Three Degrees Of Change

FROZEN FOOD IN A RESILIENT AND SUSTAINABLE FOOD SYSTEM

Summary report & initial findings
November 2023

International Institute of Refrigeration
Centre for Sustainable Cooling

Foreword

Through the collaborative work of the Centre for Sustainable Cooling, the Africa Centre of Excellence for Sustainable Cooling and Cold-chain (ACES) and our partners including The International Institute of Refrigeration (IIR), we are focused on solving a wicked problem:

How do we achieve global equitable food security in a warming world, while at the same time economically empowering 500 million small-holder farmers, many reliant on less than two hectares of land, and ensuring minimum environmental impact along with no fossil fuel usage?

Globally, 12% of food produced annually for human consumption is lost due to a lack of proper temperature management (IIR 2021). With the projected growth in global population increasing the demand for food at the same time as climate change impacts are reducing food output, it's crucial we protect farmers and other food system stakeholders to combat this loss.

Food freezing, as a form of preservation, extends product shelf life without detriment to food safety for months while also offering built-in opportunities to optimise utilisation through scheduled consumption. Research has demonstrated that frozen foods results in 47% less household food waste than fresh food categories (Martindale 2014). However, with frozen foods comes a significant energy and greenhouse gas (GHG) emissions challenge to the success of a transition to sustainable cold-chains: it is energy intensive to freeze foods and hold them at a sub-zero temperature.

At the core of this challenge is the sub-zero temperature at which stationary and mobile refrigeration systems are required to be set (the 'set-point') for handling frozen products. Currently the industry standard set-point is -18°C or lower: a temperature established in the mid-20th century which provides a good margin of safety. However, for many foods we only need to store them at just below -12°C and every degree lower requires 2-3% more energy. There is therefore an important question to be investigated: is -18°C relevant in the context of today's food products, and does reducing refrigeration temperatures to below those that are required to maintain product safety and quality lead to unnecessary energy consumption with associated avoidable GHG emissions?

Some in the industry think a standard set-point of -15°C would be more appropriate for certain food products and that a requirement to not 'over-freeze' could be introduced - without any significant negative impacts on food safety or quality. The change in this temperature could be valuable in the context of reducing the increase in energy demand and GHG emissions from the sector. It would also deliver a substantial commercial benefit to cold-chain operators through reduced energy costs.

When considering the food system of the future and developing its infrastructure and technology strategies in the low-income - but food system critical - regions of the world, such as Sub-Saharan Africa, there is a real need to undertake a thorough review of the set-point standard for refrigeration of frozen foods. Not just by calculating the energy efficiency wins, but also understanding fully the food safety and quality implications, as well as the risks and impacts on the entire food system and stakeholders.

Given that food supply chains are global, reaching from source to consumer and involving many stakeholders, this work needs to be undertaken as a collaborative activity. We hope this initial Summary Report published for COP28 can create a first step in an evidence-based collaborative discussion, to be followed up by a series of stakeholder workshops (virtual and physical) which are planned for early in the new year. Our aim is that a full report will be published in Spring 2024.

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Disclaimer

This piece of work sets out to provide a high-level indication of the size of the opportunity of three degrees of change in the set point for frozen food and to identify if there are any immediate 'no-go' critical barriers to change. It does not deliver detailed intervention strategies, nor granular, market by market bottom-up numbers. It does though aim to provide an evidence-based indication of the value, a framework, and next steps for more detailed analysis to underpin a consensus roadmap planned for publication in the first half of 2024.

While we have recognised sources for our data, we have necessarily had to make several assumptions and projections, and we have not accounted for regional variances. The conclusions are, however, highly likely to be accurate although estimates for energy and emissions are at this initial report stage approximate.

OUR FOOD SYSTEM IS BROKEN AND NEEDS TO CHANGE RADICALLY

Food loss and waste is a challenge that jeopardises global food security as well as our social, environmental and economic goals.

Each day, 25,000 people die from hunger. According to the Food and Agriculture Organization (FAO), more than 820 million people in the world are hungry today while 2 billion people suffer from food insecurity (FAO 2022). Even in North America and Europe, 8% of the population does not have regular access to safe, nutritious, and sufficient food (FAO 2019).

Foodborne diseases cause around 600 million people to fall ill and more than 400 million people to die annually (WHO 2022). Beyond this human toll, foodborne diseases also result in a substantial economic burden due to associated healthcare costs and lost productivity.

Food production will need to increase significantly to feed the expected human population of 9.7 billion by 2050 (United Nations 2022) and this will require closing of the 56% gap in the global food system between what was produced in 2010 and what will be needed in 2050 (WRI 2019).

Climate change induced extreme weather events such as droughts, floods and heatwaves can damage crops, reduce yields and lead to production failures. In Pakistan for example, 50% of exportable mango varieties and 30% of those for local consumption were lost due to the extreme heatwave experienced in 2022 (Ilyas 2022). Rising temperatures and changing weather patterns can also shift traditional growing seasons, leading to altered planting and harvesting times that disrupt established production schedules and, in extreme cases, the ability to grow certain crops in specific regions. Furthermore, higher temperatures and reduced water availability can affect livestock health and productivity. Some projections suggest that crop yields and livestock productivity could decline by up to 30% by 2050 (Giving Compass 2020). Ocean food sources are also threatened by CO_2 emissions which result in acidification of sea water.[1] The future availability of fish and seafood will diminish under such conditions, impacting the main source of protein for more than one billion of the most vulnerable people in the world (Huelsenbeck 2012).

Countries that rely on high proportions of imports for their food supply will be particularly vulnerable to system disruption. For example, the UK imports approximately 50% of its vegetables as well as more than 80% of its fruit (The Food Foundation 2022) and recent disruptions to the global food system (e.g. the COVID-19 pandemic, political conflicts, natural disasters, and the knock-on effects from increased energy, transport, and other costs) exposed vulnerabilities in supply chains which highlighted the need for a more resilient system that can absorb such shocks.

The impacts of food system disruptions are experienced disproportionately by poor, disadvantaged, and often marginalised individuals and communities in low-, middle-, and high-income countries. This will likely result in significant and potentially long-lasting adverse effects on public health, social equity and societal well-being, possibly with consequences for political and geopolitical stability.

In a world where the food system is facing multiple challenges, disruptions and shocks, ranging from rapid population growth, widespread hunger and deeply entrenched inequities to wars, health pandemics and climate change induced extreme weather events, it will be vital that we ensure enough food reaches everyone's table in a safe and good nutritional condition for consumption.

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[1] The ocean absorbs about 30% of the CO_2 that is released in the atmosphere, and as levels of atmospheric CO_2 increase, so do the levels in the ocean. When CO_2 is absorbed by seawater, a series of chemical reactions occur resulting in the increased concentration of hydrogen ions. This increase causes the seawater to become more acidic and causes carbonate ions to be relatively less abundant. Carbonate ions are an important building block of structures such as sea shells and coral skeletons. Decreases in carbonate ions can make building and maintaining shells and other calcium carbonate structures difficult for calcifying organisms such as oysters, clams, sea urchins, shallow water corals, deep sea corals, and calcareous plankton. https://oceanservice.noaa.gov/facts/acidification.html

FOOD SAVED IS AS IMPORTANT AS FOOD PRODUCED

Globally, around 13% of food produced is lost between harvest and retail (FAO 2022). A further estimated 17% of total global food production is wasted in households, in the food service and in retail all together (UNEP 2021)[2/3]. While the contribution to this figure from high-income economies is largely due to waste at the final stage of household consumption, in low-income countries it is primarily a result of 'losses' in the food system due to financial, political and technical limitations in harvesting and post-harvest management as well as a lack of cooling facilities and food storage infrastructure.

Food that is lost and wasted accounts for 38% of total energy usage in the global food system. FAO quantified the global impact of food loss and waste on natural resources, most notably the carbon footprint which was estimated at 3.6 $GtCO_2e$ in 2007, excluding land use change. Adding the latter into the calculation increased the value to 4.4 $GtCO_2e$/yr (FAO 2013). To put this into perspective, if global food loss and waste were a country it would be the third largest emitter after China and USA (FAO 2013).

Moreover, food wastage incurs costs from the wasted agricultural inputs that went into producing it, including fertilisers, land, water and energy. For example, according to the FAO, food loss and waste accounts for 250 km_3 of the world's freshwater use annually and required 1.4 billion hectares, or 30% of the global agricultural land area for its production (FAO 2013).

These global figures highlight that investing in food saved in order to feed the world sustainably is as important as food produced and that something needs to change radically.

FOOD LOSS –THE ECONOMIC COST

500 million small-holder farmers, each with less than 5 acres of land, account for a large proportion of the world's poor and hungry living on less than US $2 a day (World Bank 2016). At the same time, these farmers often account for the largest share of food production in low-income countries. For example, across Sub-Saharan Africa small-holder farmers typically contribute about 80% of the food produced within their individual country (Business Call to Action 2021). However, about 37% of the region's produce is lost between production and consumption, including almost 50% of fruits and vegetables (World Bank 2020), resulting in lost income to these financially poor farmers upon whom the global food system relies for a substantial portion of its supply. This inequity represents an economic injustice and a vulnerability within the system.

According to FAO, the total food produced for human consumption but lost within supply chains costs the global economy approximately $936 billion a year (FAO 2014)[4]. In 2018, Boston Consulting Group estimated that annual food loss and waste may reach to 2.1 billion tonnes by 2030 and have a value of $1.5 trillion (Hegnsholt, Unnikrishnan and Poll 2018).

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[2] Food loss is defined as occurring in the food supply chain up to, but not including, the retail level. Food waste, on the other hand, occurs at the retail and consumption level. Historically food loss and waste reported by FAO have been very rough estimates which originate from the original FAO numbers produced in 2011 (1.3 billion tonnes). This data is in the process of being replaced by two new indices developed by FAO and UN Environment to estimate more carefully and more precisely how much food is lost in production or in the supply chain before it reaches the retail level (through the Food Loss Index) and is subsequently wasted by consumers or retailers.

[3] As FAO report, historically food loss and waste have been very rough estimates, going back to original FAO numbers produced in 2011 (1.3 billion tonnes). This is in process of being replaced by two indices by FAO and UN Environment to estimate more carefully and more precisely how much food is lost in production or in the supply chain before it reaches the retail level (through the Food Loss Index) and is subsequently wasted by consumers or retailers (through the Food Waste Index). https://www.fao.org/3/ca6030en/ca6030en.pdf

[4] Based on the 2012 market value.

RADICAL CHANGE TO A MORE FOOD SECURE WORLD IS A COLD CHALLENGE, ESPECIALLY IN A FAST-WARMING WORLD

According to the International Institute of Refrigeration (IIR), globally each year approximately 1.8 billion tonnes of food[5] could benefit from refrigeration, representing around 40% of production after deduction of the various agricultural and post-harvest losses. Yet, only 45% of this quantity is actually refrigerated and as a result about 12% of global food production is lost annually – an amount sufficient to feed one billion people every year.

The volume of refrigerated food in low-income countries is particularly small, representing only 20% of perishable products compared with a typical value of 60% in high-income countries. This can be illustrated by the Rwanda example, where only 5% of companies in the food and agriculture sector have refrigerated trucks and just 9% have a cold room to store fresh produce (NAEB 2019). For small and marginal farmers, where the majority of post-harvest food losses occur, functional cold-chains are completely absent (less than 1% of cold-chain capacity) (NAEB 2019).

The demand for more refrigeration of foods will most certainly increase in a warming world with a growing population.

> **“Food saved is as important as food produced. 12% of global food production is lost annually due to the lack of cold-chains. If saved, this is enough to feed one billion people a year.”**

BUT MAKING HOT AIR COLD IS ENVIRONMENTALLY EXPENSIVE

Cooling technologies, such as refrigeration, air conditioning and fans, currently account for more than 7% of all GHG emissions (K-CEP 2018). It is estimated that these emissions could double by 2030 and possibly triple by 2100 (World Bank 2019). Moreover, hydrofluorocarbons (HFCs) are the fastest-growing source of GHG emissions in the world because of the increasing global demand for space cooling and refrigeration (Rand, Jaeger and Gencsu 2015).

Specifically, the GHG emissions from cold-chain equipment are expected to rise significantly as their uptake expands in low- and middle-income countries. For example, without policy and market intervention to promote the deployment of more sustainable technologies, food cold-chain related emissions are anticipated to double in India by 2027 (Kumar, et al. 2018).

In the mobile stage of a cold-chain, as well as consuming up to 20% of the diesel fuel of a refrigerated vehicle and exhausting the associated GHG emissions, the transport refrigeration unit used to keep the cargo at the correct temperature can produce high levels of airborne pollutants—specifically, as much as six times the nitrogen dioxide (NO_2) and 29 times the particulate matter (PM) emitted by a modern Euro VI truck propulsion engine (Dearman 2015). According to the World Health Organization (WHO), 7 million people die prematurely each year because of air pollution; these hidden polluters cannot be ignored (WHO 2014).

According to the IIR, upgrading the level of cold-chains in low-income economies to that in high-income countries in terms of cold-chain infrastructure and equipment performance, would reduce the global food losses by 55% and the total carbon emissions by 47% (IIR 2021).

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5 The food products considered in this modelling are meat, milk, fish, fruits, vegetables and tubers.

COLD-CHAINS ARE CRITICAL INFRASTRUCTURE

The equitable deployment of well adapted, smart, resilient, future-proofed, sustainable cold-chains is at the centre of delivering the radical change required to fix our vulnerable global food system.

In fact, we need to go further and recognise that cooling is critical infrastructure, vital for a well-functioning society and economy, and that cold-chain assets are a substantial physical component therein. Not only do they underpin our access to safe and nutritious food, but also our health through the delivery of vaccines, medicines and other temperature-sensitive healthcare products, as well as our ability to spur economic growth and deliver socio-economic development. Furthermore, cold-chain infrastructure, and the lack of it, have implications for global climate change and the environment.

As cold-chains increasingly gain attention as one of the key pillars of socio-economic development, it will be vitally important to understand how to deliver them:

1. sustainably with minimum climate impact;
2. equitably, providing access for all potential beneficiaries, including poor, disadvantaged, and marginalised farmers and their communities, as well as women and youth;
3. resilient and future-proofed against a broad suite of shocks and changes that may take place across the entire 'ecosystem' within which they function. Achieving this will require a paradigm shift towards a different way of thinking that goes beyond simply taking business-as-usual action.

THE BENEFITS OF SUB-ZERO

The focus of work to date on the role of cold-chains in the food-water-energy-social nexus and low-middle income countries has been primarily on chilled temperatures (above 0°C, normally in the range of 2-8°C) targeting fresh fruit and vegetables from small-holder and subsistence farmers. However, freezing a range of food products can bring significant benefits.

Freezing food can lead to a reduction in food wastage. For example, research has demonstrated that household food waste associated with frozen products is 47% less than is the case for fresh food categories, with a typical household wasting 10.4% of fresh food and 5.9% of frozen food (Martindale 2014).

Food freezing can also maintain a higher nutritional content than is achievable by chilling it and has the added advantage of locking-in the nutrition for a longer time period (months versus days or weeks for chilled). By freezing food at its peak freshness:

1. **its nutritional traits are preserved at their optimal stage;**
2. **post-harvest/post-slaughter life is extended;**
3. **spoilage is prevented;**
4. **utilisation is optimised by scheduled consumption.**

It is feasible to use freezing processes as a tool to ensure food safety as microorganisms are completely inactive below -12°C. Microbial growth, the cause of food-poisoning and spoilage, is not therefore an issue in frozen food.

Agricultural production fluctuates with the yearly seasons, causing peaks and troughs in supply that result in associated periods of food abundance and scarcity. Freezing food provides a method for helping to smooth out the effect of this seasonality, reducing the risk of hunger in the off-season troughs through the safe storage of excess produce at times of peak supply.

Additionally, freezing food can help stabilise the price of some products by reducing the influence of seasonal shortages or surpluses on the market; thereby making food potentially more affordable and accessible as well as reducing tensions that can lead to social and political instability.

The increased product shelf life achieved by freezing food, relative to chilling the same product, enables a modal shift in the supply chains from air transport to sea shipping. Today, despite the associated carbon footprint, certain perishable food products continue to be transported by aircraft due to their short product shelf life. A transition, where possible, to transporting them by sea as frozen products in a refrigerated container (reefer) would significantly contribute to a reduction in GHG emissions. For example, sea transport of frozen salmon from Norway to Shanghai results in a carbon footprint (7.1 Kg CO_2e/kg) which is a third of that incurred when the same salmon is transported by air (19.4 kgCO_2e/kg) (Ziegler, et al. 2021).

In a warmer, more populated world, it will be vital that enough food reaches the consumer in a good nutritional and safe condition. Frozen food could play a pivotal role in ensuring food security, which involves having consistent access to a safe, diverse, and balanced diet that meets the needs of individuals, promoting their health and well-being.

SUB-ZERO IS GROWING

The global frozen food market was $284.2 billion in 2023 and is expected to grow to $363.7 billion by 2028 representing a compound annual growth rate of 5.1% (Markets and Markets Research 2023).

The literature suggests there is an increasing preference amongst consumers in developed economies worldwide for frozen foods and that this phenomenon is mainly being driven by the longer product shelf life and lower price of these products, as well as a preference for less frequent shopping. For instance, among American consumers, while fresh food sales increased by 10% in 2021, the sale of frozen food increased by 21% and in parallel 30% of households increased their freezer capacity (Morrison 2021). Demand for frozen products is expected to increase even further as a result of permanent changes in the shopping preferences of many consumers which originated in their response to the COVID-19 pandemic.

Industry is working with academia to improve the product quality of frozen food, while maximising sustainability e.g. 'Frozen Like Fresh' (WUR 2022).

There is evidence that the preference for frozen food is also increasing in developing economies. For example, 27% of households globally are expected to own a freezer in 2027, up from 24% in 2022. Much of this growth in ownership is anticipated to be driven by middle-income countries, with consumers in Turkey, India, and Indonesia purchasing freezers at a particularly rapid rate (Barry 2023).

Reducing food wastage is often cited as a reason for the shift towards frozen food products, alongside a significant increase in the rate of women joining the employed workforce and a move to frozen 'Ready To Eat' (RTE) foods and meal packs for convenience and flexibility. Other reasons cited include youth migrating to cities and living alone, digitization of retail, increasing product innovation and growth in the deployment of cold-chains.

RADICAL CHANGE BASED ON ROBUST ANALYSIS

A group of academics led by the IIR and Centre for Sustainable Cooling, supported by DP World, have been working together with industry partners to explore the role of frozen food in a resilient, equitable, and sustainable food system. As part of this initiative the economic, environmental and social benefits to be gained from food freezing are being quantified. Overall, our work aims to develop a detailed understanding of the implications of actively expanding the role of frozen food for, inter alia:

- Energy consumption;
- Food and nutritional security;
- Economic well-being;
- Social equity;
- The food sector and cold-chain industries;
- Food supply chain resilience;
- GHG emissions;
- Food quality and safety;
- broader sustainability/ Sustainable Development Goals (SDGs) issues – reducing food loss as well as food waste to contribute to achieve food and nutrition security; and developing economies; as well as define the issues, barriers and solutions to their implementation.

THREE DEGREES OF CHANGE– A FURTHER OPPORTUNITY

With any projected growth of demand for chilled or frozen foods comes a significant increase in the energy consumption of the food system, further challenging the transition to renewable energy, as well as an associated potential rise in GHG emissions (depending on the energy sources used).

An important route to mitigating the energy and GHG emissions impact of a transition to an increased role for frozen foods in the global food system could be to undertake a review of the temperature at which the stationary and mobile refrigeration equipment used in the associated cold-chains is set (the 'set-point'[7]). Depending on the outcome of such a review, there maybe potential for adjusting the latter to a higher value. Regulations and standards are prescriptive in generally requiring the frozen food temperature set-point in cold-chains to be -18°C.

A key starting point for change is to explore whether -18°C remains relevant in the context of today's food products, shopping patterns, and real time monitoring technologies and whether there is scope for an increase in the set-point value by, for example, three degrees to -15°C. If this were possible, what would be the energy, environmental and social impacts of doing so?

Reducing refrigeration temperatures to below those that are required to maintain product safety and quality leads to unnecessary energy consumption and avoidable GHG emissions. This outcome is exacerbated by the 'oversetting' of equipment to temperatures much lower than the industry standard by individual companies, through conservative risk averse corporate policies and/or strategies to position themselves as 'gold standard' operators.

Some in the industry think that these two factors could potentially mean that a standard set-point of -15°C would be more appropriate for some frozen foods and that a requirement to not 'over-freeze' could be introduced - without any negative impacts on food safety or quality. This change could be valuable in the context of controlling the growth of energy demand and GHG emissions from the sector.

In order to build industry and consumer consensus for the development of a new standard, as well as to catalyse such a change, a comprehensive programme of scientific and engineering research focused on creating an evidence base for the choice of a new set-point is required.

The work carried out to date in this study has taken a first step to considering, at a high level, the implications of a three degree increase in frozen food storage temperature on food safety and quality aspects, current freezing practices, and standards and regulations. It has also developed an initial understanding of the potential of such a change ('size of the prize') in terms of the savings in energy consumption, reductions in GHG emissions, and economic benefits delivered.

Additionally, it has examined some of the issues and barriers to implementation and defined a set of practical next steps to be taken in exploring the potential for a 3 degree set-point increase.

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[7] The temperature set-point is a key part of cold-chain planning, process design and equipment specification. The value is sometimes set in regulation, codified in service contracts, compliance manuals and standards, so as to ensure the cold-chain is working effectively. Adopting a common set-point has proved to be the best way to engender trust between parties at every stage in the chain.

KEY CONCLUSIONS

Freezing is one of the most commonly used and simplest preservation technologies that can minimise nutritional and sensorial losses of unprocessed and processed foods while considerably increasing shelf life and allowing food to be moved around the globe.

By freezing food, we can:

- **Considerably extend the storage life of foods;**
- **Maintain the nutritional quality of food at close to its peak;**
- **Prevent deterioration due to microbial growth;**
- **Optimise utilisation of food for scheduled consumption and reduce food waste;**

Increasing the role of frozen food in the food system offers a route to significantly reducing food wastage, a vital requirement in a world where the food system is challenged by climate change and increasing population. However, the benefits of freezing food comes with energy, environmental and economic costs that need to be assessed and reduced.

Freezing also enables inter-seasonal peaks and troughs in production needs to be smoothed out and helps build flexible and affordable food access. It achieves this by allowing food that is surplus to need in peak production seasons to be stored for consumption all year round.

The increased product shelf life of frozen food facilitates a modal shift from air to sea shipping in supply chains. Perishable products are today still transported via aircraft due to their short product shelf life, despite the implications for their carbon footprint and other pollutant emissions. A transition to transport by sea as frozen produce in reefer containers has the potential to significantly contribute to a reduction of GHG emissions.

Increasing the role within the food system of frozen products, which can be stored for many months, could be an effective strategy to increase overall resilience against multiple shocks, including climate change induced extreme weather events; pandemics; political conflicts; and the incidence of foodborne and zoonotic diseases. The current system is becoming increasingly vulnerable to such shocks and building capacity for resilience will help to ensure the availability, accessibility, and affordability of food at all times.

Traditionally frozen foods are stored below -18°C. By freezing food to only -15°C, the energy consumption from the frozen food chain could be reduced by 25 TWh/yr and GHG emissions of 17 Mt CO_2e/yr could be avoided.

The energy saved would mitigate the need for nearly $15 billion of new wind generation capacity in a transition to renewables.

The emissions benefit of saving 30% of current food losses due to lack of cold-chain worldwide would be 87.9 Mt CO_2e/yr (assuming the saved food is frozen and the associated cold-chain is operating at -15°C)[8].

The safety of frozen foods would not be compromised by storing at a temperature set-point 3°C higher than higher regulations demand.

With regard to quality, how food is treated and managed prior to freezing has just as much, if not more, impact than what happens during the frozen storage stage. Produce that has benefited from an appropriate selection, handling, and storage practice prior to freezing leads to a substantial extended practical storage life (PSL).

- Raising the set-point temperature of the frozen food cold-chain from -18°C to -15°C has the potential to save energy and reduce environmental impact whilst having limited negative impacts on the food itself.
- Regardless of whether the set-point temperature is -18°C or -15°C, frozen foods can be safe, high in quality, and effective in reducing food losses when handled and stored properly. If frozen correctly, they can preserve nutritional value, have a longer shelf life compared with equivalent chilled products, and be consumed with confidence at a time convenient to the consumer.[9]

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[8] Note that this is calculated from the additional food production needed to compensate for the losses and not the emissions resulting from degradation of the food.

[9] However, the quality and safety of frozen foods can be compromised by improper handling, storage, or thawing and the key to high-quality, safe products that minimise losses is adherence to recommended handling, storage and preparation guidelines.

It's important to understand that in the practical operation of cold-chains, what should be a seamless temperature-controlled environment from product source to consumer may be interrupted at some point. These breaks in the controlled environment can be caused by, for example, equipment failure, human error or poorly executed transitions from warehouse to vehicle; from stockroom to shop floor; from shop to home. As a result, one of the key considerations in determining a new set-point temperature for frozen food will be how products might react to temperature excursions in such breaks and the variance that can be tolerated in the context of food safety and quality assurance.

Three potential 'red flags' to a 3°C change are:

- One of the most significant barriers to progress will be to build the scientific evidence base regarding the implications for food quality of moving to -15°C, especially over extended periods of time;
- It will be essential to establish a consensus for change within the stakeholder community at global, regional and national levels and encourage market acceptance;
- In ice cream production, the ice crystal size must be small to ensure customers cannot detect them (consumers can detect ice crystals of greater than 40–50 μm) (LeBail and Goff 2008). This is not an issue in most other products, such as meat, where there is little evidence that ice crystal size has a major impact on ultimate food quality. To overcome issues with ice cream it may be necessary to operate two parallel cold-chains at -15°C and -18°C (or even lower), or to provide stabilisation of ice cream products (for example using ice-structuring proteins or antifreeze proteins which inhibit or modify the growth of ice crystals (Clarke, Buckley and Lindner 2004)). This approach has been previously considered (Bogh-Sorensen 1984), however, it potentially adds complexity from an engineering and regulatory perspective, as well as for supply chain logistics companies, which may be considered by industry to negate the benefits of a 3°C change.

NB. Unilever has however recently (9 November 2023) announced it will grant a free non-exclusive licence to the ice cream industry for a variety of patents to help keep ice cream products at a warmer freezer temperature of -12°C, rather than the current industry standard of -18°C (Unilever 2023).

WHAT WOULD THREE DEGREES OF CHANGE MEAN FOR ENERGY, EMISSIONS, FOOD SAFETY AND QUALITY?

A full report will be published in Spring 2024, however, initial key findings from our work to-date on increasing the operating temperature by three degrees are outlined below.

ENERGY AND EMISSIONS

The total current energy consumption associated with all frozen food cold-chains globally, from the freezing process to the final end-point freezer, is estimated to be approximately 484 TWh/yr (based on a population-based extrapolation of UK cold-chain energy usage (Foster, Brown and Evans 2023) to worldwide and the proportion of frozen food in the cold-chain in different areas of the world).

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> **The energy savings achieved by moving from -18°C to -15°C is equivalent to twice the electricity consumption of Kenya.**
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Using a mathematical model (European food chain supply to reduce GHG emissions by 2050) that predicts the energy consumed throughout a frozen food cold-chain, we estimate the energy savings that can be achieved by moving from a set-point of -18°C to one of -15°C are between 5-7% (some stages of the frozen food cold-chain could realise savings as high as 10-12%). This would equate to a worldwide energy saving of ~25 TWh/yr which is equivalent to twice the electricity consumption of Kenya (Ritchie, Roser and Rosado 2022).

Using the US Environmental Protection Agency Emissions Calculator, emissions savings through moving the frozen food cold-chain set-point from -18°C to -15°C would be 17.7 Mt CO$_2$e/yr based on avoided generation capacity and 10.9 Mt CO$_2$e/yr based on a simple direct reduction of energy used. 17.7 Mt CO$_2$e/yr is equivalent to the carbon emitted by nearly 4 million cars/yr[10] (EPA 2023).

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[10] We have used US EPA Greenhouse Gas Equivalencies Calculator for CO$_2$e emission impacts (avoided or reduced) See https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references for how each is calculated.

“ Increasing frozen foods temperature by 3 degrees would save 17.7Mt CO$_2$e /yr carbon emissions from a reduced generation capacity, which is equivalent to carbon emitted by nearly 4 million cars/yr. ”

Along with the reductions to be gained in total energy consumption and GHG emissions, the lower energy demand can have important wider positive benefits in the world's transition to renewables – for example by reducing pressures on limited renewable energy generation capacity and allowing it to be used for other applications.

“ From the moment frozen food temperature is kept below -10°C, food safety is not an issue. ”

If we do not increase the operating temperature from -18°C to -15°C, in transitioning away from fossil fuels we would theoretically need to build more than 11.4 gigawatts of new wind generation capacity to meet the additional energy required to maintain the 3°C lower temperature of -18°C. This is more than 70% of the UK's total onshore wind generation capacity and would cost $14.8 billion.

Several other studies have been carried out which estimate the savings that can be achieved by shifting frozen food set-point temperatures from -18°C to -15°C (British Frozen Food Federation 2009) (Nomad Foods 2023). These studies estimate electrical energy savings of approximately 10%, but only consider the storage phase (see Nomad foods box page 14). Our modelling considers the whole frozen food cold-chain from the point of freezing to the consumer removing the product from their freezer for use, which results in the slightly lower figure for energy savings
Further differences are due to varied food types as well as the amount of time that the product remains in the different sectors of the food system, there being different relative efficiencies for the refrigeration equipment applied in each sector.

The benefits of a -15°C frozen food cold-chain can only be fully realised if all the actors along the chain move to the new temperature regime. Otherwise, one sector of the chain will be disadvantaged by not only operating at a lower temperature, but also through incurring the penalty of having to reduce the previously stored food from -15°C to -18°C. The latter demands extra energy to cope with an additional product load for which their refrigeration plant would not necessarily have been designed.

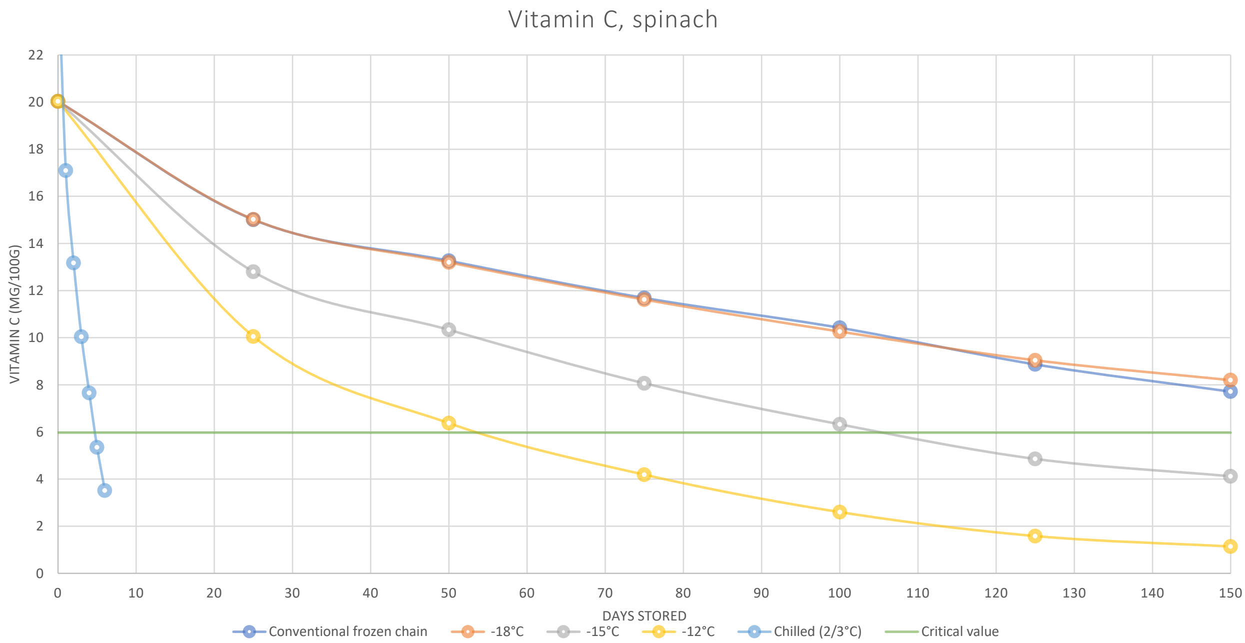

Figure 1: Evolution of vitamin C content for frozen spinach stored at different temperatures.

FOOD QUALITY

Depending on the food type, freezing can offer a very similar product compared to a fresh/raw version, particularly when food is cooked before consumption. Examples are peas, meat, fish, spinach, and poultry. Others, such as fruits (e.g. apple, strawberry, banana) will maintain their colour, nutritional traits and shape when frozen, but they will become a different product type as a result of a change to their structure, flavour and texture once thawed.

Frozen foods can still show certain nutrient loss, weight loss, shrinkage, and product colour changes (Hu et al., 2022) because freezing them requires temperature reductions below their freezing point.

However, frozen products still offer many benefits. Generally, longer storage life is achieved through freezing and frozen storage. While chilled foods lose much of their nutritional value after a matter of days, at -15°C critical nutritional components for spinach as an example do not fall below their critical threshold values for at least three months (see Figure 1).

> **“Even if stored at -18°C, if food is not properly handled before freezing, -18°C does not guarantee a quality product.”**

It is important to note that a number of factors that influence the quality of frozen food including: pre-processing (or initial quality of the food entering the chain); freezing speed (duration and its effect on ice crystal formation); storage and distribution temperature (as well as the capacity of maintaining the optimal freezing temperature at all times, with minimal fluctuations); packaging; thawing times (not applicable to all food products); and freezing methods and equipment.

> **“Studies carried out by industries report 10% electrical energy savings when increasing frozen food storage temperature by 3 degrees.”**

However, overall for frozen food quality product, processing and packaging factors are more important than temperature.

- Apart from the case of products that fundamentally require freezing for their structure, such as ice cream, the quality of food cannot be improved by freezing and it is therefore important that only food of high starting quality is frozen. Fruits and vegetables, for example, are highly perishable products with extremely rapid quality deterioration at ambient temperatures after harvesting. The vitamin C loss in peas, green beans, broccoli, carrots and spinach that occurs after harvest is accelerated by temperature and will continue until the product is blanched or frozen (Favell 1998). Freezing such produce will not reverse this quality deterioration, therefore ensuring that harvested goods are frozen as soon as possible is essential.
- In the case of product processing, the incorporation of antioxidant ingredients with preserving effects, as well as the application of heat treatments e.g. blanching for vegetables, should be considered to increase the PSL.
- Rapid freezing after product processing is required to prevent enzymic changes and preserve the quality.
- Appropriate packaging of frozen food is important to protect the product from external contamination, oxidation, dehydration and mechanical damage as it is moved through the cold-chain as well as to ensure a high quality product.

> **“Within the energy transition context: The 3 degrees of change will avoid building more than 11.4 Gw of new wind generation capacity which would cost $14.8 billion.”**

FOOD SAFETY

In terms of safety, foodborne diseases associated with frozen food are rare, providing sufficiently low temperatures are maintained at all times. Freezing to -12°C inactivates a wide range of microorganism, including moulds, yeasts and bacteria (James and James, 2014). Therefore, increasing the set-point temperature from -18 to -15°C will have no direct impact on food safety.

It is important to note that freezing does not sterilise food products. Although microorganisms may die during low temperature storage and their activity essentially stops, after thawing they can regain their activity leading to unwanted spoilage. Increasing the set-point temperature from -18 to -15°C does not change any of the existing risks.[11]

> **“To ensure frozen food quality, product selection, processing and packaging are more important than temperature.”**

Nomad Foods, the company behind frozen food brands including Birds Eye, Findus, and Iglo, earlier this year (2023) announced the results of a pilot study to investigate the potential to store frozen food at higher temperatures. The study was conducted over six months with food science and technology organisation Campden BRI. It was reported that storing frozen food at -15°C, instead of the industry standard -18°C, could reduce freezer energy consumption by more than 10%, without any noticeable impact on product safety, texture, taste or nutrition.

Nine frozen products were tested in the pilot including poultry, coated fish, natural fish, vegetables, plant based and pizza. Four temperatures (ranging from -18°C up to -9°C) and eight key areas of investigation, including food safety, texture, nutrition, energy use and packaging impact, were analysed. The results showed no significant change to the products across the areas tested at any of the higher temperatures, with the following exceptions: there was some change in sensory for Mixed Veg at -9°C and Salmon Fillets at -12°C; there was also some impact on Vitamin C for vegetable products when stored at the highest temperature -9°C.

NB. The detail of the tests has not been published in the public domain.

SOME IMPLEMENTATION ISSUES AND POTENTIAL BARRIERS TO THREE DEGREES OF CHANGE

Low-income countries are core production centres for the future global food system but currently have negligible, or very low, levels of deployed cold-chain infrastructure (frozen or chilled). There is increasing (but still limited) investment in chilled cold storage and other cold-chain assets in these nations. To consciously enable their full potential within the local and global food systems, there would need to be country-level decisions made regarding cold-chain development strategy and whether that should focus on chilled and/or frozen capability. If food freezing was the preferred route for a resilient and sustainable integrated solution, the development of the system of system approaches from farm to national markets and/or export hubs will be essential.

> **“Frozen foods are well perceived in high-income economies, however, in low-income economies there is a cultural preference for 'fresh' food somewhat due to a lack of trust in refrigeration.”**

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[11] The exception to this is Campylobacter, a common pathogen found on poultry. Levels of Campylobacter are greatly reduced after freezing.

> **“The impact of moving 3 degrees on food quality is not yet well identified, a scientific evidence about the impact of increasing the set-point is determining factor.”**

Such approach would not be merely focused on deploying more equipment, but rather on establishing a robust, seamless, affordable, temperature-controlled, end-to-end connectivity from source to fork, supported by the following:

- fit-for-market and purpose technologies. This would necessarily need to include off-grid, near to farm solutions to ensure high quality post-harvest management, so that the product is frozen/packaged spatially and temporally close to the harvest point, as well as appropriate transport and food systems infrastructure that ensures seamless operation and connectivity from source to destination;
- robust temperature monitoring at all stages of the cold-chain;
- policies and regulations to facilitate uptake of appropriate solutions at scale;
- finance and business models to enable equitable distribution of risks and costs to overcome issues of affordability and viability, as well as the value created from investments in cold-chain equipment and infrastructure;
- skills and capacity at all levels from farmers (to ensure uptake and improve post-harvest practices) to technicians and engineers (to ensure adequate installation and maintenance of technologies);
- strategies to achieving the desired outcomes without using conventional fossil fuel-based, inefficient, and climate- polluting technologies that increase GHG emissions;
- campaigns to shift consumer attitudes and preferences towards frozen foods.

The purchase of frozen food is far less common in many low-income countries when compared with those that are regarded as high-income. This is largely for two reasons: 1) they generally lack the end-to-end farm to fork cold-chain infrastructure required to facilitate frozen products (apart from, in some cases, fully integrated cold-chains to support access to high-income export markets); and 2) in some communities/populations cultural perceptions are prevalent that underpin a suspicion of the quality and safety of frozen food. While frozen food may be perceived positively in high-income economies, particularly in relation to its competitive price and consumption flexibility, low-income and emerging economies often have a cultural preference for fresh food partly due to a lack of trust in refrigeration (Hasani, et al. 2022).

The scientific evidence for the impact of increasing the set-point temperature of frozen products from -18°C to -15°C on food quality will be a key determinant in any decision to make the change (food safety is well understood and not a material issue).

As part of this, currently minor fluctuations of 1-2°C above -18°C are generally considered unimportant. However, the impact of such temperature fluctuations at a higher temperature of -15°C is as yet not well qualified. Although further work is proposed in this area, regardless of the outcome, it would be prudent to improve temperature control technology in frozen food cold-chains if a move to a -15°C set-point were to be implemented. This could be achieved using smart controls, variable speed drive motors, thermal storage, and better control of heat loads.

A set-point temperature for frozen food products of -18°C is standard in the relevant industry/sector regulations in almost all countries worldwide. However, the value of this temperature is not globally governed, so a change from -18°C to -15°C would require interventions at different governance levels in numerous jurisdictions around the world, as well as the building of a supporting consensus involving many national and international stakeholders.

Although studies have shown that frozen foods have a higher nutritional value than fresh products stored for multiple days, consumer perceptions often do not reflect this. Consumers, particularly in high-income countries, have become more demanding with respect to food safety and quality. Unless clear, easily accessible evidence is provided, gaining public acceptance for increasing frozen storage temperature by 3 degrees may be challenging.

> **“The 3 degrees of change would involve actions from different stakeholders at a national level: industry, science, government, but also at an international level, as -18°C is set as a global standard.”**

However, consumers have also developed a better understanding of today’s environmental challenges. According to the French Ministry of Agriculture, 61% of the nation’s consumers are concerned about the impact of food systems on the environment, almost as many as the 69% that are focused on safety, quality and health related issues (Xicluna 2018). Evidence based recommendations, improved information, and stimulating consumer awareness about the environmental implications, can all help facilitate acceptance of new standards.

Freezer storage temperatures rarely impacts the physical structure of a product, but when it does (e.g. ice cream), temperatures above -15°C can potentially soften them and make their structure susceptible to damage. This may be an issue for some stakeholders handling such products as they would need to re-design their cold-chains and operations to take account of 2 or 3 set-point temperatures, adding engineering, regulatory and logistics complexity.

A frozen food cold-chain operating at a set-point temperature of -15°C can only really be beneficial if all actors in the system adopt the new temperature regime. Otherwise, one sector of the chain will be disadvantaged by not only operating at a lower temperature but also through incurring the penalty of having to reduce the previously stored food from -15°C to -18°C. This demands extra energy to cope with an additional product load for which their refrigeration plant would not necessarily have been designed.

Most existing refrigeration equipment will be able to operate satisfactorily at a higher temperature, but some may need to undergo modification to increase efficiency and/or be re-commissioned. For example, the equipment’s compressors may be oversized to operate at the higher temperature and thus need to be reconfigured or adapted through the application of variable speed drives. In all cases, a performance audit should be undertaken and the equipment re-optimised for the new operating conditions. It should be noted that the latter may coincidentally lead to further savings which are not directly attributed to the higher operational temperature alone.

Although there are clearly multiple benefits to be gained by adopting a higher set-point temperature for frozen food cold-chains operation, this will potentially reduce redundancy in the case of breakdowns, thereby decreasing resilience, and result in constrains on an operator’s ability to apply demand side management procedures. Currently, frozen food products often experience temperature increases at certain stages in the supply chain (for example when being loaded from a cold store into a transport vehicle, or during defrosts), however there is a reasonable level of redundancy which would be less available in a cold-chain with a -15°C set-point.

> **“Smart temperature and humidity control systems, detect instantaneous fluctuations for immediate actions.”**

While current frozen food storage facilities and refrigerated vehicle fleets might already have the capability for adjusting their set-point temperature to -15°C, some consideration needs to be given to controlling temperature fluctuations adequately. Smart sensors for real-time temperature measurement, humidity monitoring and/or control, time-temperature integrators (TTIs), as well as cloud resources for data and management, will be key to increasing the robustness of the food cold-chain,[13] through early detection of anomalies and the timely implementation of corrective measures.

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[13] Trends in Food Science & Technology Volume 133, March 2023, Pages 189-204 https://doi.org/10.1016/j.tifs.2023.02.010.

RECOMMENDATIONS FOR FURTHER ACTION

A detailed roadmap for filling research gaps, building consensus for change, and moving to implementation will be developed in the main report planned for publication in Spring 2024, but here we present some key initial recommendations for next steps. These are designed to support policy-makers in making a 'go/no-go' decision, regarding whether frozen food should become a focus for cold-chain deployment in developing markets and whether increasing the operating set-point temperature by three degrees should be further explored.

In order to move to a 'go/no-go' decision, we strongly recommend that in the first instance there is a collaborative effort across key stakeholders to understand the impact of a change and build global consensus about strategy and next steps.

FURTHER ACADEMIC AND INDUSTRY RESEARCH

Food Safety and Quality

- Scientifically assess the potential impacts of changing the set-point temperature for frozen food on product quality and product shelf life.
- Assess the impacts of temperature fluctuations on product quality at higher storage temperatures and potential routes to mitigation where required.
- Further develop stabilisation additives for temperature sensitive products such as ice cream.
- Assess the impacts of packaging and optimise packaging to minimise impacts of temperature fluctuations and extend storage life.

System impacts

- Quantify food wastage (loss and waste) reductions achievable through transition scenarios to an increased role of frozen food in the food system.
- Life cycle assessment of frozen products, in order to better understand the energy consumption and associated emissions profile for different types of food and supply chain.
- Fully quantify the projected energy and emissions impacts across the whole food supply chain out to 2050, from processing to consumer storage, considering an accelerated uptake of frozen food globally and a revised set-point temperature of -15°C, and compare to a chilled food approach. This necessarily needs to include food loss and waste, modal shifts (air to sea/rail), and an assessment of whether optimisation and potential modifications to refrigeration systems applied in the frozen food cold-chain could be beneficial, particularly through enabling greater energy savings to be realised.

Note: It is important that we do not take a 'one size fits all' approach to solutions – each product has its own requirements and research should clearly characterise the needs for each food group, so that we can ensure high quality products (physiological and nutritional).

We also need to work internationally, as supply chains are global, and our collaboration should include both producers and consumers.

Consider the economic, social, cultural, environmental, energy, and skills base implications for low-income countries in the adoption of frozen food alongside chilled food strategies.

Consider the impacts and optimum strategies in a warming, more populated world and delivering food security in 2050.

Test for unintended consequences through the system.

Implementation

- Further assess energy and GHG emissions impacts of both

  1 moving more food from chilled to frozen and

  2 the set-point temperature change (i.e. impacts on quality and operational issues), with a small group of cold-chain operators from farm to market.
- Work with trade bodies and professional bodies, end users and regulatory groups (politicians, standards organisations, health/enforcement officers) to better understand the technical, behavioural, political, operational, and regulatory issues surrounding a move to a -15°C set-point temperature in frozen food cold-chains.
- Better understanding of consumers' preferences and how they would respond to an increase in frozen food availability as well as reduced shelf life due to an increased ambient temperature.

From the above, work towards raising awareness and building stakeholder consensus on the importance of tackling food loss and waste and the role frozen products can play in minimising this risk and ensuring food security.

POLICY ACTIONS

As a fast-start and to catalyse a direction of travel, regulators could assess the possibility of applying differentiated set-point temperatures per product group, as is already applied in countries like Germany, France and Spain, and allow optional storage at -15°C where supporting evidence is available.

Changes would need to be underpinned by a co-ordinated national and international policy as well as industry and consumer awareness raising campaigns.

Acknowledgement of research gaps and an indication of what evidence is needed for consideration of policy change. Other areas of longer-term collaborative industry and academic research if frozen food/three degrees supported by industry and consumers and greenlighted by policy-makers.

> “
>
> **Collaborative efforts are needed to explore the opportunities of 3 degrees of change, this implies politics, industries, scientists and consumers to work together.**
>
> ”

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