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PACKAGING AS A PART OF ENERGY EFFICIENCY STRATEGIES IN FOOD COLD SUPPLY CHAINS

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Abstract: *Cold supply chains are an important part where perishable food can be transported and kept fresh until it reaches the desired destination. The lack of these systems which provide the necessary temperatures can lead to large food loss, which has multiple consequences from hunger to increased environmental impacts in the form of waste of invested greenhouse gases during production. The strategies of keeping the food under a certain temperature can be achieved by active, passive and hybrid systems combining electrical components (coolers and freezers) and packaging materials in the form of insulating materials. The energy consumption of the cooling devices is running in many cases on fossil fuel sources and requires energy efficiency to achieve decarbonization efforts. On the other hand, certain passive packaging systems are made from materials which are not yet fully recyclable on the scale throughout the EU. In the paper, an overview of potential energy efficiency strategies combining hybrid systems (electric and packaging) are presented with possible savings in energy and carbon footprint values.*

Key words: cold supply chain, insulating packaging, energy efficiency, carbon footprint

1. INTRODUCTION

Food loss is a significant global issue, with nearly one-third of all food produced annually being lost or wasted. This not only represents a loss of valuable resources such as water, energy, and labour but also contributes to environmental problems like methane emissions from decomposing food in landfills (U.S. Food and Drug Administration, 2024). Food is both an essential aspect of life and a considerable source of greenhouse gas (GHG) emissions. The agriculture sector is responsible for nearly half of methane (CH_4) emissions, two-thirds of nitrous oxide (N_2O) emissions and 3% of carbon dioxide (CO_2) emissions from human activities worldwide (Ivanovich et al., 2024). Packaging plays a crucial role in mitigating food loss. Proper packaging can protect food from mechanical damage during transportation and storage, preserve its quality under various environmental conditions, and extend its shelf life. For instance, adequate packaging can shield food from extreme temperatures, humidity, and contamination, ensuring that more food reaches consumers in good condition (Beltrami, 2019). By optimizing packaging, we can significantly reduce the amount of food lost along the supply chain, particularly in developing countries where losses are more prevalent before food reaches consumers. If we investigate the food types which contribute to GHG emissions (Figure 1), a large portion of them need to be cooled or chilled during the postharvest and transportation stage (Center for Sustainable Systems, 2024).

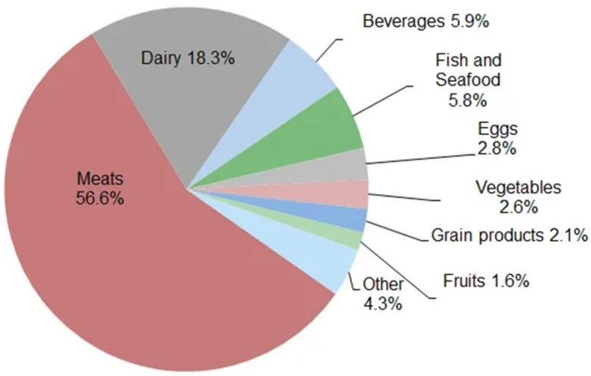

Figure 1: Greenhouse Gases Contribution by Food Type in Average Diet

The average temperature of the Earth is rising and the last year was the warmest one (if we compare the global average surface temperature) in several decades according to the NOAA (Figure 2).

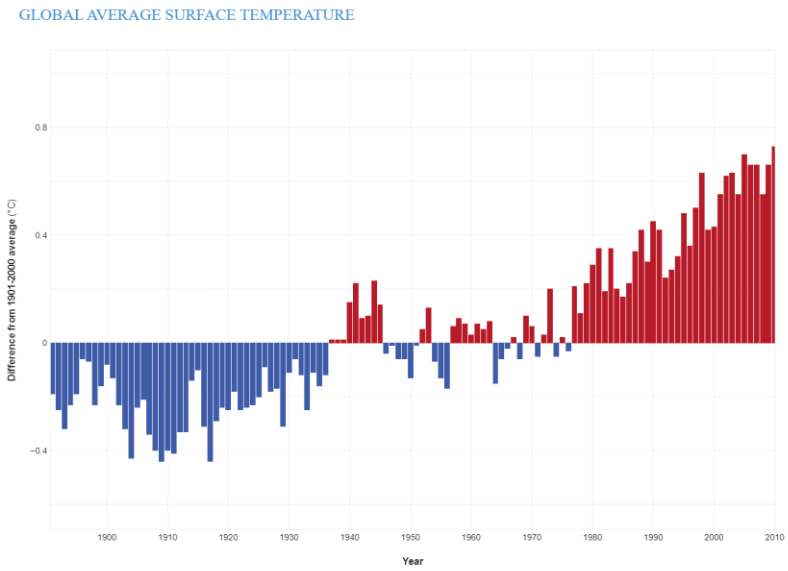

Figure 2: Average global surface temperature

According to the 2023 Global Climate Report from NOAA National Centers for Environmental Information (National Centers for Environmental Information*,* 2023), every month of 2023 ranked among the 7 warmest for that month, and the months in the second half of the year (June-December) were each their hottest on record. In July, August, and September, global temperatures were more than 1.0°C (1.8°F) above the long-term average—the first time in NOAA's record any month has breached that threshold. Although the warming has not been uniform across the planet, the upward trend in the globally averaged temperature shows that more areas are warming than cooling. According to NOAA's 2023 Annual Climate Report, the combined land and ocean temperature has increased at an average rate of 0.11° Fahrenheit (0.06° Celsius) per decade since 1850, or about 2° F in total. The rate of warming since 1982 is more than three times as fast: 0.36° F (0.20° C) per decade. So, there is data on the rising temperatures on the surface which will increase the food loss due to this temperature rise. Hotter countries appear to have more food waste per capita in households, - increased consumption of fresh foods with substantial inedible parts and lack of robust cold chain. Higher seasonal temperatures, extreme heat events, and droughts make it more challenging to store, process, transport, and sell food safely, often leading to a significant volume of food being wasted or lost. From the GHG point of view, food loss and waste generate 8-10 per cent of global greenhouse gas (GHG) emissions – almost five times the total emissions from the aviation sector (UNEP 2024 Food Waste Index Report).

To mitigate this food loss during the postharvest period and transportation cold supply chains are used. On the other hand, the food cold chain is responsible for about 4% of global greenhouse gas emissions1. This includes emissions from refrigeration technologies and the energy used to power them. In 2017, emissions from food loss and waste due to inadequate refrigeration were estimated at around 1 gigatons of CO_2 equivalent, roughly 2% of total global emissions (United Nations, 2022). Cold chains require a significant amount of energy to maintain low temperatures throughout the supply chain. This energy consumption often relies on fossil fuels, further contributing to carbon emissions (The Food and Agriculture Organization, 2022). Another challenging issue is the refrigerants. Many active refrigeration systems use hydrofluorocarbons (HFCs), which are potent greenhouse gases. Efforts are being made to phase out HFCs in favour of more environmentally friendly alternatives (UN Enviroment Programme & The Food and Agriculture Organization, 2022) To mitigate these impacts, there is a push towards developing sustainable cold chain technologies. This includes improving energy efficiency, adopting renewable energy sources, and using low-global-warming-potential refrigerants1. There are some researches regarding multi-dimensional optimization (Arabsheybani, Arshadi Khamseh & Pishvaee, 2024) but they overlook the environmental components in more depth but focus on food safety and profitability. Some work has been done on the Life Cycle Analysis (LCA) of cold food chains by (Meng et al., 2023) where their study conducted a comparative environmental impacts analysis of two food cold chain packaging systems using LCA, for ice cream transportation. The reusable vacuum insulated panel (VIP) box packaging system demonstrates superior environmental performance when compared to the disposable expanded polystyrene (EPS) box packaging system across all evaluated impact categories. The result of the study suggests that conclusions regarding lower environmental impact cannot be exclusively based on the choice of insulation material. The weight of the packaging and the transportation distance also exert a significant influence on the overall environmental performance of the systems in terms of environmental impact calculation.

While these efforts are partially mitigated through technology design in the cooling industry, overall standardization and mitigation are just in their beginnings. For example, a standardized way of defining cold food supply chains has just a recent standard in the form of the: ISO 23412:2020 Indirect temperature-controlled refrigerated delivery services – Land transport of parcels with intermediate transfer. This basic standard mainly defines the basic terminology and splits the food types into two large groups (chilled and frozen) – positive and negative service transport temperature delivery. The positive systems maintain temperatures between 0°C and 15°C and are used for products that need to be kept cool but not frozen, such as fresh fruits, vegetables, dairy products, and certain beverages. Refrigerated trucks, cold storage rooms, and refrigerated display cases in supermarkets are typical system components. The negative temperature delivery systems maintain temperatures below 0°C. They are essential for products that have to be kept frozen to prevent spoilage, such as ice cream, frozen meats, and seafood. Typical parts in the cold supply chains are freezer trucks, deep-freeze storage facilities, and frozen food sections in supermarkets. The typical temperatures needed for different kinds of food transports (mixed loads) are presented in Table 1 (Australian Food and Grocery Council, 2017).

Table 1: Recommended thermostat setting used for mixed loads

Thermostat setting	**Frozen food -18⁰C or less**	**Chilled food 0 ⁰C to + 4⁰C**	**Fresh food +5⁰C to + 7⁰C**	**Confectionery App. +15⁰C**	**Ambient goods +15⁰C to 30⁰C**
+15⁰C (all runs)				x	x
+5⁰C (all runs)			x	x	x
+2⁰C (run> 2hr) +4⁰C (metro run)		X	x	x	x
+4⁰C (all runs)		X	x		
-22⁰C (all runs)	X	X			x

These values follow the main principle of the "never the warmer rule": All products must be kept at temperatures never warmer than the manufacturer or producer's recommended maximum temperature. In most cases, chilled foods need to be kept at a temperature between 0°C and +4°C to ensure the product temperature is never warmer than +5°C, For frozen foods and ice creams in most cases, the temperature must never be warmer than -18°C (Australian Food and Grocery Council, 2017).

2. PACKAGING IN THE FOOD COLD SUPPLY CHAINS

Cold supply chain packaging materials are crucial for maintaining the integrity of temperature-sensitive products during transport and storage. They can be categorized as passive components as they do not use any active coolants like electric drive ones or ice packs with different phase change materials. The typical materials due to their lightweight structure and good thermal insulation properties are expanded polystyrene (EPS), and polyurethane (PUR) which on the other hand do not have a very high recycling ratio. There have been some recent efforts to use corrugated boards (Thermoboxes from Smurfit Kappa), different kinds of cellulosic foams (Liao et al., 2022) and even wool (WoolCool, 2024). All these materials are, also sometimes used as single-use products during the storage and transport of food their carbon footprints need to be considered for decarbonization efforts.

The calculation of heat transfer into an insulated container can be expressed as (Equation 1) (Russell & Crespo, 2004):

$$Q = n\,x\,L = A\,(T0 - Tb)/R \quad (1)$$

Where: n = rate at which the coolant melts (e.g. lb/hr)
L = latent heat of coolant (e.g. Dry Ice = 246 BTU/lb)
A = area of container walls
T0 = coolant temperature
Tb = temperature outside the container
R = resistance to heat flow (R-value)

The type of material is normally selected in cold chain design based on cost and thermal performance. Thermal performance is typically referred to as "R-value." The term R-value is predominantly used in the building industry to rate the insulative properties of construction materials and building. The SI unit for the R-value is K·m²/W. The R-value describes thermal insulating products including heat being transferred by all three mechanisms -- conduction, radiation, and convection. R-value should also not be confused with the intrinsic property of thermal resistivity and its inverse, thermal conductivity. The SI unit of thermal resistivity is K·m/W. Thermal conductivity assumes that the heat transfer of the material is linearly related to its thickness. All values presented in Table 2 are approximations, based on the average of the values (Russell & Crespo, 2004). We have also included the $eC0_2$ values per packaging material for 1kg.

Table 2: Insulation packaging material R values (per cm thickness) and $eC0_2$ values per 1kg

Material	R-Value (per cm)	eCO_2 (kg CO2e per kg)
Expanded Polystyrene (EPS)	1.42 - 1.65	3.5 - 4.0
Polyurethane Foam	2.36 - 2.56	2.5 - 3.0
Extruded Polystyrene (XPS)	1.97 - 2.17	4.0 - 4.5
Vacuum Insulated Panels (VIP)	9.84 - 11.81	8.0 - 10.0
Fiberglass	1.14 - 1.50	1.0 - 1.5
Cellulose Foam	1.38 - 1.57	1.5 - 2.0
Corrugated Board	0.39 - 0.47	0.5 - 0.7
Wool	1.38 - 1.57	0.2 - 0.5

From Table 2 we can see that the EPS and PU as well as XPS foams have a good R-value but due to the density of materials like corrugated board can be lighter and equalize the initial $eC0_2$ values which are achieved in the production phase of the basic packaging materials. In determining the right choice both values need to be considered of course with the no more than the temperature rule.

3. CASE STUDY

So, considering many different aspects involved in the cold supply chain and cooling of food a proposal for new ways of energy efficiency can be established by covering the missing link between the active cooling system driving and the passive packaging in the refrigeration units for example in the supermarkets. According to the International Institute of Refrigeration, 7.8 per cent of GHG emissions can be attributed to the heating, ventilation, air-conditioning and refrigeration (HVACR) sector (IIF-IIR, 2017). While direct emissions from refrigerants account for around 35 per cent of emissions from cooling systems, the remaining 65 per cent are caused by indirect emissions from electricity consumption. The proportion of indirect and direct emissions varies according to leakage rates, the Global Warming Potential (GWP) of refrigerants and electricity grid emission factors. Supermarkets consume approximately 3-4 per cent of the annual electricity production in industrialized countries and usually have one of the highest specific energy consumptions of commercial buildings (energy consumption per sales or total area) (Funder-Kristensen, 2024). Refrigeration systems consume 30-60 % of this total (depending on the climate, social habits and other factors) (EU, 2024). So by using the interactions of both systems (passive and active) and intelligent monitoring of the active cooling system and food monitoring (intelligent) packaging the energy consumption and thus electricity consumption can be reduced. If renewable energy were to be used this decarbonization would have a greater effect on savings and with the right food amount can decrease both losses in food and other natural resources (Figure 3).

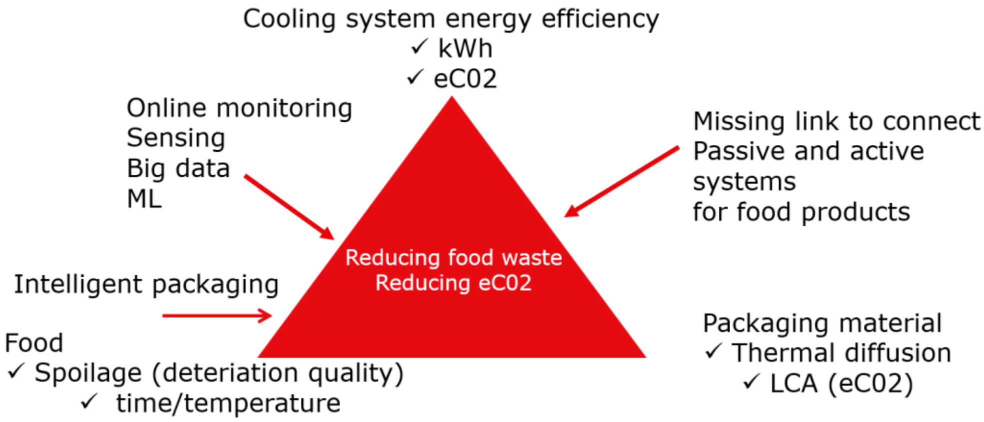

Figure 3: Proposed framework for passive and active cooling calculation

If we investigate the data (Evans, Scarcelli & Swain (2007) (which is not easily accessible to the wider public) to which extent the energy efficiency varies (Figure 4). It is obvsious there are lot of saving potential not just by upgrading to newer better cooling systems, but also more intelligently using the passive systems without compromising food safety.

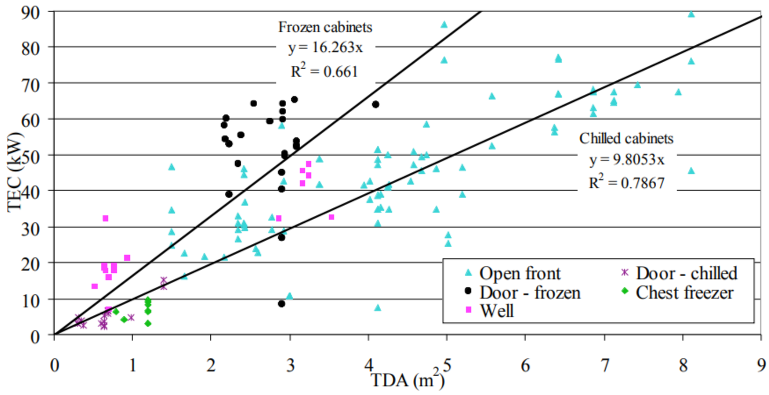

Figure 4: Relationship between total display area (TDA) and the total energy consumed (TEC) for all chilled and frozen cabinets (Evans, Scarcelli and Swain, 2007)

If we presume a display area of 2 m^2 for a chilled cabinet with a higher TCE of around 3000 kWh/year, what energy could be saved by intelligently switching off the electricity on certain time frames and using passive packaging systems? If we set the typical time limits without cooling could be 24 hours in appropriate insulated packaging of the right thickness. The food would be displayed in a appropriate insulated container, where the staff would cover it at the end of the last shift before the store closes down.

The average normal consumption would be 3000 kWh/year (24/7 running loop) in a non-leap year we have 24x365=8760 hours. Sunday (as a typical non-working day in some EU countries) is for non-leap year 52 and that would bring 1248 hours when the chiller is off. This would bring the reduction of electricity from 3000kW to around 2573, or 427 kWh per year would be saved, which would mean around 14% of energy or 17 days of working chiller. For example, the newer generation of home refrigerators consumes 300-800 kWh per year, so if we would use 2 chillers, we could save 1 home refrigerator per year. These time limits can vary based on factors such as the initial temperature of the food, the external temperature, and the specific design of the packaging. If we turn it off for 4-6 hours for chilled food (at a safe temperature without chilling at room temperature), then approximately 4,45 days of chiller working could be spared with 106,82 kWh. As the average $eC0_2$ per 1kWh in the EU (different energy source mixes can change this a lot) is 275g $eC0_2$ we can assume for every Sunday shut we could decarbonize by 117,43kg $eC0_2$ and by the 6-hour shut-off regime it would be 29,38 kg $eC0_2$ saved in decarbonization efforts. For this of course we could subtract the $eC0_2$ of the packaging (1kg of EPS -4 kg of $eC0_2$) so the overall decrease for 24/6 hour shut down every year would be 113,43-25,38 kg $eC0_2$. In this case, the reuse of the material would be mainly polymer-based as due to moisture fluctuations during the shutoff and refreezing the cellulose-based materials could have a decrease in mechanical properties which could hamper long-term reuse. To ensure any potential hazard to human health cold chain sensors as a part of the intelligent packaging could be applied to these bulk display systems (and reducing a per product application of these sensors).

4. CONCLUSION

Cold supply chains are an important part of providing basic human needs, by providing bacteria-free fruits in the regions otherwise prone to potential hazards and food loss to spoilage. The active cold chain systems employ electric energy which is still mainly derived from fossil fuels. The importance of using the right active system and passive systems (regarding $eC0_2$ values – production, use and end-of-life stages) with possible intelligent systems which can actively monitor the temperature so some kW/h can be spared, which can further help the overall decarbonization efforts and lowering the outside temperatures which are again interconnected with the cooling systems. The importance of right supply chain decisions, with the right tracking technology and the use of artificial intelligence and machine learning algorithms can provide energy savings needed for a more sustainable future. This applies to all food chain steps from transportation to storage and display. Small behavioural changes with the right technology can have a larger impact on the food packaging (and food waste) than focusing on just single changing of materials to a more sustainable one.

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