouraged through a mandatory approach that aims to breakdown existing silos and achieve optimised multi-agenda outcomes? Essentially, should national policies be devised that force local authorities to use local thermal sources, if they exist, and recover waste energy - should it be embedded for example in planning policy? And how can competing and mis-aligned policy agendas at local, regional, national and international levels be resolved?

Cold-chains are perceived as a private sector enterprise, particularly in the agriculture and food sector, but they need to be considered as critical infrastructure (i.e., similar to power and water distribution networks) and treated as such in policy making. There needs to be a focus on co-operation and collaboration across governments and the private sector in an approach through which conflation can be financed, policy ambitions and targets aligned, and the respective responsibilities of all the various stakeholders understood (a novel Public-Private-Community Partnership (PPCP) model is considered in detail in item 7 below which could form the basis of such an approach).

Ultimately, conflation of energy is a win-win approach that is essential to adopt on the journey to successfully delivering sustainable and resilient cold-chains.

5. Transitioning to natural / ultra-low GWP refrigerants.

A fundamental requirement of establishing sustainable and resilient cold-chains is a significant scale up in the roll-out of cooling technologies using natural/ultra-low GWP refrigerants, thereby reducing the GHG emissions resulting from leakage and/or spillage during use and end-of-life disposal. In total, around 80% of the GHG emissions from refrigeration, air-conditioning and heat pump systems is associated with indirect emissions from energy use, whereas about 20% is associated with direct emissions from refrigerant use[26]. The refrigerants that are widely used today have a high GWPs and are hundreds to thousands of times more damaging to the atmosphere than CO_2. Currently, there are some 16 pure HFCs and 30 blends used in refrigeration, with GWPs ranging from under 100 to close to 15,000[5]. For example, a common blend used in medium- and low-temperature refrigeration applications R-404A[6], especially in the food retail and transport sectors, has a high GWP of 3,920[38].

To address this issue, the Kigali Amendment to the Montreal Protocol, which entered into force in January 2019, calls for the phase-down of HFCs by cutting their production and consumption, targeting a reduction of more than 80% by 2047 compared to baselines. This HFC phase-down could avoid up to 0.4°C of global warming by 2100[28]. Under the European Union's F-gas legislation, the use of refrigerants with a GWP of 2,500 and above, such as R-404A, was banned in stationary refrigeration applications for new equipment and servicing as of 1 January 2020.

In most instances lower GWP refrigerant alternatives, such as natural refrigerants, require minimal equipment design modifications and provide comparable efficiencies to the high GWP refrigerants. While per unit manufacturing costs

[5] The GWP of a refrigerant is the total contribution to global warming resulting from the emission of one unit of the refrigerant relative to one unit of CO_2 with a GWP of 1. However, there is some controversy within the cooling sector as to the timescale over which the contribution should be calculated. The currently accepted scientific consensus is 100 years but there is an increasing call for it to be 20 or 30 years, to reflect more accurately the significant short-term damage that is done to the atmosphere by gases with short lifespans, including methane and some refrigerants. Adopting such an approach would substantially increase their GWP values.

[6] A blend of R-125, R-143a and R-134a (Climalife UK 2021).

and market prices may be higher, economic cost savings are often possible from new equipment that meets higher energy efficiency and refrigerant standards. However, barriers to such a shift including a lack of funding, relevant standards and regulations, inadequate training provision, and insufficient coordination and cooperation, may slow down the transition[7]. Certain refrigerants may also present operational challenges such as flammability (i.e., hydrocarbons), toxicity and high pressure that could result in public safety risks if not handled properly. As such, the full range of technology alternatives and best-in-class systems must be explored to assess their optimality in terms of energy efficiency and emissions as well as operational use. Ammonia, CO_2, Hydrocarbons, Propane etc all have advantages and disadvantages, essentially it is about utilising the right fluid in the right system and keeping it simple yet efficient.

However, despite the availability of alternative, natural/ultra-low GWP, refrigerants, issues of equipment cascading to low- and middle-income countries and the availability of counterfeit refrigerants are a long-existing problem that needs to be tackled. The latter emerged as an issue in 1987 with the Montreal Protocol-led phase-out of ozone-depleting substances and has subsequently grown in the wake of restrictions posed by efforts such as the Kigali Amendment and the European Union's F-gas regulations. In 2020, the Environmental Investigation Agency conducted an undercover operation to reveal the illegal trade methods and companies and individuals involved in such activities. Investigators were offered 17.5 tons of suspected non-quota HFCs in total, with a global warming impact of 31,255 tons of CO_2e[39]. Many low- and middle-income countries lack sufficient capacity to monitor and enforce refrigerant regulations and there is an urgent need to assist them in strengthening these systems.

In the case of equipment cascading, as mature developed economies implement increasingly stringent equipment and refrigerant standards, there is a significant risk of low- and middle-income economies becoming targets for the 'dumping' of none-compliant equipment with low energy efficiencies and high GWP/ozone-depleting refrigerants. This could include both second-hand and end-of-range new products that cannot be sold in the country of origin. In the absence of adequate regulatory environments to prevent illegal imports, low- and middle-income nations such as those of sub-Saharan Africa could be locked into obsolete and sub-standard technologies for the next 15-20 years. In Ghana, for example, during the 10-year period 2004 to 2014 imported second-hand refrigeration equipment represented 75% of sales[40]. Recognising that non-compliant units containing HFCs, and indeed HCFCs, that are already installed will be operational for many years to come as equipment replacement cycles play out, it is also essential to ensure that the necessary maintenance skills are available to service them with minimum risk of leakage.

6. Enabling optimal utilisation of cold-chain infrastructure.

Cold-chain infrastructure is critical infrastructure and is resource hungry in terms of equipment, energy, people, and money, as such to ensure sustainability it is essential to optimise its deployment and use. In this regard there are two key challenges to be tackled: the poor utilisation of space within stationary and mobile elements of cold-chains; and the use of cold-chains to deliver products that are not necessarily needed. An example of the latter is the use of cold-chain infrastructure to deliver vaccines that are not necessarily required.

Current vaccination programmes, such as those undertaken around the world for measles immunisation, take a mass vaccination campaign approach predicated on the fact that the antibody status of individual members in the population is unknown, so everybody is vaccinated. This potentially results in the unnecessary vaccination of a substantial portion of the population and therefore the unnecessary shipping of large volumes of vaccine requiring cold-chain utilisation. Effectively a waste of cold-chain infrastructure. An alternative, less wasteful approach is to use point

[7] For example, the WHO Performance, Quality and Safety (PQS) catalogue [77] of approved equipment for vaccine cold-chains still lists equipment using R404A, which has a GWP of 3922, the highest of all the commonly used refrigerants, and has been banned in Europe.

of-care (POC) lateral-flow tests (LFTs) for qualitative antibody detection (e.g., measles immunity tests) to provide same-day vaccination decisions and determine exact vaccine supply requirements for a given population. Those in the target group (community, village etc) who test sero-positive are immune and therefore their vaccine dose is spared, whereas the sero-negative cohort are non-immune and a high priority for vaccination, thereby determining the number of doses required. This approach, in combination with highly targeted, rapid, delivery services that work within the product temperature degradation limits to reduce refrigeration burdens, such as those based on utilisation of drone technology, can help reduce the wasteful use of cold-chain infrastructure assets. Indeed, estimates suggest that POC testing, and similar approaches, could reduce vaccine volumes required by as much as 70%[8]. Efficiency of vaccine use leads to efficiency of cold-chain use.

Barriers to the use of this radical approach to vaccination programmes include risk aversion and the unavailability of appropriate standards. However, it is a potential breakthrough for low- and middle-income economies and could be used in conjunction with the Community Cooling Hub model (which could be the POC testing site), as well as in areas with difficult terrain and/or poor road infrastructure. In such cases the use of drones to replace trucks for vaccine delivery can not only reduce time to point of vaccine administration, thereby mitigating dose degradation issues (in Rwanda for example, Zipline carry out around 300 drone flights per day with a maximum delivery time to the nation's furthest location of 45 minutes), but also reduces energy consumption, costs of delivering immunisation programmes (capital and operational), and GHG emissions, as well as improving overall sustainability and supply resilience.

In the parallel area of the poor utilisation of space within stationary and mobile elements of cold-chains, there are many examples from the food supply sector. For instance, the unnecessary use of pallets and the inefficient placing of them within the valuable space of cold stores, refrigerated transport vehicles and shipping containers, as well as the storage and movement of fish products on a bed of ice within the temperature-controlled environment of a cold-chain. These practices, and other similar ones, lead to inefficient energy use and unnecessary GHG emissions, as well as exacerbate issues of inequitable access to cold-chain infrastructure in low- and middle-income economies. It is therefore an imperative that space utilisation within cold-chain equipment is optimised on the food products themselves, thereby resulting in efficient energy use and more space being available in existing and future infrastructure for additional users. Such changes are an essential factor in the delivery of sustainable and resilient cold-chains.

7. New business and investment models.

The capital and operating costs of cold-chain equipment is high relative to the affluence level of potential users in developing nations, limiting their uptake in food and health product supply chains. To address this issue new finance and business models are needed that make access to sustainable cold-chains affordable to potential users, enable equitable distribution of risks and costs, and overcome investor concerns regarding the value created from their investments. Such models could provide an essential catalyst to enabling groups of smallholder farmers (for example in a cooperative model) or local entrepreneurs purchase equipment and reduce payback periods by linking repayment amounts to income generation. In addition, financial barriers and investment risk could be addressed through Pay-As-You-Go (PAYG) and Cooling-as-a-Service (CaaS) servitisation models, which negate the need for cold-chain equipment users to incur the capital costs of asset ownership or operational/maintenance costs. Other approaches to financial models to increase cold-chain equipment uptake could include direct subsidies that reduce the upfront cost of ownership, as well as equipment rental/leasing mechanisms and bulk procurement programmes.

[8] Dr Christopher Green, Associate Clinical Professor & Consultant Physician in Infectious Diseases, University of Birmingham.

One example of how cold-chain technology needs can be supported by innovative business models, that enable a fairer environment for end users in developing economies to utilise the equipment and earn income, is that of Promethean Power Systems[41]. The company is based in India and the Efficiency for Access Research & Development Fund[42] (EforA R&D Fund), managed by the Energy Savings Trust, supported them to install thermal storage milk chilling hubs for both subsistence and larger farmers. The organisation trained community hub operators to pay the subsistence farmers according to the quality of the milk that they deliver to the hub and implemented a quick quality testing mechanism for this purpose. This ensured that farmers were paid a fair price for their milk.

Another example from Africa is UK company SureChill's PAYG and CaaS offers to potential users of their highly innovative, sustainable, clean energy powered refrigerators[43]. The company currently operates these business models in 5 countries across the continent and, in the case of the former offer, has designed a pay-as-you-go enabled solar fridge (its 'PAYGo' product) that is bringing affordable and reliable cooling to households and small businesses. These are customers who previously had no access to cooling or the financial means to purchase it. In this model, solar distribution companies have the option to add solar powered fridges to the suite of products that they offer their customers, safe in the knowledge that they have a secure and efficient way to collect their payments. The PAYGo technology embedded into the units allows distributors to provide the fridge through financing models suited to their customers' needs and to collect, track and analyse payments. Underserved consumers' who previously had no access to these life-changing products now have the ability to purchase cooling in an accessible and affordable way. SureChill's CaaS rental model is also broadening access to cooling via their 65-litre unit, which can be rented at an affordable price on a "no commitment" basis where customers can opt to keep the fridge for as long as they require it. Whilst they are renting the fridge they do not have to worry about costly repairs or service costs as this is all included as part of the CaaS model. The latter is a pioneering scheme that allows people to have access to essential cooling through which they can run a profitable business.

These innovative finance and business models drive value creation and sharing as well as help to overcome the equipment affordability perceptions of potential end users. However, there is also a need upstream of deployment in the form of early-stage technology funding. The latter presents itself as a classic 'chicken and egg' scenario, where technologies must be proven and tested to attract funding/investment, yet there is little appetite to fund and incubate the initial technology R&D. As a result, many companies struggle to reach the commercialisation/ investment stage. R&D is not only costly, but also requires long-term commitment to prove out technologies, and often funding organisations and investors want rapid results which are rarely possible. It is therefore important that the existence of this gap is communicated across the industry, to raise awareness, manage expectations regarding funding of innovation, and attract the right type of funding/investment from patient sources that have the appetite for high risks on returns. The EforA R&D Fund is working to help meet the funding gap by supporting companies/organisations in early, mid- and late stage of technology development (pre-commercialisation) with grant funding and is planning to additionally focus on supporting business model development, which is crucial to the success of a technology and the impact it can create.

In the developed economies of the world, a 'tried and tested' business model led by private enterprise has become deeply entrenched in the cold-chain sector during the period since the second world war. Attempts to apply this model in low- and middle-income countries have, typically, resulted in cold-chain initiatives in both food and health product supply suffering from sub-optimal investments and a fragmented approach to their deployment. At the core of this market failure is the fact that the groups that are in most need (such as remote, difficult to physically access poor communities, smallholder farmers and marginalised populations etc) often do not present a compelling business case for the private sector due to uncertainties regarding the timescale and magnitude of financial returns on investments. This reality underpins the issue of inequitable access to cold-chain infrastructure worldwide. Overcoming this challenge will require a step-change in approach where governments become a partner in the development of cold-chains as critical infrastructure, unlocking investments in acute areas that are often perceived as high risk by the private sector, but are key for the social, economic, and environmental benefits to be gained, and ensuring an inclusive and equitable access to cold-chains.

Global partnerships

There is a need for governments of both high- and low- income countries to work together on shared goals of sustainably improving the resilience of local and global supply chains to achieve food and health security for the benefit of all their citizens. To facilitate this collaboration a novel Public-Private-Community Partnership (PPCP) model could be used, in which there is a shift in focus from direct cash returns for private sector cold-chain owners and operators as the only parameter of success, to inclusive, equitable and sustainable development underpinned by the active involvement of the community and a rigorous in-country cooling needs assessment[44]. Through this approach, governments of low-income countries would complement their resources with direct investments from high-income countries and by gaining access to sustainable technologies and associated skills. A PPCP approach could simultaneously:

- enable governments of low-income countries to complement resources with direct investments from high-income countries and access sustainable technologies, knowledge and skills in collaboration with the private sector.

- facilitate the collaboratively working of public, private and community stakeholders in the development of cold-chains that seamlessly integrate producers, manufacturers, processors, distributors, retailers and end-users in product source nation and recipient end-user nation, helping establish the safety and quality of food and health products across borders.

- reduce investment risks for the private sector through the policy-making powers of the collaborating governments, as well as by the communities' direct involvement as product source (e.g., smallholder farmers) or the end-user recipients (e,g. vaccination targets), securing the demand for services. It could also enable private sector stakeholders to reach the wider community and provide a structure that would contribute towards achieving Corporate Social Responsibility aspirations.

- enable communities to access sustainable cold-chain technologies, market connectivity, and training and knowledge for skilled employment.

- improve acceptance and take-up of new technologies and practices through direct involvement of the community in the co-design and co-development of cold-chains and associated service provision that better responds to community needs as identified in a rigorous in-country cooling needs assessment. Under PPCP, the communities' traditional consumer-only or user-only role could be transitioned into a co-provision role. For example, they could be co-owners/investors of their local cold-chain facilities, provide resources for the energy production or complement energy demand of facilities (e.g., biomass or surplus energy from decentralised renewable energy technologies). Furthermore, within the PPCP model, non-governmental organizations can play an intermediary role between the actors in the partnership, mediating between community interests and those of the governments and the private sector.

Return on investment

However, to secure participation of governments in such a radical change of the business model for cold-chains, a clear, robust articulation of the real "value" and "return on investment" of sustainable, resilient, and equitable cold-chains will be required. This will involve identifying, quantifying and, where possible, monetising the multiple benefits that can be delivered. These benefits often translate into reductions in other costs or lower economic losses.

Examples might include the reduced cost of food loss to the economy; reduced healthcare expenditure associated with malnutrition, air pollution and lack of immunisation; reduced undernutrition, which can exacerbate death rates among children; reduce cost of workforce absenteeism and impacts of mortality rate on national productivity; and savings for governments that subsidise energy production and consumption (through reduced cooling energy demand). If these impacts are quantified and monetised as part of cost-benefit analyses, it can greatly improve the return on investment (ROI).

Hence, more detailed analyses are needed locally, nationally, and globally across multiple dimensions such as health, productivity, education, and income with established links to strategic goals, targets, and commitments, considering equity issues to understand the real cost of lack of cold-chains to economies and societies.

What needs to be done?

Addressing the seven key factors identified as essential to a successful outcome to the 2050 imperative of delivering sustainable resilient cold-chains aligned with food security, energy security, nutritional and health needs globally, requires a range of actions to be carried-out by stakeholders. These cover three principal areas: filling research gaps; addressing deployment issues; and meeting policy needs.

Research gaps

Future proofing cold-chain decision making.

The scale of the sustainable and resilient cold-chain challenge is such that resources cannot be used on initiatives that will not significantly contribute to achieving the required goals and delivering a successful outcome. To meet this challenge, deep innovative thinking is urgently needed supported by wide ranging research programmes that rapidly conceptualise, build, test and deploy methodologies for identify high impact global roadmaps for future proofed cold-chain related research, development, and deployment. These methodologies need to anticipate and allow for the fact that the characteristics of the food and health products sectors could be significantly different by mid-Century, requiring a suite of technologies, finance, business models, policies and regulations as yet unknown. In doing so, rather than focussing on specific technology suites for individual sectors, they must take a system-based, sector agnostic, approach to cold-chain research design and roadmap development. In short, the key to a successful outcome will be to avoid developing, deploying and supporting solutions that may become redundant on the journey to 2050, because the sector/sub-sector/market disappears after a substantial amount of resource has, effectively, been wasted.

Resetting temperature set-points for frozen foods.

With the projected growth of demand for frozen foods comes a significant energy and GHG emissions challenge, at the core of which is the set-point temperature for cold-chain equipment handling frozen products. Currently, the industry standard set-point is -18°C, a temperature established in the mid-20th Century and arguably not relevant in the context of today's food products and affordability and flexibility of real time monitoring technologies. Some in the industry think that a temperature of -15°C would be more appropriate and that a requirement to not 'over-cool' could be introduced, without any negative impacts on food safety or quality. To tackle this challenge a comprehensive, wide-ranging programme of scientific and engineering research, focussed on creating an evidence base for the choice of a new set-point, is urgently required. A starting point for such a programme would be to carry out an initial scoping study in order to: estimate the 'size of the prize', in terms of current and future energy and GHG emissions savings; determine issues and barriers to implementation; consider the implications for low- and middle-income economies; determine what a roadmap to making such a change might look like: define the next steps. This work needs to be undertaken in the sector as a collaborative pre-competitive activity and consider the food safety and quality aspects, as well as implications for energy systems; cold-chain economics; food supply chain resilience; GHG emissions; and broader sustainability issues, in a warming world with an increasing population characterised by rapidly shifting demographics.

Transitioning to natural / ultra-low GWP refrigerants.

A fundamental requirement of establishing sustainable and resilient cold-chains is a significant scale up in the roll-out of cooling technologies using natural/ultra-low GWP refrigerants, thereby reducing the GHG emissions resulting from leakage and/or spillage during use and end-of-life disposal. In most instances lower GWP refrigerant alternatives, such as natural refrigerants, require minimal equipment design modifications and provide comparable efficiencies to the high GWP refrigerants. However, certain refrigerants may present operational challenges such as flammability (i.e., hydrocarbons), toxicity and high operational pressures that could result in public safety risks if not handled properly. Ammonia, CO_2, Hydrocarbons, Propane etc all have disadvantages as well as advantages and there is a need for research to explore the full range of technology alternatives and “best-in-class” systems. The primary objective of such research would be to assess their optimality in terms of energy efficiency and emissions, as well as operational use, and essentially to determine the right fluid for the right system.

New business and investment models.

To secure participation of governments of both high- and low-income countries in driving a radical change to the business model for the deployment of cold-chains in middle- and low-income economies, a clear, robust articulation of the real value and ROI of sustainable, resilient, and equitable cold-chains will be required. This would involve identifying, quantifying and, where possible, monetising the multiple benefits that can be delivered. These benefits often translate into reductions in other costs or lower economic losses. Examples might include the reduced cost of food loss to the economy; reduced healthcare expenditure associated with malnutrition, air pollution and lack of immunisation; reduced undernutrition, which can exacerbate death rates among children; reduce cost of workforce absenteeism and impacts of mortality rate on national productivity; and savings for governments that subsidise energy production and consumption (through reduced cooling energy demand). If these impacts are quantified and monetised as part of cost-benefit analyses, it can greatly improve the ROI. Hence, research is needed to deliver a more detailed analyses of value and ROI locally, nationally, and internationally across multiple dimensions such as health, productivity, education, and income with established links to strategic goals, targets, and commitments, considering equity issues to understand the real cost of lack of cold-chains to economies and societies.

Deployment issues.

Enabling optimal utilisation of cold-chain infrastructure.

Cold-chain infrastructure is resource hungry in terms of equipment, energy, people, and money, and as such it is essential to optimise its deployment and use to ensure sustainability. Not to do so, is effectively a waste of national and international critical infrastructure. In this regard there are two key deployment challenges that must be tackled: the poor utilisation of space within stationary and mobile elements of cold-chains; and the use of cold-chains to deliver products that are not necessarily needed. An example of the latter highlighted in this report is the use of cold-chains to deliver vaccines that are not necessarily required.

Current immunisation programmes typically take a mass vaccination campaign approach predicated on the fact that the antibody status of individual members in the population is unknown, so everybody is vaccinated. This potentially results in the unnecessary immunisation of a substantial portion of the population and therefore the unnecessary shipping of large volumes of vaccine requiring cold-chain utilisation. An alternative, less wasteful approach is to use a point-of-care testing mechanism to determine exact vaccine supply requirements for a given population. This approach, in combination with highly targeted, rapid, delivery services that work within the product temperature degradation limits to reduce refrigeration burdens, such as those based on utilisation of drone technology, can help reduce the wasteful deployment of cold-chain assets. It is a potential breakthrough for low- and middle-income economies, who often struggle to acquire sufficient doses of vaccine for effective implementation of immunisation programmes, as evidenced by the COVID-19 pandemic, and face the delivery challenges presented by high ambient temperatures and widely dispersed populations in areas with difficult terrain and/or poor road infrastructure. However, barriers to the use of this radical approach to immunisation and cold-chain deployment, which should be adopted by health authorities across the world, include risk aversion and the unavailability of appropriate standards. The World Health Organisation (WHO) and other high-profile national and international health organisations need to create a positive enabling environment and support the adoption of approaches to immunisation programmes that eliminate the current unnecessary waste of cold-chain infrastructure.

In the parallel area of the poor utilisation of space within stationary and mobile elements of cold-chains, there are many examples from the food supply sector. For instance, the unnecessary use of pallets and the inefficient placing of them within the valuable space of cold stores, refrigerated transport vehicles and shipping containers, as well as the storage and movement of fish products on a bed of ice within the temperature-controlled environment of a cold-chain. For example, in the UK, almost 30% of vehicle-kilometres are running empty, and vehicles are utilized to only 63% of their weight capacity[45]. These practices, and other similar ones, lead to unnecessary cold-chain capacity to accommodate inefficiency with associated unnecessary energy use and associated GHG emissions, as well as exacerbate issues of inequitable access to cold-chain infrastructure in low- and middle-income economies. It is therefore an imperative that space utilisation within deployed cold-chain assets is optimised on the food products themselves, thereby resulting in efficient energy use, more space being available in existing and future infrastructure for additional users, and right-sized infrastructure capacity.

New business and investment models.

The capital and operating costs of cold-chain equipment is high relative to the affluence level of potential users in low- and middle-income nations, limiting their uptake in food and health product supply chains. To address this issue new, tailored, finance and business models need to be deployed in-country that make access to sustainable and resilient cold-chains affordable to potential users, enable equitable distribution of risks and costs, and overcome investor concerns regarding the value created from their investments.

Such models can provide an essential catalyst to enabling groups of smallholder farmers (for example in a cooperative model), or local entrepreneurs, purchase equipment and reduce payback periods by linking repayment amounts to income generation. In addition, financial barriers and investment risk can be addressed through proven Pay-As-You-Go (PAYG) and Cooling-as-a-Service (CaaS) servitisation models, which negate the need for cold-chain equipment users to incur the capital costs of asset ownership or operational/maintenance costs. Other approaches to financial models to increase cold-chain equipment uptake could include direct government subsidies that reduce the upfront cost of ownership, as well as equipment rental/leasing mechanisms and bulk procurement programmes.

Policy needs

Continuous training and skills.

A significantly underappreciated factor for successfully delivering sustainable and resilient cold-chains is the need for national government policy to develop a well-trained and appropriately skilled industrial workforce. This is critical not only to support equipment development, deployment, operation, maintenance and decommissioning, but also to create a better prepared market for absorbing new technologies and ensure that the broader economic, social, and environmental benefits are realised. In this regard, continuous education and training provision is essential for all stakeholders, including project developers, contractors, and end-users, such as smallholder farmers and medical outreach practitioners, to raise awareness of the benefits of sustainable and resilient cooling access, facilitate behavioural change and increase the uptake of systems thinking, best-in-class technologies and best professional practice. To this end, there is a need for policymakers to urgently assess and strengthen the skills and training required to deliver, operate, use and maintain current sustainable technologies in the market, as well as to scan the horizon by engaging with industry and technology developers to understand the potential future skill requirements to meet the needs of equipment in development. Specifically, in low- and middle-income countries the deployment and implementation of best cooling practices will require particular attention to skills and capacity building for design, installation, commissioning, inspection, operation, use, maintenance and disposal of cold-chain equipment, as well as enabling, coordination, implementation, financing, regulatory enforcement and evaluation of policies and programmes. However, in all countries regardless of development stage, as well as closing the skill gaps at all levels across multiple disciplines and attracting new entrants into the industry, policymaking for continuous professional development (CPD) will be essential to avoid the issue of 'rusty skills'.

Conflation of energy for tackling energy inflation.

The current global energy crisis has significantly impacted the full range of national economies, from developed to least developed, and the attention of governments worldwide is now strongly focussed on the urgent need to improve their country's energy security, particularly as demand for energy is projected to increase substantially in the decades ahead. Given that cold-chains are highly dependent on secure and affordable energy supplies for their operations, this issue is critical to their broader deployment and use. Conflating energy demands and energy sources, that is bringing them together, can enhance energy security through end users and suppliers taking opportunities to share infrastructure, benefit from energy that would otherwise be wasted, and utilise locally sourced energy which would not otherwise be exploited. By using a conflated energy system, significant cost savings can also be achieved and GHG emissions reduced, whilst simultaneously helping to deliver other national and international policy targets for energy, economic growth, and sustainability more broadly. To realise these benefits, national governments worldwide need to adopt conflation as an urgent policy issue and create an environment that drives its widespread adoption. This means empowering local policymakers to make conflation work as without local drive it is unlikely to be implemented. In this regard, governments need to consider whether it should be encouraged through a mandatory approach that aims to breakdown existing silos and achieve optimised multi-agenda outcomes. For example, national policies could be devised that force local authorities to use local thermal sources, if they exist, and recover waste energy, possibly as a part of national planning policy. Additionally, policymakers at all levels need to resolve competing and mis-aligned policy agendas at local, regional, national and international levels. Cold-chains are perceived as a private sector enterprise, but they need to be considered as critical infrastructure (ie similar to power and water distribution networks) and treated as such in policy making. There needs to be a focus on cooperation and collaboration across governments and the private sector in an approach through which conflation can be financed, policy ambitions and targets aligned, and the respective responsibilities of all the various stakeholders understood.

Transitioning to natural / ultra-low GWP refrigerants.

Despite the availability of alternative natural/ultra-low GWP refrigerants, issues of equipment cascading to developing and low- and middle-income countries and the availability of counterfeit refrigerants are a long-existing problem that needs to be tackled by policymakers. Many nations lack sufficient capacity to monitor and enforce refrigerant regulations and there is an urgent need for governments of high-income economies to assist them in strengthening these systems. More specifically, as developed nations implement increasingly stringent equipment and refrigerant standards, there is a significant risk of middle- and low-income economies becoming targets for the 'dumping' of none-compliant equipment with low energy efficiencies and high GWP/ozone-depleting refrigerants. This could include both second-hand and end-of-range new products that cannot be sold in the country of origin. In the absence of adequate regulatory environments to prevent illegal imports, low- and middle-income nations such as those of sub-Saharan Africa could be locked into obsolete and sub-standard technologies for at least the next 15-20 years. In addition to helping these countries to build capacity for regulatory control, it is therefore important that governments of high-income countries tighten their own export controls to prevent the shipping of none-compliant equipment, both new and second-hand, and regulate for the appropriate internal disposal of such units.

New business and investment models.

Attempts to apply the 'tried and tested' private sector lead cold-chain business model of the developed world in middle- and low-income countries has typically resulted in sub-optimal investments and a fragmented deployment. At the core of this market failure is the fact that the groups that are in most need (such as remote, difficult to physically access poor communities, smallholder farmers and marginalised populations etc) often do not present a compelling business case for the private sector due to uncertainties regarding the timescale and magnitude of financial returns on investments. Overcoming this challenge will require a step-change in approach where governments of both high- low-income become partners in the development of cold-chains as critical infrastructure, unlocking investments in acute areas that are often perceived as high risk by the private sector, but are key for the social, economic, and environmental benefits to be gained, and ensuring an inclusive and equitable access to cold-chains. There is a need for government policymakers of developed and low- and middle-income countries to work together on shared goals of sustainably improving the resilience of local and global supply chains to achieve food and health security for the benefit of all their citizens. To facilitate this collaboration a novel Public-Private-Community Partnership (PPCP) model could be used, in which there is a shift in focus from direct cash returns for private sector cold-chain owners and operators as the only parameter of success, to inclusive, equitable, sustainable development that builds resilience and is underpinned by the active involvement of communities and a rigorous in-country cooling needs assessment. Through this approach, governments of low-income countries would complement their resources with direct investments from high-income countries and by gaining access to sustainable technologies and associated skills. A PPCP approach would simultaneously facilitate the collaboratively working of public, private and community stakeholders to establish seamlessly integrated food and health cold-chains across borders while reducing investment risks for the private sector through the policy-making powers of the collaborating governments, as well as by the communities' direct involvement as product source (e.g., smallholder farmers) or the end-user recipients (e.g., vaccination targets), securing the demand for services. It would also help communities to access training and knowledge for skilled employment.

There is also a policy need upstream of deployment in the form of support for early-stage technology development, where typically technologies must be proven and tested to attract funding/investment, yet there is little appetite to fund and incubate the initial technology R&D. As a result, many companies struggle to reach the commercialisation and scale-up stage. R&D is not only costly, but also requires long-term commitment to prove out technologies, and often funding organisations and investors want rapid results which are rarely possible. Government policymakers need to work to help meet this funding gap by supporting companies/organisations in early, mid- and late stage of technology development (pre-commercialisation) with grant funding, which is crucial to the success of a technology and the impact it can create.

Recommendations

1. **Academia and industry need to work collaboratively to fill the research gaps identified in this report as being essential to meeting the 2050 Imperative of delivering sustainable and resilient cold-chains.** These include establishing pre-competitive, multi-disciplinary, multi-sector, international collaborative research programmes to:

- rapidly conceptualise, build, test and deploy methodologies for identify high impact roadmaps for future proofed cold-chain related research, development, and deployment. These methodologies need to anticipate and allow for the fact that the characteristics of the food and health products sectors could be significantly different by mid-Century, requiring a suite of technologies, finance, business models, policies and regulations as yet unknown.

- create a comprehensive evidence base to build consensus for the choice of a new temperature set-point to be applied across all stages of the frozen food cold-chain. This work should, in the context of a warming world with an increasing population characterised by rapidly shifting demographics, include estimates of the current and future energy and GHG emissions savings; determine issues and barriers to implementation; consider the food safety and quality aspects; and implications for cold-chain economics, energy systems, food supply chain resilience, and a broad range of sustainability issues.

- explore the full range of natural and ultra-low GWP refrigerant alternatives and associated “best-in-class” systems with the primary objective of assessing their optimality in terms of energy efficiency and emissions, as well as operational use.

- deliver a more detailed analyses of the “value” and ROI of the multiple benefits that can be delivered locally, nationally, and internationally by the deployment of sustainable resilient cold-chains, across multiple dimensions such as health, productivity, education, and income. This work should be linked to established strategic goals, targets and commitments, as well as consider equity issues, to understand the real cost of lack of cold-chains to economies and societies. These analyses are essential to secure the participation of governments of both high- and low-income countries in driving a radical change to the business model for the deployment of cold-chains in developing and least developed economies. As such, once undertaken, they need to be disseminated widely amongst relevant policymakers and investor communities.

2. **The cold-chain industry needs to address the deployment issues identified in this report as being essential to meeting the 2050 Imperative of delivering sustainable and resilient cold-chains.** These include:

- eliminating the waste of cold-chain infrastructure to optimise its deployment by tackling the poor utilisation of space within stationary and mobile elements of cold-chains. This requires a focus on ensuring that the deployed assets are optimised on the food and health products themselves, through improved space packing and reductions in unnecessary materials, thereby resulting in efficient energy use, more space being available in existing and future infrastructure for additional users, and right-sized infrastructure capacity.

- offering customers new, tailored, finance and business models designed to be deployed in developing and least-developed nations that make access to sustainable and resilient cold-chains affordable to potential users, enable equitable distribution of risks and costs, and overcome investor concerns regarding the value created from their investments. Such models include proven Pay-As-You-Go (PAYG) and Cooling-as-a-Service (CaaS) servitisation approaches, which negate the need for cold-chain equipment users to incur the capital costs of asset ownership or operational/maintenance costs.

3. **The World Health Organisation (WHO) and other high-profile national and international health organisations need to tackle the unnecessary use of cold-chain infrastructure assets for the delivery of vaccines that are not necessarily needed.** As highlighted in this report, such an outcome can be achieved by redesigning immunisation programmes to use approaches that are more targeted than mass delivery focussed, as well as by creating a positive enabling environment to support their adoption.

4. **Government policymakers should deliver on the policy needs identified in this report as being essential to meeting the 2050 Imperative of delivering sustainable and resilient cold-chains.** These include a need to:

– treat cold-chains assets as critical infrastructure in national and international policy making (ie similar to power and water distribution networks), rather than as a private sector only enterprise.

– urgently assess and strengthen the skills and training required to deliver and use current sustainable cold-chain technologies in the market, as well as to scan the horizon by engaging with industry and technology developers to understand the potential future skill requirements to support and use equipment in development, including the need for continuous professional development (CPD).

– focus particular attention in middle- and low-income countries on skills and capacity building for design, installation, commissioning, inspection, maintenance and disposal of cold-chain equipment, as well as enabling, coordination, implementation, financing, regulatory enforcement and evaluation of policies and programmes.

– recognise the critical role that end-users, such as smallholder farmers and medical outreach practitioners, play in the success of pathways to establishing sustainable and resilient cold-chains and nurture, support and protect them through training provision, regulation and, where appropriate, financial incentives. End-users not only take entrepreneurial risks, invest their time in learning new skills, raise community and peer awareness, but also have an active part in the process of equipment development, use and economic effectiveness by providing feedback that helps generate knowledge that improves equipment performance and, most importantly, the realisation of new market opportunities.

– adopt conflation as an urgent policy issue and create an environment that drives its widespread adoption. This means empowering local policymakers to make conflation work on the ground, as without local drive it is unlikely to be implemented, possibly through a mandatory approach that aims to breakdown existing silos and achieve optimised multi-agenda outcomes.

– devise policies that require local authorities to use local thermal sources, if they exist, and recover waste energy, possibly as a part of national planning policy.

– resolve competing and mis-aligned policy agendas at local, regional, national and international levels. There needs to be a focus on cooperation and collaboration across governments and the private sector in an approach through which conflation can be financed, policy ambitions and targets aligned, and the respective responsibilities of all the various stakeholders understood.

– tighten the export controls of high-income developed nations to prevent the shipping of equipment that is none-compliant with the latest energy efficiency, sustainability and refrigerant use regulations, both new and second-hand, and regulate for the appropriate internal disposal of such units.

- urgently implement policy that increases assistance from high-income developed nations to middle- and low-income countries for the strengthening of their capacity to monitor and enforce refrigerant regulations.

- create collaborative groups composed of government policymakers from developed high-income nation and middle-income and low-income countries working together on shared goals of sustainably improving the resilience of local and global supply chains to achieve food and health security for the benefit of all citizens of their respective jurisdictions. To facilitate this collaboration a novel Public-Private-Community Partnership (PPCP) model should be used, in which there is a shift in focus from direct cash returns for private sector cold-chain owners and operators as the only parameter of success, to inclusive, equitable, sustainable development that builds resilience and is underpinned by the active involvement of communities and a rigorous in-country cooling needs assessment.

- develop policy to support early-stage technology development, where typically technologies must be proven and tested to attract funding/investment, yet there is little appetite amongst traditional investors to fund and incubate the initial technology R&D. As a result, many companies struggle to reach the commercialisation and scale-up stage. Government policymakers need to work to help meet this funding gap by supporting companies/organisations in early, mid- and late stage of technology development (pre-commercialisation) with grant funding, which is crucial to the success of a technology and the impact it can create.

CHOGM 2022, COP27 president Alok Sharma’s visit to ACES

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