



# ENOUGH

EUROPEAN FOOD CHAIN SUPPLY  
TO REDUCE GHG EMISSIONS BY 2050

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## OVERVIEW ON TASK 6.7

### 1 GENERAL SUMMARY

This final report presents the outcomes of the ENOUGH project's demonstrator activities focused on the fish sector. The overarching aim was to reduce greenhouse gas (GHG) emissions and improve energy efficiency in food processing, while keeping the product quality unaffected or better than alternative systems and methods. The carbon footprint of the fish supply chain varies significantly depending on species, processing methods, and logistics, offering both challenges and opportunities for climate impact reduction.

Drawing on the expertise of project partners SINTEF, NTNU, MMC, ENEX, and CNR, the demonstrators showcased innovative technological solutions designed to optimise freezing processes in fish processing. These included the implementation and testing of **three key technologies: brine freezing, blast freezing, and plate freezing**. Each was assessed for its potential to reduce specific energy consumption and GHG emissions, using key performance indicators (KPIs) such as freezing time and specific energy use.

The demonstrators also underscored the importance of transitioning to natural refrigerants and integrating energy-efficient technologies across the cold chain. By promoting technology transfer and providing validated, scalable solutions, the project contributes to a more climate-resilient and sustainable seafood industry. These findings support the broader ENOUGH objective of reducing specific energy use, contributing to the EU Farm to Fork Strategy's targets for climate neutrality and sustainability in food systems.

**The brine freezing demonstrator** consisted of three parts:

- 1) Brine freezing of a single pelagic fish, which showed a freezing time from 4°C to -17°C on 1 hour.
- 2) Partial brine freezing of pelagic fish showing a potential to reduce the industrial freezing time of 20 kg blocks by 50%, along with 14% reduction in energy and
- 3) Brine freezing of whole salmon, also showing a potential to reduce the freezing time by up to 50%.

**The blast freezer demonstrator** showed that the technology using 100% use of natural refrigerants achieved a low evaporation temperature down to -50°C, which can improve food quality and reduce process time. Control technology demonstrated technical application limits close to the triple point, resulting in an improvement of energy efficiency of about 15% compared to single-stage HFC/HFO units.

**The plate freezer demonstrator** showed that the system exhibited significantly lower specific energy consumption compared to the baseline case operating at -40 °C using a CO<sub>2</sub>-NH<sub>3</sub> cascade system. It achieved reduction a 59% in energy consumption (kWh/kg) at -50 °C compared to the baseline case. By decreasing the evaporation temperature from -36 °C to -50°C, the freezing time was reduced by 43.2%.

For the **blast- and plate-freezers**, design layouts for integrated vapour compression systems were developed and validated through prototype testing. The results highlighted several areas for improvement, including system dimensioning, defrosting cycle optimisation, and enhanced regulation of components to ensure more consistent energy use. These environmentally friendly refrigeration systems are suited for hotter climates.

The demonstrations highlighted several key achievements:

- KPI: Specific Energy Consumption (SEC), GHG emissions and freezing time
  - Achieved up to a 14 and 15% reduction in energy use for two freezers, and 59% for the third, compared to the baseline case. The GHG emissions reduction depends on the electricity-mix of each country. Moreover, reduction of freezing time makes the process more efficient and will indirectly reduce the overall energy use in production.
- Improved process control and product quality
  - Enabled continuous freezing with tailored programmes for each product, helping preserve optimal quality and consistency.
- Use of natural refrigerants
  - Demonstrated feasibility of replacing synthetic refrigerants with ammonia and CO<sub>2</sub>, offering energy-efficient and environmentally friendly alternatives.
- Increased stakeholder and public awareness
  - Promoted understanding of the relationship between freezing processes and product quality through monitored operations, labelling, traceability, and dissemination at public, scientific, and stakeholder events.

## 2 RECOMMENDATIONS

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The three demonstrated freezing technologies can accelerate the industrial adoption of these proven technologies by promoting the uptake of energy-efficient freezing technologies that have been demonstrated in industrial settings but are not yet widely applied.

- Reduce Specific Energy Demand in the Fish Supply Chain
  - Implement advanced freezing systems to significantly lower energy consumption and reduce the environmental impact of frozen fish processing.
- Support Technology Transfer Across the Food Sector
  - Encourage the application of demonstrated freezing technologies beyond fish, as they are suitable for a wide range of food products.
- Benchmark Against Long-Term Climate Goals
  - Align technology deployment with 2050 decarbonisation roadmaps to ensure long-term relevance and impact.
- Demonstrate Economic Viability
  - Provide quantified evidence of financial payback and operational benefits to support investment in low-emission technologies.
- Enable Broad Roll-Out Across the Food System
  - Design technologies for scalability and adaptability to maximise their impact beyond the project's duration.
- Engage and Inform Stakeholders
  - Use widespread communication and dissemination to raise awareness and accelerate the adoption of viable, low-emission solutions across the food industry.

### 3 DESCRIPTION OF THE SECTOR

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According to EUMOFA (European Market Observatory for Fisheries and Aquaculture Products), per capita fish consumption in 2023 was 23.7 kg (The EU fish market, 2024<sup>1</sup>), with wild-caught species accounting for three-quarter of this figure. Total consumption of fish and seafood in Europe amounted to 10.6 million tons. The oceans provide billions of people with healthy and nutritious food, with a smaller environmental footprint than land-based products (sustainablefisheries.org<sup>2</sup>). Emissions from the seafood industry vary depending on processing procedures, transportation, and fish species. Fish are distributed frozen or cold fresh. Freezing of fish is carried either onboard fishing vessels or in land-based processing plants, then stored frozen and transported. Cooling is typically carried out using either ice or refrigerated seawater (RSW), with the choice of method depending on the species and handling requirements of the fish. In Norway, approx. 60% of the wild-caught fish is frozen, while only 5-8% of the farmed fish is frozen (Svendsen et.al, 2024<sup>3</sup>). The production of clipfish is mainly done from frozen fish.

Freezing fish requires more energy than cooling, but it significantly extends shelf life. This allows products to be transported by sea rather than by air, which can substantially reduce greenhouse gas (GHG) emissions. A study comparing the emission footprints of different salmon supply chains from Norway found that transport account for the dominant share of overall emissions of the chain when air transport is involved, regardless of market, distance, product form, and air transport type (Johansen et.al., 2022<sup>4</sup>).

Some freezing technologies are suitable only for specific product categories, while others are versatile and applicable across a wide range of food sectors. The three freezing technologies demonstrated in this project can also be effectively applied to products other than fish.

- i) Brine freezing of unwrapped products is only suitable for whole or gutted fish with the skin on. Fillets absorb salt and get brown slightly. Vacuum-packed products, like fish fillets, meat and others, are ideal for brine freezing.
- ii) Blast freezers are already used for various products like fish, meat, fruit and berries, bread and others.
- iii) Horizontal plate freezers are well suited for products packed and distributed in flat carton boxes, typically fish, shellfish, seaweed, frozen berries and juices and others.

### 4 DESCRIPTION OF THE TECHNICAL SOLUTIONS

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The food chain relies on quite traditional technologies for thermal processes. Perishable food, such as fish, require temperature control by freezing or cooling, which is almost exclusively provided by vapour compression cycles. These systems operate by circulating a refrigerant through a closed loop of

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<sup>1</sup>The EU Fish market, 2024 edition, page 29. ISBN 978-92-68-22586-8

<sup>2</sup>Sustainablefisheries-uw.org, (2018), The Environmental impact of food, University of Washington scientists.

<sup>3</sup>Svendsen, E.S., Nordtvedt, T.S., Bless, M., Sæther, F., Patanou, E., Lunde, M., Berger, G. (2025). Roadmap for energy efficiency in whitefish- and shrimp industry (In Norwegian), SINTEF Report: 2025:00041

<sup>4</sup>Johansen, U., Nistad, A.A., Zieger, F., Metha, S., Langeland, M., Wocken, Y., Hognes, E.S. (2022). Greenhouse gas emissions of Norwegian salmon products, SINTEF Report: 2022:00041

evaporation, compression, condensation, and expansion. In the ENOUGH demonstrators, advanced configurations of vapour compression systems were explored; including integrated layouts designed for improved energy efficiency and reduced environmental impact. Technologies such as brine freezing, blast freezing, and plate freezing were implemented and tested, each offering specific advantages in terms of heat transfer efficiency, product handling, and suitability for different production scales.

Natural refrigerants are increasingly being adopted across various sectors of the food chain, driven in part by regulations such as the F-gas Regulation. In fish processing, ammonia is already widely used due to its high efficiency and suitability for large-scale systems. However, carbon dioxide (CO<sub>2</sub>) is also emerging as a viable alternative, particularly for smaller systems or in settings where specially trained operators for ammonia systems are not available.

The most innovative freezing technologies were demonstrated and evaluated under real-life conditions, where their potential was both qualified and quantified. These technologies not only showed strong performance in fish processing but also demonstrated how similar innovations could be applied to other stages of the food supply chain. Innovations were implemented at the component, system, and integrated system levels, with a consistent focus on maintaining product safety and quality at all times.

Three freezing technologies were demonstrated: brine freezing, blast freezing, and plate freezing. Each offers different advantages depending on the product type, processing scale, and operational context. Brine freezing enables rapid and uniform cooling. Blast freezing provides flexibility and high throughput, making it ideal for a wide range of products. Plate freezing, known for its high energy efficiency and compact design, is particularly effective for flat or packaged products.

Several of these systems utilised CO<sub>2</sub>-based vapour compression cycles, capable of reaching evaporation temperatures as low as -50 °C, which is particularly beneficial for rapid freezing and preserving product quality. Additionally, the condenser heat from these systems can be recovered and used for other thermal needs within the facility, such as cleaning or space heating. This integrated approach not only improves overall energy efficiency but also supports the transition away from fossil fuels by enabling the use of renewable energy sources and surplus heat.

## 4.1 KPIs and benchmarks

One of the key objectives of the ENOUGH project was to assess technological opportunities for reducing greenhouse gas (GHG) emissions, communicate these findings to the food industry, and demonstrate the most promising solutions in real-world conditions. To evaluate the effectiveness of these innovations, a benchmarking exercise was first conducted to establish reference values for conventional freezing technologies. This provided a baseline against which improvements could be measured and validated.

Following the demonstrations, a set of Key Performance Indicators (KPIs) were evaluated (SEC, GHG and freezing time) to quantify the benefits of the new technologies and identify areas for further optimisation. These KPIs focused on:

- Specific Energy Consumption (SEC)
  - This KPI measures the energy used per kilogram of fish processed (kWh/kg). It directly reflects the energy efficiency of the freezing process. The ENOUGH demonstrations showed a reduction in SEC from 14 to 59% depending on the technology.

- Greenhouse Gas (GHG) Emissions
  - GHG emissions can be calculated and expressed in carbon dioxide equivalents (CO<sub>2</sub>e), allowing for a standardised comparison across systems. Emissions were assessed from:
    - Indirect sources: electricity consumption, multiplied by the emission factor of the local grid (kg CO<sub>2</sub>e/kWh), directly connected by the SEC reduction.
    - Direct sources: refrigerant leakage, multiplied by the refrigerant GWP (e.g. R404A ≈ 3,900 kg CO<sub>2</sub>e; CO<sub>2</sub> = 1 kg CO<sub>2</sub>e; ammonia = 0 kg CO<sub>2</sub>e).
- Freezing time
  - Freezing time can increase the overall production efficiency and indirectly reduce the total energy consumption.

By using natural refrigerants such as ammonia and CO<sub>2</sub>, and improving system efficiency, the demonstrated technologies can significantly reduce both direct and indirect GHG emissions compared with conventional systems with synthetic refrigerants. These KPI assessments provided a robust, evidence-based foundation for validating the environmental benefits of the freezing solutions, while ensuring product quality and safety.

## PRESENTATION OF DEMONSTRATORS

### 5 DEMO 15: BRINE FREEZING OF FISH

#### 5.1 Description

Seafood is an important source of the world's food supply, and demand is growing. More and more seafood is being sold frozen, which extends the shelf life and creates more sustainable transportation options. Depending on the type of product, different freezing methods and equipment are used with widely varying energy intensity. Brine freezing enables fast freezing of the products with much lower energy consumption than conventional freezing in air. The challenges are mainly on the product side: there is a risk of contamination of the product with the brine fluid. The system development included identifying the optimal equipment and brine, as well as evaluating the need for packaging and various operational parameters (e.g. temperature levels and freezing times).

Brine freezing, with its good heat transfer properties, is one method that can improve the energy efficiency of this process but is not widely used. The demonstration activities explore the implications of introducing brine freezing into different seafood production chains, focused on potential reductions in energy consumption, quality attributes and practical aspects. Particular focus is placed on brine freezing of mackerel as part of a two-stage freezing process, including results from preliminary trials that show rapid freezing times but also revealed some practical barriers.

The demonstration activity showed the utilisation of brine freezing as alternative to other freezing methods:

- Partial freezing in cold brine of mackerel in cartons before air tunnel freezing
- Brine freezing of whole gutted salmon
- Brine freezing of wrapped salmon filets.

The goal was to demonstrate the reduced energy consumption by 10-20%, the reduced freezing time by 50%, and the preservation of product quality.

#### 5.2 Application methodology and assessment

##### 5.2.1 Brine freezing of single pelagic fish

Most of the pelagic fish (90% of total volume) such as mackerel and herring, that is caught and landed in Norway are exported, and about 95% of the exported volume is frozen round. Freezing of pelagic fish is done in air tunnels where mackerel and herring are packed in 20 kg cardboard boxes and put on racks. Large amounts of fish are frozen in batches, and typically 100-300 tons are frozen within 20-22 hours in each tunnel. Large fans circulate air through the tunnel, and heat transfer decreases towards the end of the freezing period. For domestic purposes, where filets are the main product, individually frozen whole mackerel or herring are an option. After freezing and storage, the fish are tempered to -2 to -3°C to maximise yield and quality after filleting.

##### 5.2.2 Partially brine freezing of pelagic fish

For export, it is essential that the cardboard is filled with 20 kg of fish. When packing single fully brine-frozen mackerel or herring, only 13-14 kg are fitted due to their stiffness. To fit 20 kg, tests were carried out where the objective was to find the 'sweet spot', i.e. how much heat could be extracted from the mackerel while maintaining the flexibility of the fish to fill the cardboard boxes. The objective of the

second test was to run a complete two-stage freezing cycle to see how much time-reduction could be achieved in the tunnels.

By partially freezing the mackerel in a brine freezer before entering the air tunnels, the goal is to reduce the freezing time in the tunnel to 11 hours. As a result, the capacity of the plant can be doubled compared to current production. Brine freezing is about 50% more energy efficient than air tunnels, and the air tunnels are also more energy effective when lowering the freezing time. The challenge is to partially freeze the mackerel to a level where the amount of ice is high, but the stiffness is still low enough to get 20 kg in each cardboard box.

### 5.2.3 Brine freezing of salmon

Another potential application is the freezing of salmon products in brine, portioned, round, either packed or unpacked. Norway holds the position as the primary producer of farmed Atlantic salmon, annually exporting approximately 1-1.2 million tons, with the majority (~90%) being fresh (Norwegian Seafood Council, 2023). Filleted (and portioned) products are usually vacuum-packed and frozen individually (or 4x4-linked packaging) employing air-based IQF freezers. Such equipment is very efficient in terms of freezing time, but as for other air freezing equipment, a significant share of the heat load and energy consumption is due to air fans.

Whole salmon is typically single-frozen in tunnels, unpacked and placed on specially designed trays with the gutted belly facing upwards although some producers also use gyro freezers to freeze whole salmon as well. Two salmon trials have been carried out in this demonstrator: freezing of vacuum-packed portions and freezing of whole salmon in salt brine (NaCl, 23%, -14 °C). The main objective of these trials was to investigate freezing rates, but also to observe for any potential changes in sensorial quality attributes.

## 5.3 Results

### 5.3.1 Brine freezing of single pelagic fish

During the first set of trials, it was concluded that freezing of mackerel in NaCl-brine (23.6%, -20 °C) followed by packaging was the most feasible approach. Freezing rates were recorded between 2.5-4.6 min/°C (dependent on the weight (300-600 gr) after freezing) to -18 °C in the lab-scale rig. In the continuous rig, production rates between 450-700 kg/hour, freezing from an initial core temperature of 3-4 °C to -14.7 - -17.8 °C in 55 minutes were achieved. During the latter trial the energy consumption of the refrigeration compressor and brine circulation pump was also measured and the energy consumption during steady-state production was found to be approximately 33 kW, giving an SEC of 0.054 kWh/kg. Frozen mackerel was thawed after 3 months of storage, and sensory evaluation showed that the brine-frozen raw fish (round, filleted) had slightly better scores (but not significantly) than the tunnel-frozen fish. The most noticeable difference was that the brine-frozen fish retained its natural, straight shape much better than the tunnel-frozen fish which is important for the filleting process.

### 5.3.2 Partially brine freezing followed by tunnel-freezing

Energy evaluation of two-stage freezing concept for mackerel:

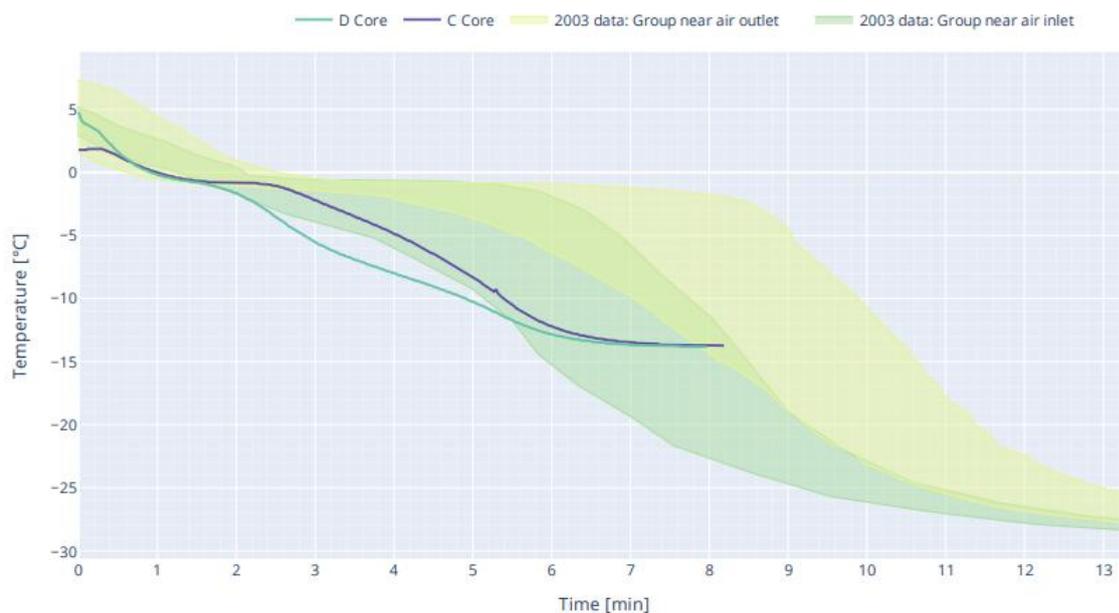
- A theoretical approach, combined with some empirical findings, was used to compare the conventional method of mackerel freezing (tunnel freezing) with the two-stage approach.
- This work was prepared for the ICCC 2024 paper *'Improving energy efficiency in seafood freezing with brine technology'* by Svendsen et al 2024.

- Details on the method is given in the reference Svendsen et al 2024. Briefly, the calculations for conventional freezing were based on previous work (simulation data, 20 hours of freezing), and the two-stage approach was calculated assuming that the tunnel freezing time was halved. Energy use for the brine freezing stage was based on empirical findings from previous work.
- **Results: Conventional method requires a total of 7,701 kWh, or 77 kWh/tonne, while the two-stage concept requires a total of 6,631 kWh – a 14% reduction.**

Finding a suitable industrial environment is currently quite challenging. Therefore, the demonstrator is being expanded to include a larger portion of the fish freezing chain.

### 5.3.3 Brine freezing of salmon

The temperature development for the vacuum-packed salmon is shown in Fig. 1. The figure also shows measurements from a previous study, where salmon was frozen individually only in tunnels (i.e., conventional method) (Nordtvedt et al., 2003). Air distribution in tunnels is an important factor affecting the freezing rate, and products placed at different locations will experience different conditions. Therefore, the data were divided into two groups based on location, in front of (Air inlet - best location) and in the rear of the tunnel.



*Figure 1. Core temperature development for whole salmon in brine freezing rig, overlaid on the previous measurements of salmon freezing in tunnels*

The freezing rates obtained in the brine trial is as expected the fastest rates observed for tunnel freezing, but obviously, when using brine at  $-14\text{ }^{\circ}\text{C}$ , the rate slows down around  $-10\text{ }^{\circ}\text{C}$ . As mentioned earlier, it is possible to operate NaCl brine as low as  $-20\text{ }^{\circ}\text{C}$  in practical operation. Still, one would likely expect a similar slow rate when the product reaches the brine temperature in these conditions. To further develop this approach, one could either go the route of two-stage freezing, i.e., pre-freezing salmon in brine and completing the freezing cycle in tunnels, similar to the two-stage freezing concept of mackerel. Alternatively, one could consider using other brines,  $\text{MgCl}_2$  or  $\text{CaCl}_2$ , which, when saturated, have eutectic points at  $-33.6$  and  $-55\text{ }^{\circ}\text{C}$ , respectively.

## 5.4 Impacts

This demonstration activity explored the latest research on brine freezing of seafood and found that there has been a renewed interest in this method, mostly due to its promising energy efficiency. In recent years, there have been projects and studies focused on whitefish (cod, haddock) and on mackerel, showing promising results with respect to the practical feasibility of this technology. However, the salt uptake can be a problem for some products, and results regarding the oxidation of fatty fish are conflicting. Furthermore, as a demonstrator in the ENOUGH project, a brine-freezing rig was used to conduct several small-scale trials in different applications. For brine freezing of mackerel, a two-stage freezing concept was described and tested, yielding promising results. The concept shows that for the fish to be flexible enough to fit 20 kg in a standard cardboard box, the mackerel must be frozen-thawed in brine before frozen completely in a tunnel. A theoretical energy evaluation showed that the energy savings for this concept was 14% compared to using air tunnels only. Brine freezing of salmon also shows rapid freezing rates, although the conventional methods are probably faster for portions. However, since these methods are based on air blasting, there is a potential for reducing energy demand.

## 5.5 Business potential

Brine freezing has been more interesting for producers of frozen fish and filets in recent years. Reduction of freezing time and energy consumption is promising, and further developments are being reported for the industry. For partially brine freezing of pelagic fish before freezing them completely in existing tunnels, there is the potential to double the capacity of the tunnels by reducing the freezing time to 10-12 hours. There are 24 pelagic freezing plants in Norway, which consume an average of 151 GWh of electricity per year. With a potential reduction of 14%, this accounts for 21 GWh annually.

The potential of this technology business faces some challenges such as:

- **Salt Uptake (for brine freezing):** A significant challenge with brine immersion freezing, particularly for species like mackerel and salmon, is the potential for salt uptake, which can affect taste, texture, and consumer acceptance. Research and technological advancements are ongoing to mitigate this, such as using alternative freezing liquids or optimizing the freezing process to minimize salt penetration.
- **Equipment and Infrastructure Investment:** Implementing immersion freezing technology may require significant upfront investment in specialized equipment and adapting existing processing lines.
- **Corrosion in Equipment:** Brine solutions can be corrosive, necessitating equipment made from resistant materials and careful maintenance.

## 6 DEMO 18: BLAST FREEZER

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### 6.1 Description

The most common type of industrial freezer using air as cooling medium consists of a spiral belt moving inside a thermally insulated ambient, while cold air is flowing through.

The velocity and length of the belt determines the productivity (kg/hour) of frozen products. The productivity of one industrial freezer plant depends on various factors, mainly air temperature, dimensions and type of product to be frozen, time available for the process, hence length and velocity of the belt. Moreover, the evaporator can be either superheated (dry expansion) or overfed, i.e., all the heat transfer surfaces are at the same temperature. Overfeeding, which is the most efficient way, can be achieved by liquid recirculation with a pump or by gravity feeding. Using a pump is the most flexible solution, as it is not affected by geometry constraints.

Fast freezing is achieved through extremely low air temperatures, i.e., low evaporation temperature below  $-40^{\circ}\text{C}$ , and high air flow.

Natural refrigerants are key to emission reduction and environmental protection, and  $\text{CO}_2$  is the only natural refrigerant that is non-toxic nor nonflammable.

Based on the above technical background, Demo 18 is an ultra-low temperature  $\text{CO}_2$  direct expansion unit for food blast freezing, suitable for implementation in freezing tunnels, conveyors, spirals, etc. Fast freezing is achieved through extremely low evaporation temperature (close to  $-50^{\circ}\text{C}$ ) and high air flow. State-of-the-art technologies are applied for optimal use of heat transfer surface, capacity control, compressor and lubricant, defrosting and unit control.

According to specific requirements and application constraints, like climatic area, the system performance can be improved by using two-phase ejector design. The system is suitable for hot climate (South Europe). Heat recovery is straightforward, as is integration with renewables (geothermal or PV).

The design choices depend on:

- System type (2-stage, booster, cascade)
- Operating constraints (evaporation temperature, admitted discharge temperature)
- Refrigerant distribution configuration (dry expansion, gravity overfeeding, pump overfeeding).

Regarding  $\text{CO}_2$  application, the knowledge gaps that were addressed were:

- Triple point ( $-56^{\circ}\text{C}$ ; 5,2 bar). Little experience about the behaviour of the actual machine when operating - on the suction side - close to the triple point.
- Oil behaviour is also unknown and there is no general, defined solution for very low temperatures (miscibility, recovery from evaporator).
- Discharge temperature can be a problem at high pressure ratios.

### 6.2 Application methodology and assessment

#### 6.2.1 Preparatory stage

Enex prepared for the actual demonstration campaign by installing a dry expansion booster system designed for commercial refrigeration applications. This solution was the result of a well-defined and improved design during a period of more than 10 years. In 2022, Enex installed a full-scale freezer prototype, designed for the evaporation temperature of  $-40^{\circ}\text{C}$  in a freezing plant in Milan, Italy. The recorded performance was satisfactory. However, some minor vibration problems occurred during commissioning.

### 6.2.2 Technical focus on specific challenges

The second stage involved the design and building a test rig (see Fig. 2) for experimental measurement of more severe conditions, down to  $-45\text{ }^{\circ}\text{C}$  of evaporation, since there was no direct experience with  $\text{CO}_2$  under such conditions.

The system was equipped with a circulation pump, as this choice allows for flexible arrangement of the evaporator, for example, at different heights or distances from the compressor unit, which meets different market requirements. The system was also designed to test two different overfeeding methods, i.e., gravity and pump circulation, as overfeeding is a more efficient way of using heat transfer surface of the evaporator rather than dry expansion.

The test rig was designed and built according to the simplified P&ID presented in Fig. 3. The height of the liquid receiver was selected to allow for both pump and gravity feeding of the evaporator. To focus only on the most relevant challenges, the design was kept rather simple: a cascade system with one-stage compressors in each stage, using a standard chiller as the first - high temperature - stage. The pump used in this stage was a gear type with magnetic coupling between shaft and motor, while the compressor installed in the lower stage, one of the investigated components, was a DORIN CD360M with a swept volume of  $3.0\text{ m}^3/\text{h}$ .



*Figure 2.  $\text{CO}_2$  system at Enex*

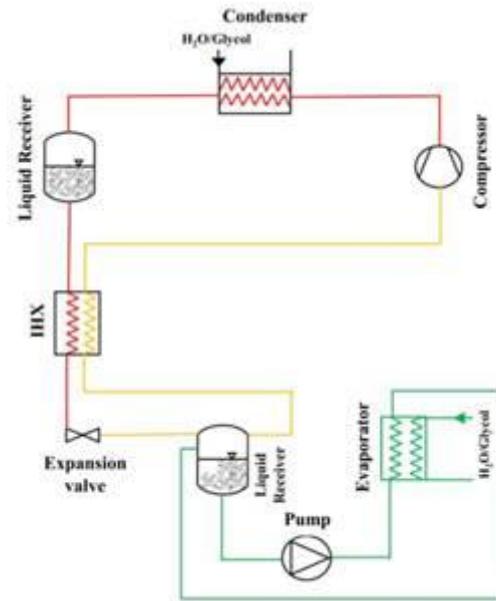


Figure 3. Simplified P&ID of the Enex unit

### 6.2.3 Field installation of blast freezers based on booster design

Several booster type units, like the first one, were installed between 2023 and 2024. The limit conditions were also redefined for a very warm region (Oman). Another system with an extended operating range was installed in Milan and has been in operation since late 2024. The P&ID of the unit is reported in Fig. 4. The unit serves a freezing tunnel for bakery products. All this information confirms that the design and product are suitable for general commercial use.

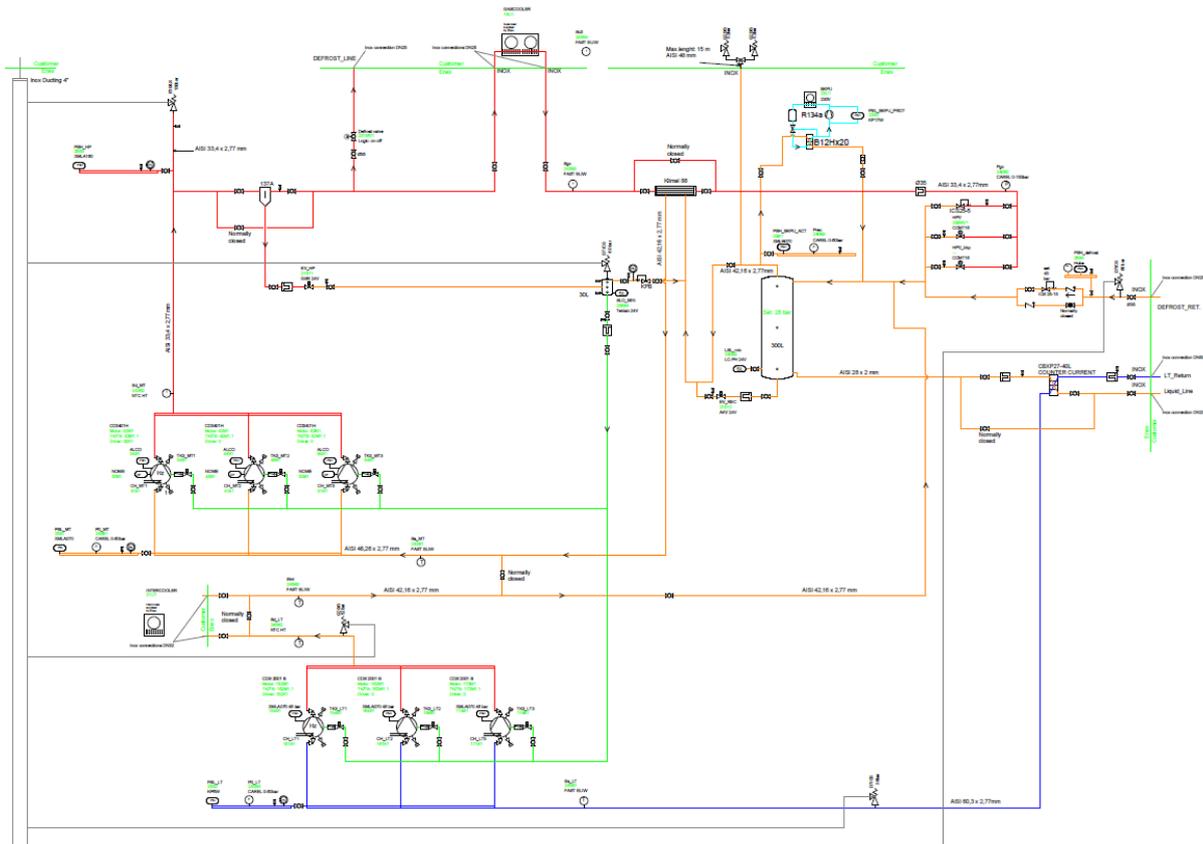


Figure 4. P&ID of the Blast Freezer unit installed in Milan (late 2024)

### 6.2.4 Evolution - further reduction of evaporation temperature

The final step taken in the demonstration campaign was to understand system behaviour at the triple point. This activity derives from the fact that system control algorithms are not always capable of maintaining strictly the set temperature, but some flexibility (+1/-3 K) needs to be adopted. Moreover, industrial sensors can have low accuracy or might experience some de-location in operation. As the system works close to the triple point, it is important for safety reasons to know what happens when this condition is reached.

In summary, the experimental activity allowed the investigation and definition of the following aspects:

- Discharge temperature at very low suction temperature.
- Optimal intermediate pressure.
- Oil separation and management.
- Circulation by gravity.

On the other hand, the circulation of refrigerant at the saturation temperature of  $-50^{\circ}\text{C}$  and lower using a pump has not yet been verified. Based on the analysis performed, it is very likely that the reason for malfunction was the limited NPSH value (about 1.5 m). This suggests that deeper analysis is required. For the practical implementation of the technical concept, however, it will be necessary to define the requirements for a proper operation of the pump.

## 6.3 Results

### 6.3.1 Operation verification at the evaporation temperature of -50 °C

Tests were performed down to -45 °C and -50 °C evaporation. Despite the extremely low temperature, tests were run safely for the system, also in terms of oil recovery back to compressors. Table 1 shows results (average value of measured parameters) for the 20-minute test. The compressor operated at the very limit of its envelope, as shown in Fig. 5 by the green dot. The tests were supported by dynamic modelling and simulations carried out by CNR.

Table 1: Results for the 20 min test

	Unit	Value
Compressor suction pressure	bar	6.6
Evaporation temperature	°C	-50.6
Compressor suction temperature	°C	-30.9
Superheat at compressor suction	K	19.7
Compressor discharge pressure	bar	25.5
Condensation temperature	°C	-11.5
Compressor discharge temperature	°C	110.9
Condenser outlet temperature	°C	-12.2
Liquid receiver pressure	bar	6.8
Liquid CO <sub>2</sub> temperature at evaporator inlet	°C	-47.8
CO <sub>2</sub> temperature at evaporator outlet	°C	-47.3

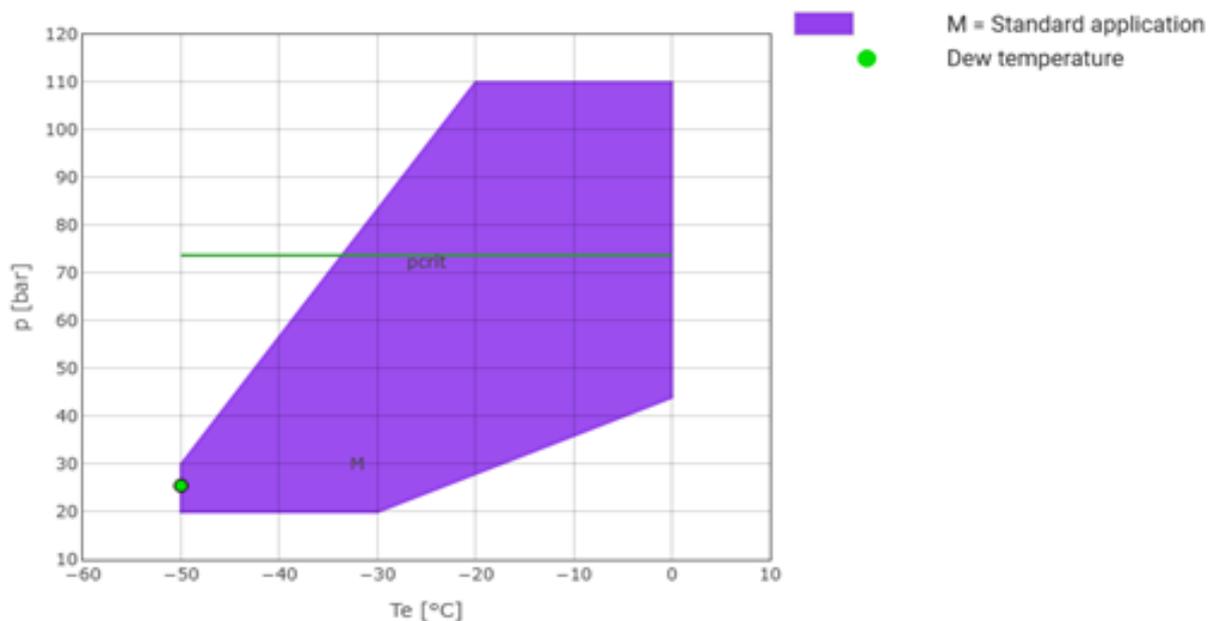


Figure 5. Compressor envelope and working conditions during the test.

### 6.3.2 Field installation of 120 kW Blast Freezer

In late 2024, a 120 kW Blast Freezer (design evaporation temperature of  $-42^{\circ}\text{C}$ ) was installed near Milan in northern Italy. The unit is intended for pastry production, thus showing the flexibility and potential for expanding such a technology into the food sector.

The PI&D of the unit is reported in Fig. 4 the unit features a booster system with heat recovery for hot water production and hot gas defrosting is in place. The unit has been successfully commissioned, and the production site is regularly operating. The unit is equipped with remote monitoring system.

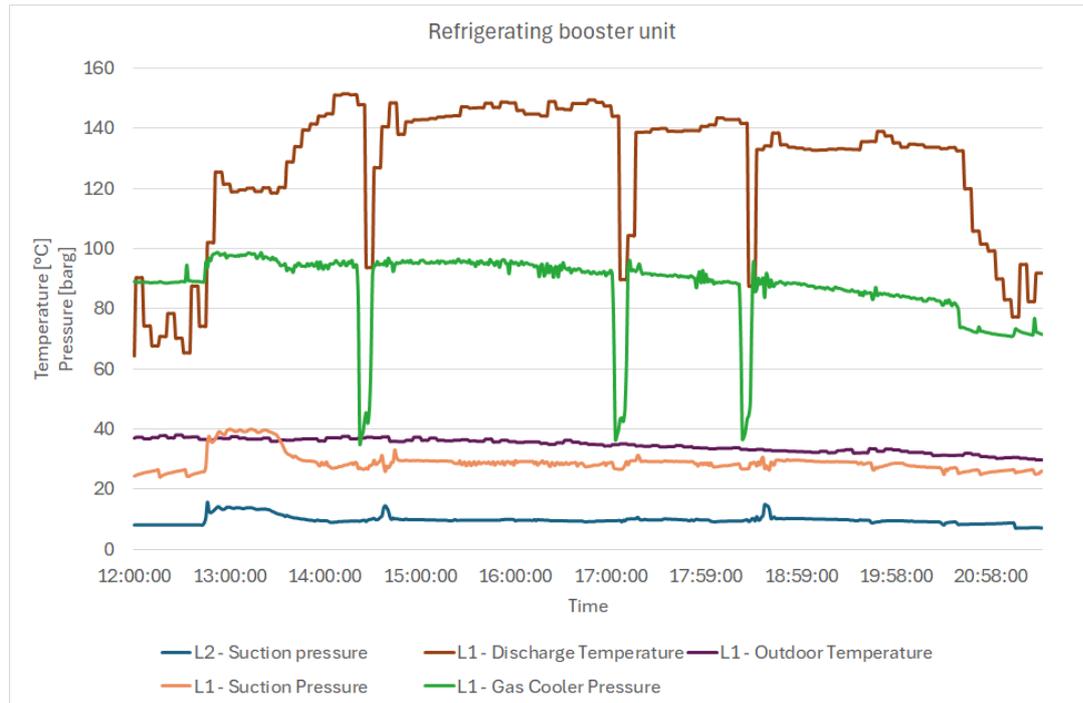


Figure 6. Main parameters recorded during the operation of the blast freezer

Fig. 6 presents data recorded from a field, highlighting evaporation pressure (L2-suction pressure), corresponding to about  $-40^{\circ}\text{C}$  saturation during the “production” phase, and discharge temperature (up to  $150^{\circ}\text{C}$ ) when outdoor temperature exceeds  $36^{\circ}\text{C}$ . Discharge temperature is still within the limit of the compressor envelope. However, it might be necessary to reduce the suction temperature at the high stage compressor not to exceed the maximum discharge temperature.

Fig.6 is related to a period of 9 hours, from 12.00 a.m. until 9.00 p.m., during “production phase”. It is possible to see the “starting” of 3 defrosting periods, and the transient effect which lasts about 5 minutes each time. This is due to the time required for rotation of defrosting motor valves. One can see, from the graph, that during “production phase”, with ambient temperature between  $30$  and  $35^{\circ}\text{C}$ , evaporating temperature is  $-40^{\circ}\text{C}$  approximately while high pressure varies between 95 and 80 bar (green line). The transient effect due to defrosting motor valves has little influence on suction pressure.

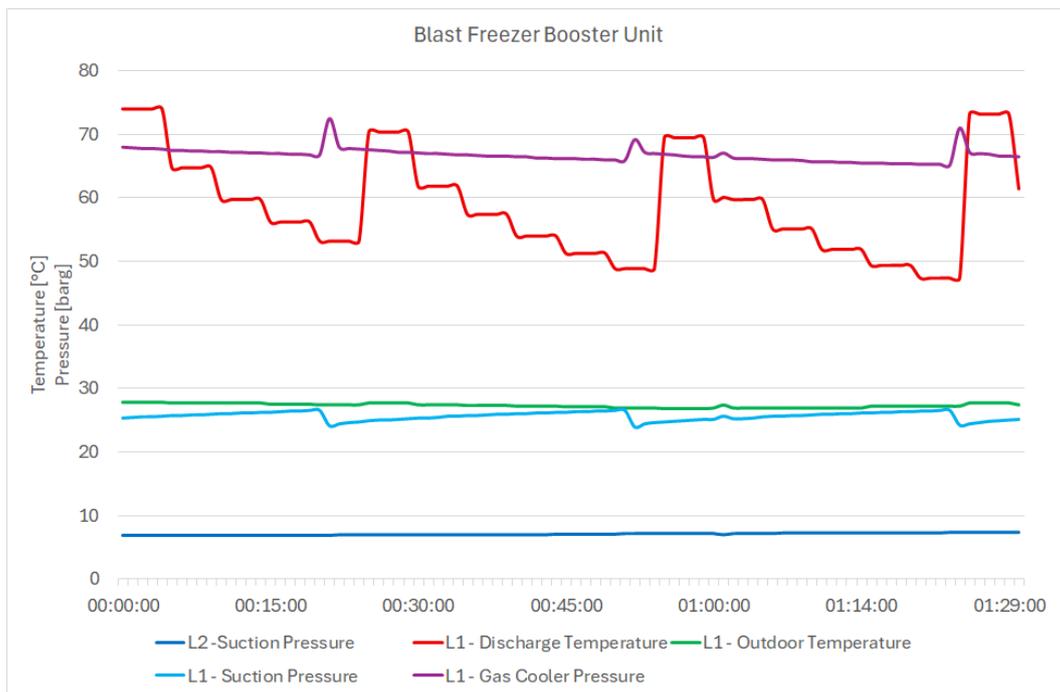


Figure 7. Main parameters recorded during the “temperature maintain” phase operation of the blast freezer

During the “temperature maintaining” phase, the evaporation temperature can reach  $-45^{\circ}\text{C}$  (see Fig. 7– L2 Suction Pressure)

Fig. 7 shows 1h 30’ of “maintaining phase”, during the night (or out of production time). One can see three short switch ON/OFF of one compressor (increase of gas cooler pressure and decrease of suction pressure) to keep down the pressure in the circuit. As said above during this period low pressure remains approximately down to 7 bar ( $p \sim -45^{\circ}\text{C}$ ).

### 6.3.3 Triple point conditions - verification of safe operations

Several tests were performed at Enex to simulate this demanding condition, reaching a suction pressure of 5.2 bar and a saturated temperature of  $-56^{\circ}\text{C}$ . The operation was stable: as experienced, it takes some time to obtain ice, due to the system inertia, so there is a sufficient safety margin for the system operation and recover from the off-design condition. The pressure was reduced down to 4 bar, to allow for the formation of solid  $\text{CO}_2$ .

During the execution of the test, the circulation pump was identified as the most critical components as it was not working smoothly. The reason was identified in the low “head” or reduced pressure at pump suction. For this reason, the final tests were performed using gravity overfeeding of evaporator. The video frame presented in Fig. 8 shows the moment when the presence of solid R744 inside the liquid accumulator LT was evident.

The gravity circulation is one of the two methods allowed for liquid distribution, but it requires a significant height. The pump circulation is more general and there are few constraints in terms of layout, but as specified above, a higher head than the one adopted in the experiments is necessary. Very likely it is necessary to have a suction head higher than 2 meters.



*Figure 8. Solid phase formation inside liquid phase (triple point)*

## 6.4 Impacts

The demonstrated blast freezer retains a large impact for implementation in the food industry. Only natural refrigerants can support the transition to a net-zero emissions food chain. Ammonia is an established refrigerant used in industrial freezing plants at evaporation temperatures down to  $-40^{\circ}\text{C}$ . It has been used for many years, but there are some concerns related to its toxicity. Hydrocarbons are highly flammable, and there are concerns related to their use in freezing systems, as they are normally installed in or close to working areas.  $\text{CO}_2$  is the only non-toxic, non-flammable natural option for ultra-low evaporation temperature: it can be installed indoors, close to working areas, and is also suitable for small and medium systems.

With a  $\text{CO}_2$  blast freezer, 100% use of natural refrigerants is possible. The low evaporation temperature (down to  $-50^{\circ}\text{C}$ ) improves food quality and reduces process time. The demonstrator impacts control technology as it shows technical application limits close to the triple point.

The simplified P&ID of the unit installed in Milan in 2024 (Fig. 4) is shown in Fig. 9a. A version with higher efficiency (Fig. 9b) was studied and the addition of one (or more) compressor(s) for flash gas recompression was approved. Moreover, the evaporator overfeeding (using pumps or through gravity circulation) can further increase efficiency. Two cycle modifications allowed for the improvement of the Energy Efficient Rate of about 15% compared to single-stage HFC/HFO units.

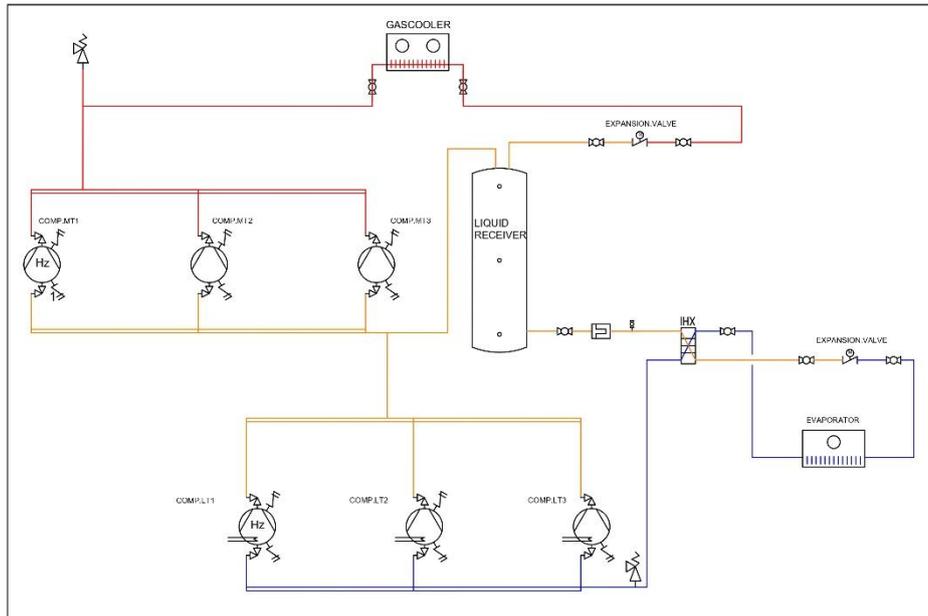


Figure 9a. Simplified P&ID of the unit installed in Milan in 2024

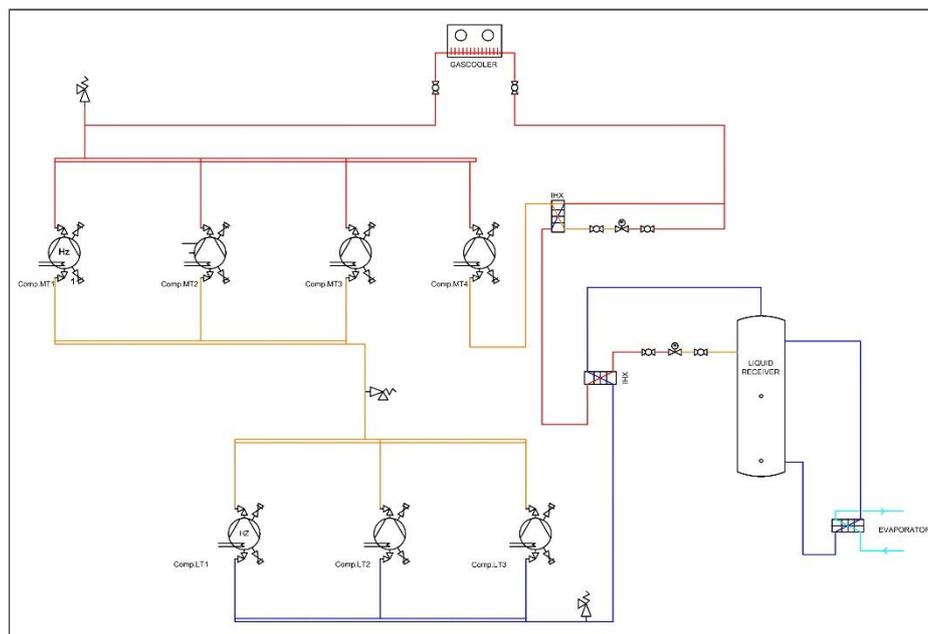


Figure 9b. Simplified P&ID of the system modifications for efficiency improvement

## 6.5 Business potential

Target Industries are typically food transformation. For example, meat and fish processing (freezing), frozen food factories (i.e. pastry and bread, and many others).

**Sales of Ultra-Low Temperature Freezing Systems:** this is the primary revenue stream. Enex's current installations (around 10) and forecasts (15-20 pieces in 2025 and 2026, with interesting potential for 2027-2028) indicate a growing market for their specific technology.

**Another source of income could be Technology Licensing to Freezer Manufacturers:** this would allow Enex to scale its reach without direct manufacturing of every system, leveraging the existing production capabilities of other companies.

**Installation Services and maintenance contracts:** It would be a natural extension of system sales, ensuring proper setup and commissioning.

Enex is mainly focused on the Food Industry. For this industry the most interesting Key Drivers for Business Growth are:

- **Quality Preservation:** The ability to significantly reduce ice crystal damage and dehydration is a major selling point for high-value food products.
- **Energy Efficiency:** As energy costs fluctuate and environmental regulations tighten, systems that offer verified energy savings are highly attractive. Performance-based agreements further enhance this.
- **Increased Shelf Life & Reduced Waste:** For food processors, extending shelf life means greater market reach, reduced spoilage, and improved profitability.
- **Compliance with Food Safety Standards:** Rapid and consistent freezing helps meet stringent food safety requirements.

Identified challenges and opportunities are:

- **High Initial Investment:** Ultra-low temperature systems can be more expensive up-front, which might deter smaller businesses. One of the next practical activities is the economic analysis – energy saving versus higher performances – of Ultralow temperature freezing systems. The clear advantage of the Ultra-Low Temperature Freezer Market is the economic aspect of production: a lower evaporation temperature increases the productivity of freezing plants. Reducing freezing time brings lower overall energy consumption, to be evaluated in comparison with the need for a lower evaporation temperature (with lower punctual EER) and with the advantages described above.
- **Technical Complexity:** Installation and maintenance require specialized knowledge, which Enex addresses through its services and maintenance contracts.
- **Competition:** The broader ULT freezer market has established players (e.g., Thermo Fisher Scientific, Eppendorf, Haier Biomedical), though many of these focus heavily on biomedical. Enex's specific focus on industrial food processing with booster technology could be a differentiator.

In summary, Enex is well-positioned to capitalize on a growing market for ultra-low temperature freezing systems in the food processing sector. Their focus on quality preservation, energy-efficient booster technology, and comprehensive service offerings (sales, licensing, installation, maintenance, performance agreements) creates a strong business model for capturing this potential in the coming years.

## 7 DEMO 20: CO<sub>2</sub> -50°C PLATE FREEZER

### 7.1 Description

Food loss and waste responsible for at least 6% of the global greenhouse gas emissions (FAO, 2015<sup>5</sup>). To reduce food loss and waste in the cold chain of food supply, efficient cool and freezing systems are necessary. To examine and improve the freezing of product inside the fish production, a demonstrator was selected that is commonly used: a plate freezer for batch freezing of fish.

The state-of-the-art solution for horizontal plate freezers is currently the use of ammonia (NH<sub>3</sub>) as a refrigerant. However, it is difficult to achieve freezing temperatures lower than -35 °C with NH<sub>3</sub>. Using CO<sub>2</sub> as refrigerant, it is possible to reduce the freezing temperature down to -50 °C (Dopazo and Fernández-Seara 2012<sup>6</sup>). Moreover, CO<sub>2</sub> is an environmentally friendly, with negligible ODP and GWP, non-toxic and non-explosive refrigerant. Due to the decreased freezing temperature, faster freezing times can be achieved which leads to higher utilization, better food quality with reduced drip losses, improved shelf life, higher consumer acceptance and greater market demand. To study the capabilities and real-life performance of a CO<sub>2</sub> plate freezer, a test rig was designed and built at the NTNU in the scope of the H2020 ENOUGH project, as shown in Fig. 10 (Ren et al. 2024<sup>7,8</sup>).



Figure 10. CO<sub>2</sub> plate freezer test rig at the NTNU (Ren et al. 2024)

<sup>5</sup> FAO (2015). Food Wastage Footprint and Climate Change, [www.fao.org/nr/sustainability/food-loss-and-waste](http://www.fao.org/nr/sustainability/food-loss-and-waste) accessed 10.03.2021

<sup>6</sup> Dopazo, A., Fernandez-Seara, J. (2012). Experimental evaluation of freezing processes in horizontal plate freezers using CO<sub>2</sub> as refrigerant. *International Journal of Refrigeration* 35, nr. 8: 2093-2102. DOI: 10.1016/j.ijrefrig.2012.08.018

<sup>7</sup> Ren, S., Hafner, A., Rekstad, I.H., Widell, K.N., Svendsen, E.S., Nordtvedt, T.S. (2024). Design of a CO<sub>2</sub> plate freezer test facility with -50 °C evaporation temperature, *11th IIR Conference on Compressors and Refrigerants*, DOI: 10.18462/iir.compr.2024.0640

<sup>8</sup> Ren, S., Hafner, A., Rekstad, I.H., Widell, K.N., Svendsen, E.S., Nordtvedt, T.S. (2024). Design and freezing performance study of a CO<sub>2</sub> plate freezer at -50 °C evaporation temperature, *16th IIR Gustav Lorentzen Conference on Natural Refrigerants - GL2024: Proceedings. International Institute of Refrigeration*, DOI: 10.18462/iir.gl2024.1198

This demonstrator implements an industrial-sized plate freezer (Plates: 2x3 m) manufactured by Optimar AS, into a dedicated CO<sub>2</sub> refrigeration system in the laboratory infrastructure. Due to CO<sub>2</sub> liquid circulation, the unit can provide more than 100 kW of cooling capacity at evaporation temperatures between -30 and -50 °C. A scientific approach was applied to understand how to optimise the freezing time and product/package thickness with energy demand and shelf life. The goal was to disseminate operational instructions and recommendations to minimise the carbon footprint of dedicated products within the fish and meat sector.

The working principle of the plate freezing system is shown in Fig. 11. The existing CO<sub>2</sub> heat pump system features three suction lines with different suction temperatures and one supply line. A horizontal plate freezer is incorporated into this CO<sub>2</sub> system, functioning as a flooded evaporator. The main components of the test facility include a sub-cooler, a separator, a pump, a plate freezer, a compressor, and an expansion valve. The compressor is utilised in the defrosting circuit. The CO<sub>2</sub> liquid at the outlet of the condenser is at 14 °C and 50 bar. Through the expansion valve, the high-pressure liquid CO<sub>2</sub> is throttled to -50 °C and 6.8 bar. Then the two-phase CO<sub>2</sub> is separated in a separator to ensure that only liquid CO<sub>2</sub> is pumped into the plate freezer. In the freezer, the liquid CO<sub>2</sub> is evaporated by absorbing the cooling duty from the product to be frozen. The liquid-vapour mixture from the plate freezer is then returned to the separator and the CO<sub>2</sub> vapor is returned to the suction line of the central CO<sub>2</sub> system. When the experiment is completed, the refrigerant in the plate freezing system is returned to the receivers of the central CO<sub>2</sub> system to prevent the high standstill pressure.

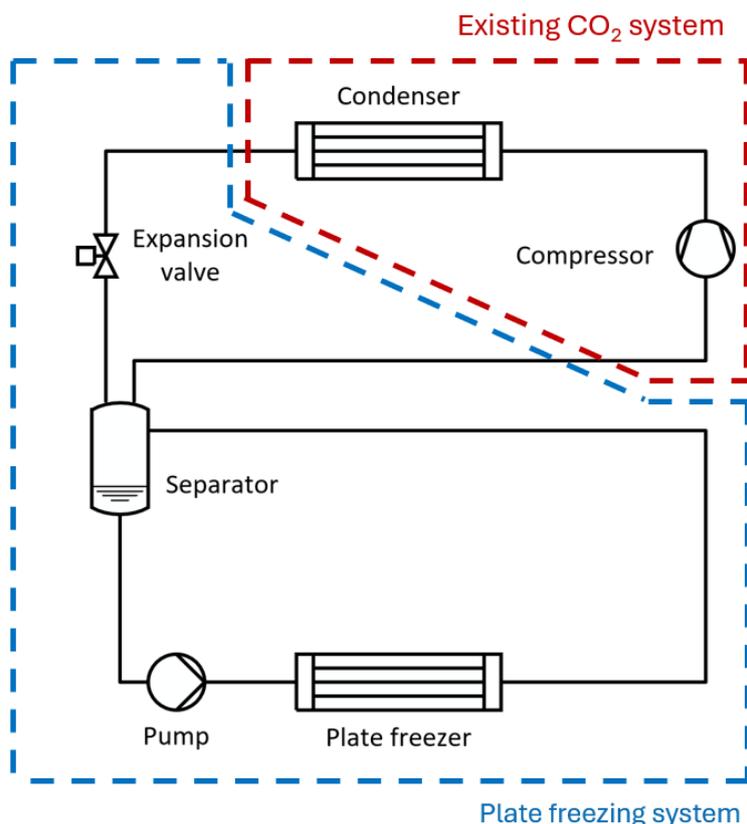


Figure 11. Simplified working principle sketch of the plate freezing system (Ren et al. 2024)

The plate freezing technology has a TRL of 5 at the starting point. The technology has been validated in industrial relevant environment. The final TRL is 8, with the system completed and qualified.

## 7.2 Application methodology and assessment

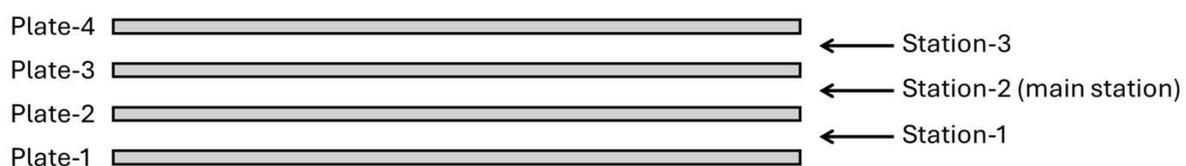
The demonstrator commenced in February 2024, following the amendment. Since then, a plate freezing system has been designed for integration into the existing CO<sub>2</sub> refrigeration system within the laboratory infrastructure. Key components of the test facility, including the separator tank, plate freezer, pump, expansion valves, and measuring instruments, were ordered, manufactured, and delivered to the laboratory. The construction of the freezing facility was completed in August 2024, and the installation of the measuring instruments and data acquisition system was finalized in September 2024.

A numerical study was carried out in parallel with the experimental work to support the system design. A dynamic model of the plate freezing system was developed using Modelica in Dymola. The system performance was analysed numerically under varying conditions, including different product weights and heights, evaporation temperatures, and circulation ratios. The NTNU team held regular meetings with the plate freezer manufacturer to discuss design details, potential collaboration, and the schedule for constructing the plate freezer test facility and conducting subsequent tests.

Following the completion of the test facility, several joint tests were carried out in collaboration with the manufacturer and their customers. Freezing times were measured at evaporation temperatures of -40 °C and -50 °C for various fish products, including salmon fillets, salmon portions, pseudo-fish tissue, whole mackerel, whole herring, and mackerel fillets, under different packaging methods and product heights.

In addition to the collaboration with the industrial partners, experimental studies were conducted using pseudo-fish tissue to evaluate the performance, energy consumption, and emission reductions of the plate freezing system under various operating conditions.

As shown in Fig. 12, the plate freezer consists of four plates, forming three product stations. The middle station (Station 2) was used as the primary testing station, where the products under investigation (fish, pseudo-fish tissue or apple juice) were loaded. Stations 1 and 3 were loaded with apple juice cartons to simulate thermal load. Each station contained 14 boxes, with each box holding 10 cartons of apple juice. Thermocouples were placed in the centre of the tested product to measure the temperature evolution during the freezing process. The distance between adjacent plates, that is the height of each station, was controlled by a hydraulic system in combination with spacers located at the four corners of each plate. This allows for adjustable station heights and controlled pressure on the product surfaces. Proper pressure ensures good contact between the plate surfaces and the product, promoting efficient heat conduction.



*Figure 12. Description of the plate arrangement*

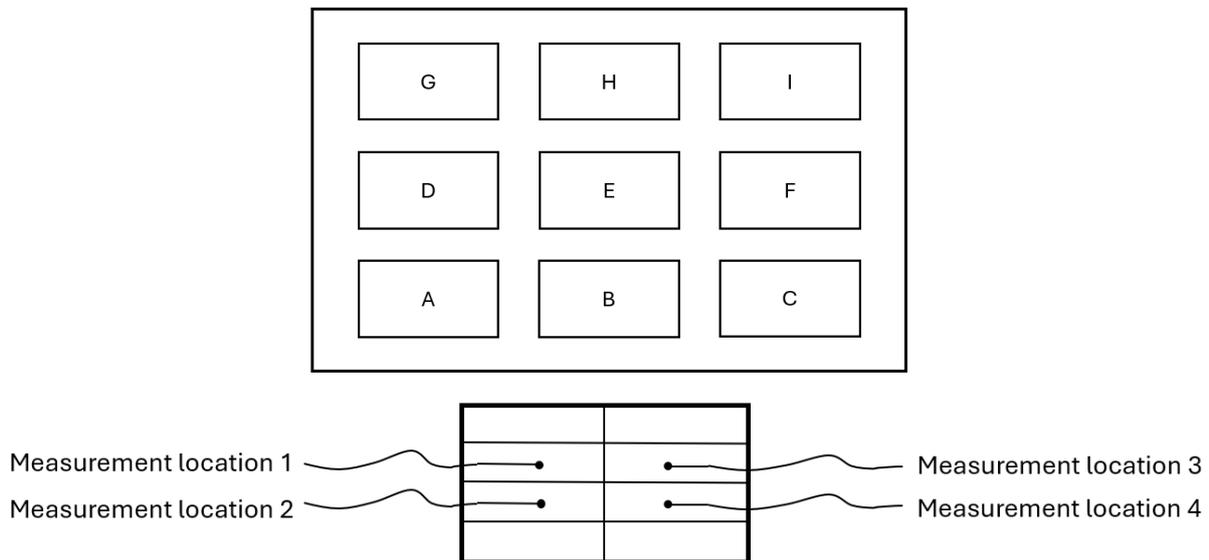
## 7.3 Results

### 7.3.1 Freezing time measured for different products

#### 7.3.1.1 Freezing time for apple juice

The freezing time for apple juice was measured at an evaporation temperature of  $-50\text{ }^{\circ}\text{C}$ . The total product weight was 700 kg. The height of the tested product was 133 mm, so the volume expansion during freezing was horizontal. Nine product blocks were placed in Station 2, as shown in Fig. 14. Prior to testing, the apple juice was stored in a cooling room set at  $0\text{ }^{\circ}\text{C}$  to ensure an initial product temperature of approximately  $0\text{ }^{\circ}\text{C}$ . The target freezing temperature was  $-18\text{ }^{\circ}\text{C}$ . Four thermocouples were inserted into each block to measure the centre temperature of the tested product during freezing, as shown in Fig. 13.

The  $\text{CO}_2$  temperature at the inlet and outlet of the plate freezer is shown in Fig. 14. The  $\text{CO}_2$  temperature across the plate freezer was maintained between  $-49\text{ }^{\circ}\text{C}$  and  $-48\text{ }^{\circ}\text{C}$  during the entire freezing process, with the outlet temperature slightly lower than the inlet pressure due to the pressure loss.



*Figure 13. Layout of the test apple juice blocks in Station 2 and the measurement locations for each block*

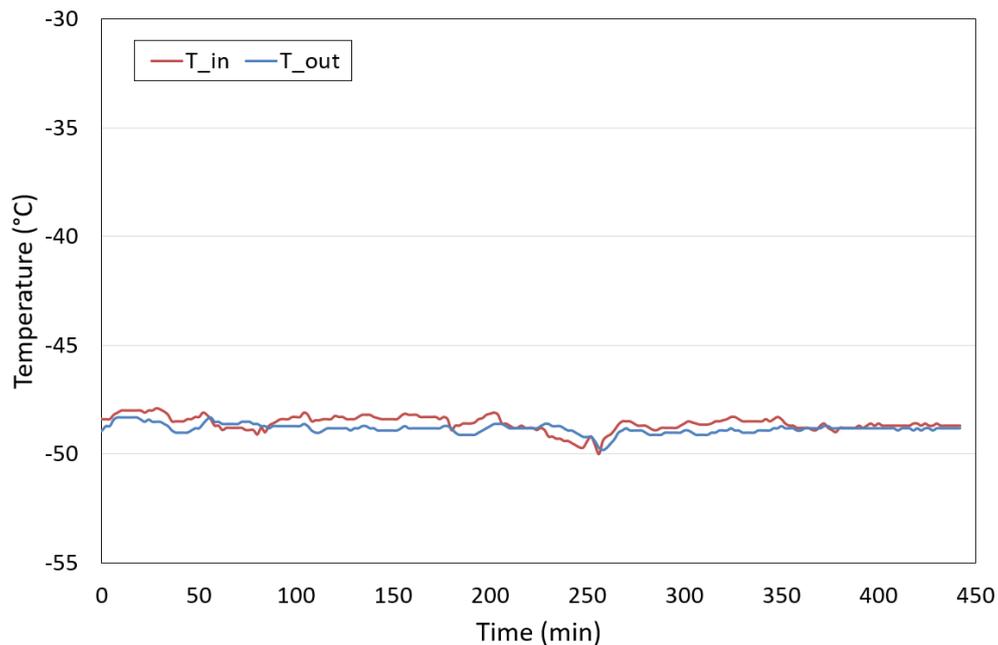


Figure 14. Evolution of the CO<sub>2</sub> temperatures at the inlet and outlet of the plate freezer

Product Block E, located at the centre of the tested station, exhibited the longest freezing time, with 410 minutes measured at Location 1 and 420 minutes measured at Location 2, as shown in Fig. 16. In contrast, Product Block G had the shortest freezing time, with 284 minutes measured at Location 1 and 290 minutes measured at Location 2, as shown in Fig. 17. Generally, products placed in the middle row experienced longer freezing times, which may be attributed to the uneven spacing between the plates. The hydraulic pressure applied to the product surface was higher near the plate corners, resulting in a smaller plate distance in those areas. As a result, products near the corners had better thermal contact with the plate surfaces, while those positioned closer to the centre had poorer contact, leading to the longest freezing time for the central block. However, in an industrial setting, plate spacing would not be allowed to be affected by hydraulic pressure in this manner. Industrial freezers are typically equipped with central dividers to maintain the required spacing. Additionally, a full load of products in all stations, combined with a robust top frame capable of withstanding the pressure, helps eliminate uneven spacing between plates.

As illustrated in Fig. 15 and Fig. 16, for all product blocks, the measured freezing times at Location 3 and 4 were longer than those at Location 1 and 2. This phenomenon is more obvious during the final phase of freezing, i.e., the cooling down of the already frozen product. The differences in freezing times within the same product block can be attributed to the packaging method using plastic bags. As shown in Fig. 18, the side where the bag was sealed with tape had a thicker and ununiform plastic layer. This added thickness increased thermal resistance, which led to a longer freezing time for the thermocouples inserted on that side. This indicates that the packaging material and manner have a significant impact on freezing time.

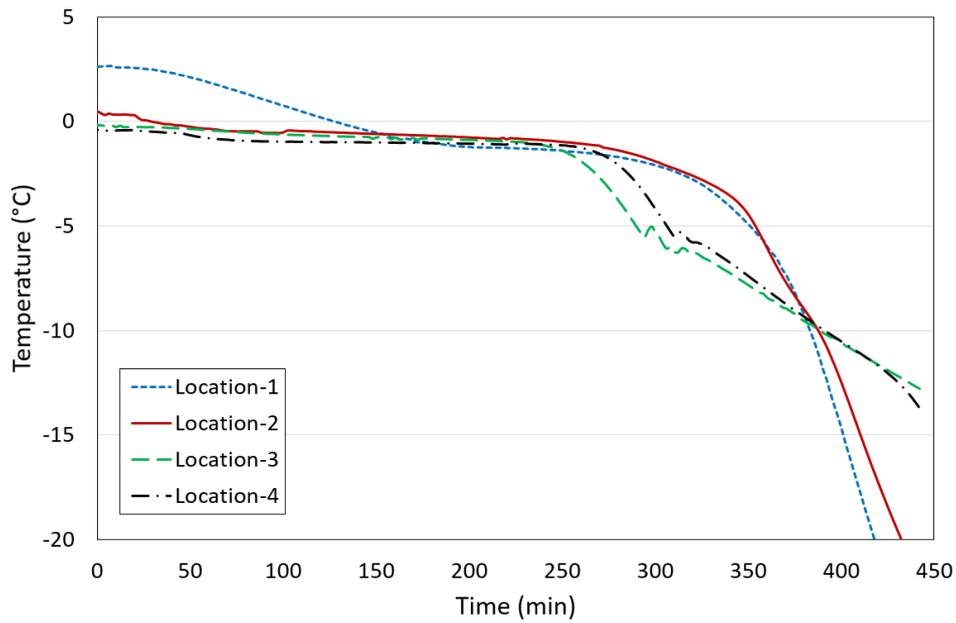


Figure 15. Evolution of the centre temperature of Block E

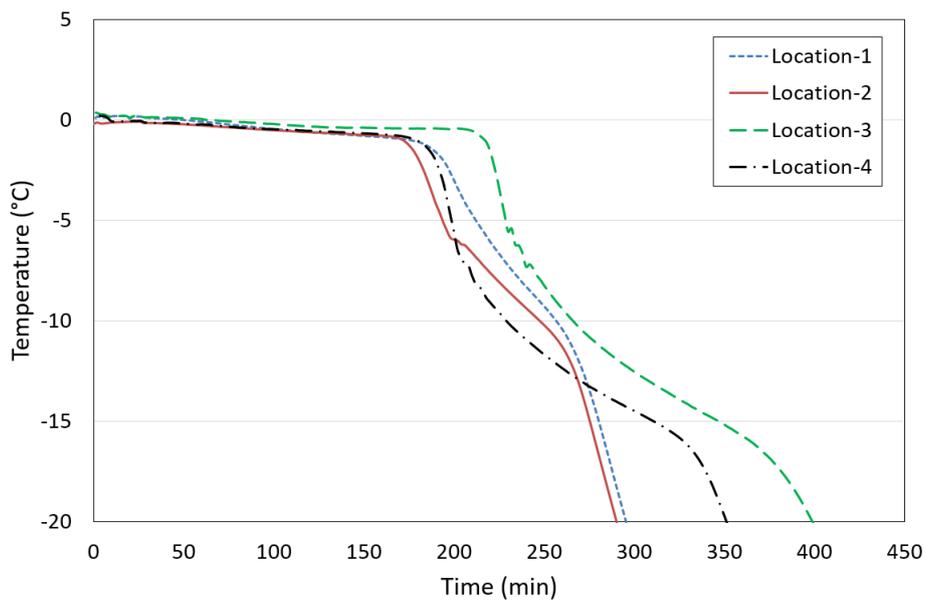
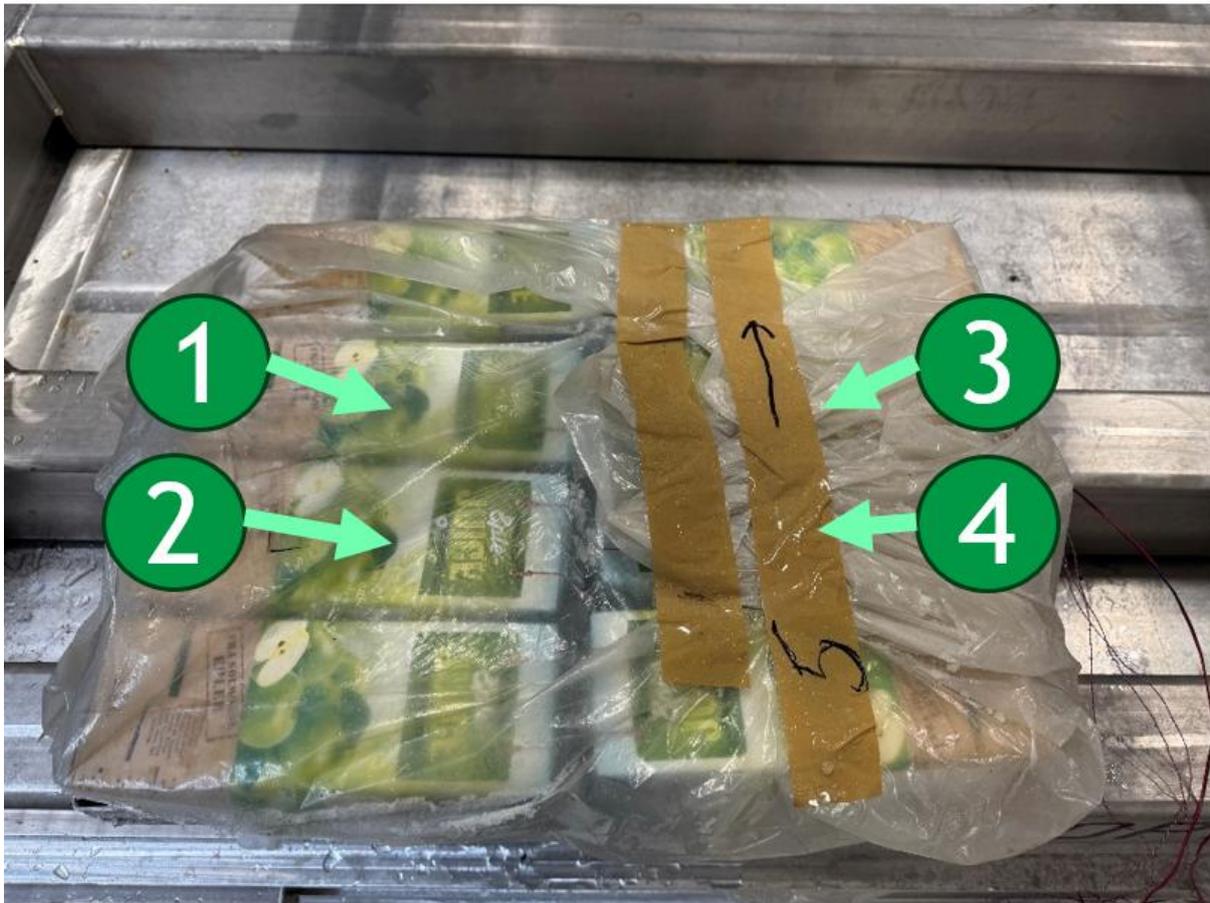


Figure 16. Evolution of the centre temperature of Block G



*Figure 17. Apple juice block with packaging*

#### 7.3.1.2 Freezing time for herring

Freezing times for whole herring and herring fillets were measured at an evaporation temperature of  $-50\text{ }^{\circ}\text{C}$ . The test products were packaged in plastic bags and placed in stainless steel frames with a height of 100 mm. Two product blocks, each weighing 20 kg, were placed in Station 2 (Fig. 12), as shown in Fig. 18. Prior to testing, the test products were stored in a cooling room set to  $0\text{ }^{\circ}\text{C}$  to ensure an initial temperature of approximately  $0\text{ }^{\circ}\text{C}$ . The target freezing temperature was  $-18\text{ }^{\circ}\text{C}$ .

For clarity, the freezing times recorded at three measurement points for each block are presented in Fig. 19 and Fig. 20. The freezing time measured for whole fish ranged from 222 to 280 minutes, while for fillets from 206 to 255 minutes. The freezing times measured for fillets were generally shorter than those for whole herring, primarily due to the more compact packing of the fillets. There were fewer air gaps in the fillets than in the whole fish, resulting in better thermal contact and more efficient heat conduction.

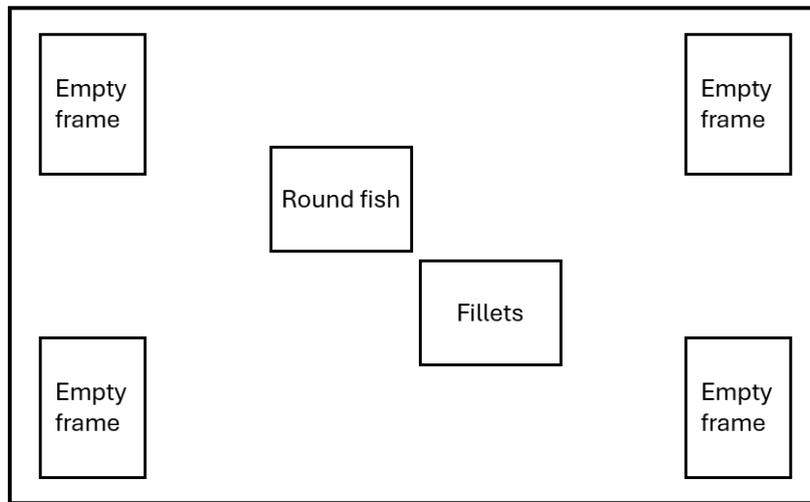


Figure 18. Layout of the test fish products on the plate surface

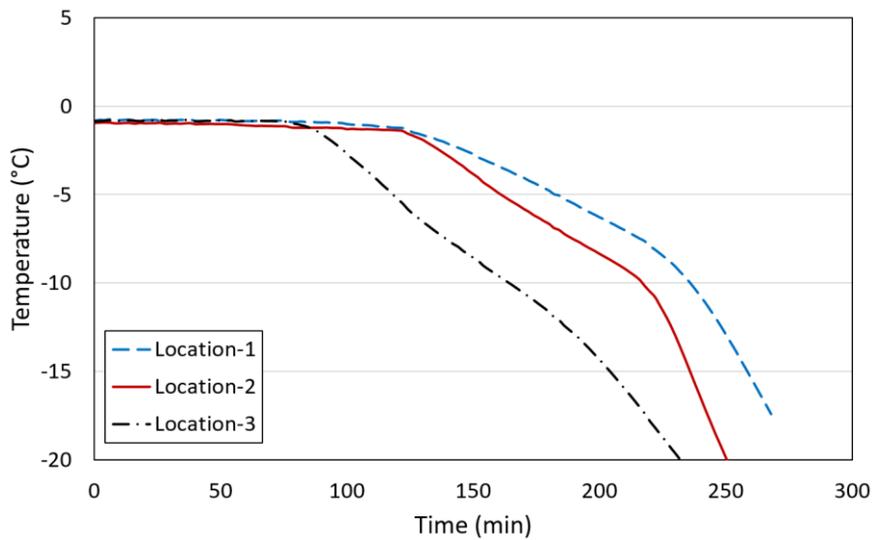


Figure 19. Temperature evolution at the centre of the whole herring block

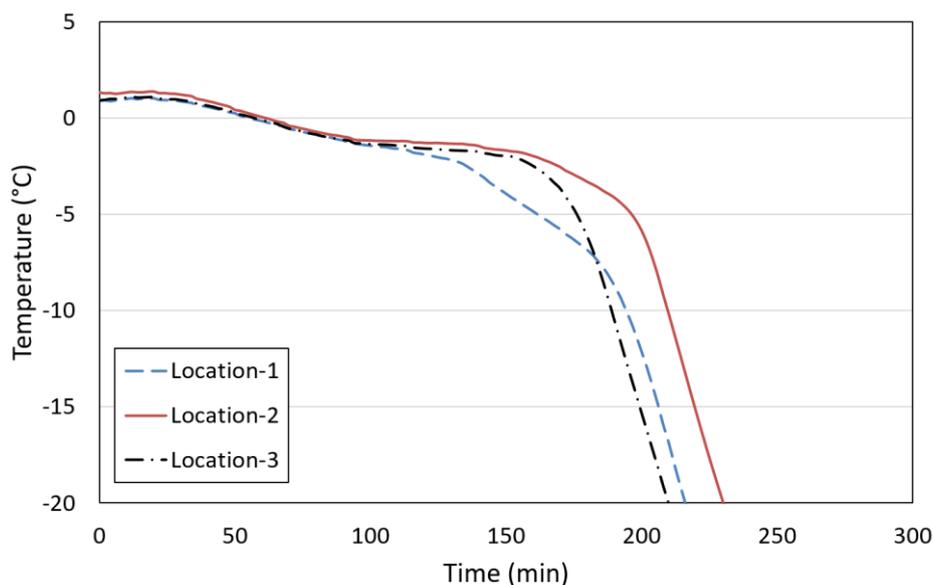


Figure 20. Temperature evolution at the centre of the herring fillet block

### 7.3.1.3 Freezing time for mackerel, herring, and mackerel fillets

Freezing times for whole mackerel, whole herring, and herring fillets were also measured at an evaporation temperature of  $-50^{\circ}\text{C}$ . The test products were packaged in plastic bags and placed in stainless steel frames. Two product heights were investigated: 100 mm and 75 mm. For the 100 mm product height test, a total of 8 fish blocks were evaluated, including 3 blocks of whole mackerel, 2 blocks of whole herring, and 3 blocks of fillets. For the 75 mm product height test, 9 fish blocks were tested, consisting of 3 blocks each of whole mackerel, whole herring, and fillets. All the products were stored in a cooling room set to  $5^{\circ}\text{C}$  before the test to ensure an initial temperature of approximately  $5^{\circ}\text{C}$ . The target freezing temperature was  $-18^{\circ}\text{C}$ .

For each product block, two thermocouples were inserted into the centres of two fish positioned in the middle layer of the frame. The weight of each product block varied slightly, with some blocks packed more tightly and others more loosely. As a result, when the plate freezer was closed, the tightly packed blocks had better thermal contact with the upper plate. The results also showed that these blocks exhibited shorter freezing times. The freezing times measured for the most compact block of each product type are illustrated in Fig. 21 and Fig. 22. The test fish products after freezing are shown in Fig. 23. The fillet blocks showed the shortest freezing times, i.e., 205 minutes and 135 minutes for the 100 mm and 75 mm height tests, respectively, due to the more compact packing of fillets. For the 100 mm height test, the initial temperature of the fillet blocks was approximately  $0^{\circ}\text{C}$ . The shortest freezing times measured for the mackerel blocks were 325 minutes (100 mm height) and 178 minutes (75 mm height). For the herring blocks, the shortest freezing times were 380 minutes and 250 minutes for the 100 mm and 75 mm heights, respectively.

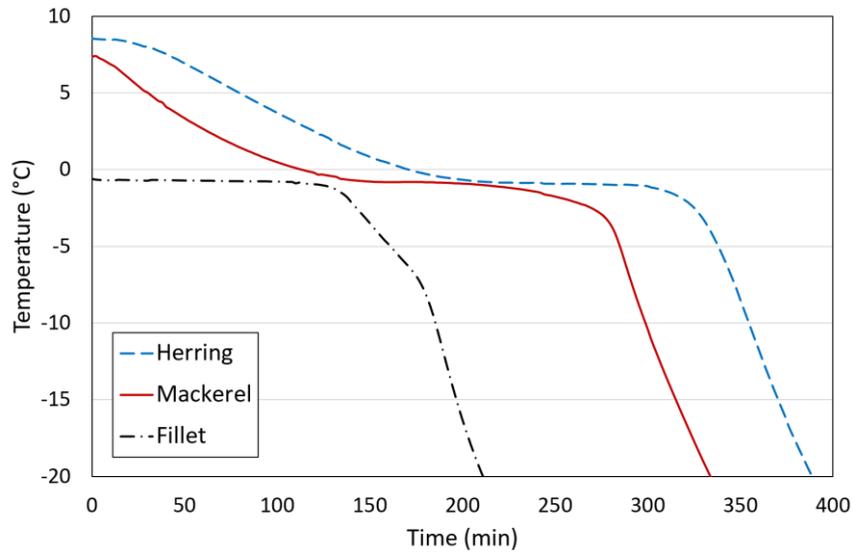


Figure 21. Evolution of the temperature at the centre of the test products for 100 mm product height

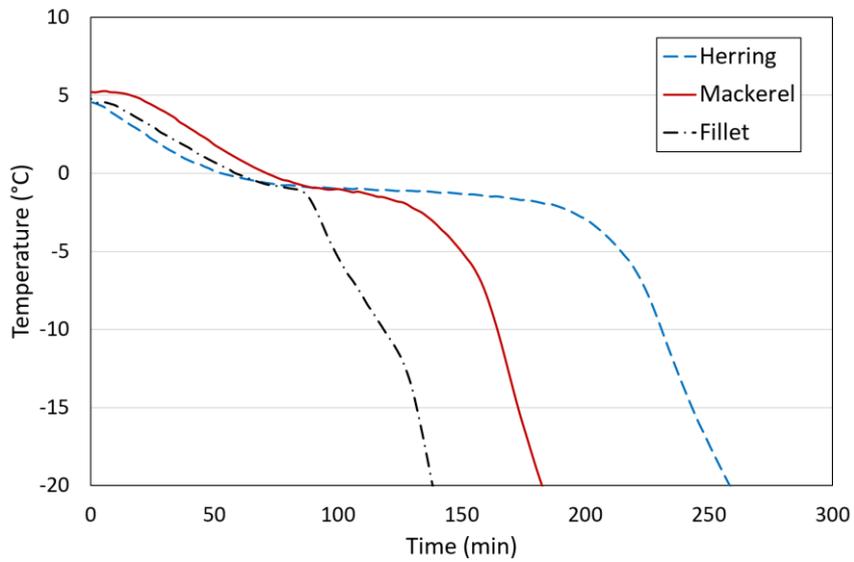


Figure 22. Evolution of the temperature at the centre of the test products for 75 mm product height



Figure 23. Test fish products of whole mackerel (left), herring fillets (centre), and whole herring (right) after freezing

### 7.3.1.3 Freezing time for salmon fillets and portions

Freezing times for salmon fillets and salmon portions were measured at an evaporation temperature of  $-40\text{ }^{\circ}\text{C}$ . The test products were vacuum-packed in plastic bags and placed in cardboard boxes with a height of 100 mm. Three blocks of salmon fillets and four blocks of salmon portions were loaded into Station 2. Two of the salmon fillet boxes were fully filled, each weighing approximately 17 kg, while one box was half-filled and weighed 8.8 kg. Each salmon portion block weighed 10 kg. All products were stored in a cooling room set to  $5\text{ }^{\circ}\text{C}$  prior to testing to ensure an initial temperature of approximately  $5\text{ }^{\circ}\text{C}$ . The target freezing temperature was  $-18\text{ }^{\circ}\text{C}$ . For each product block, four thermocouples were used: two inserted into the centre of the block, one positioned at the top, and one at the bottom.

The temperature development over time for the salmon products are illustrated in Fig. 24 and Fig. 25. The test fish products after freezing are shown in Fig. 26. The freezing times measured at the centre of the salmon fillet block were 389 and 397 minutes. In contrast, the temperatures measured at the top and bottom of the block dropped much more rapidly. Their corresponding freezing curves appeared more linear over time, without clearly distinguishable freezing phases. After 516 minutes of freezing, the centre temperature of the salmon portion block was measured at  $-16\text{ }^{\circ}\text{C}$ . The longer freezing time observed for the portion block was attributed to the loose packing of the portions inside the cardboard box. As shown in Fig. 26, the portions were arranged loosely, creating significant air gaps between them and thereby reducing thermal efficiency.

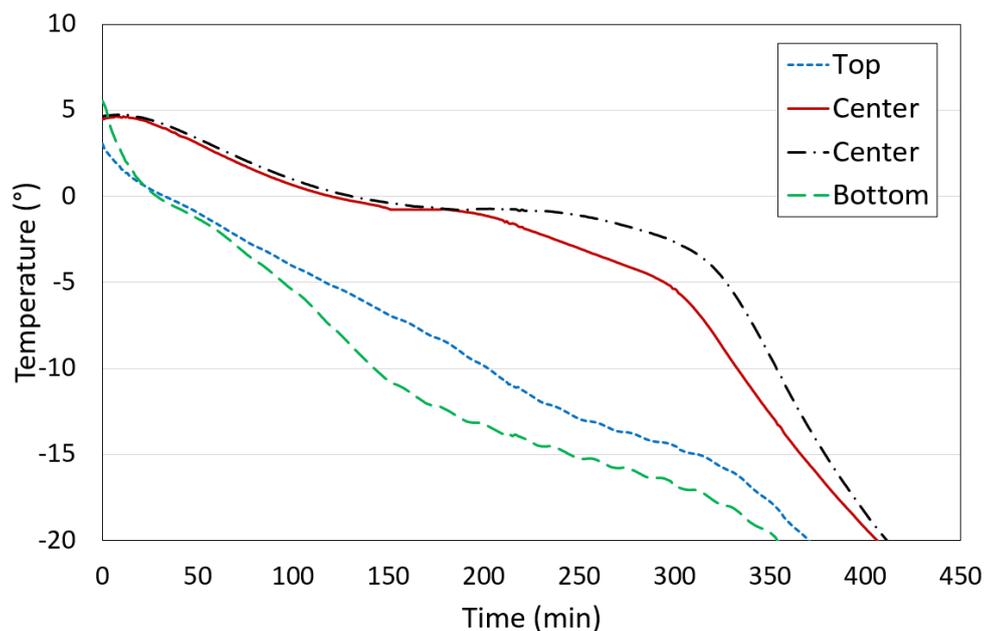


Figure 24. Evolution of the temperature at the different locations of the salmon fillet block

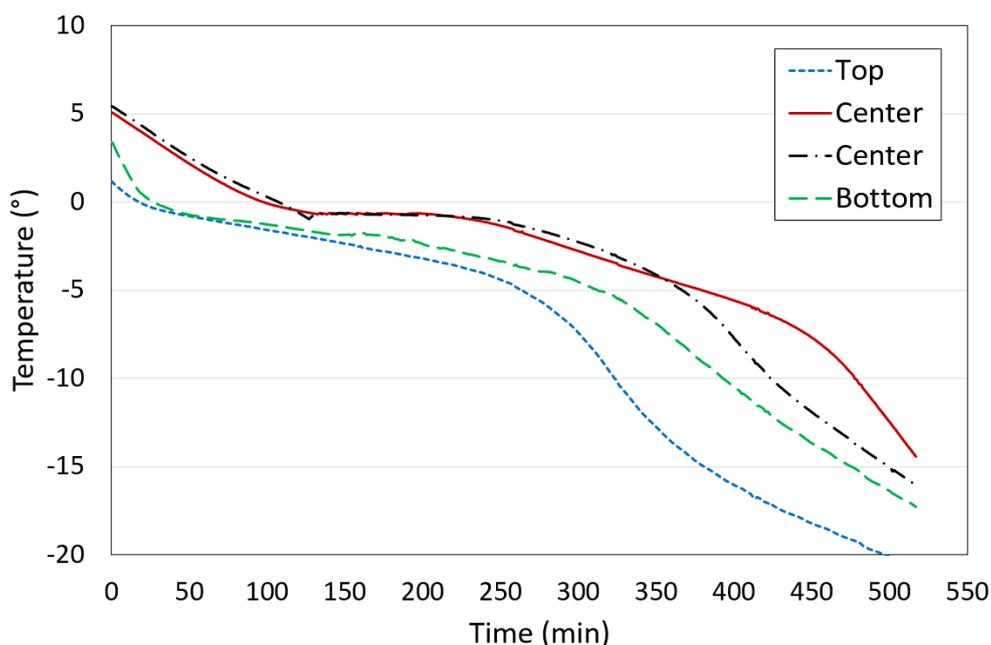


Figure 25. Evolution of the temperature at the different locations of the salmon portions block



Figure 26. Test salmon products in fillets (left) and portions (right) after freezing

#### 7.3.1.4 Freezing time for pseudo-fish tissue

Freezing times for pseudo-fish tissue blocks were measured at evaporation temperatures of  $-40\text{ }^{\circ}\text{C}$  and  $-48\text{ }^{\circ}\text{C}$ . The test products were packed with plastic film and placed in cardboard boxes with a height of 100 mm. Two blocks were evaluated at each evaporation temperature, with each block weighing approximately 22.3 kg. The products were stored at a room temperature of around  $22\text{ }^{\circ}\text{C}$  prior to testing. The target freezing temperature was  $-18\text{ }^{\circ}\text{C}$ . For each product block, four thermocouples were used: two inserted into the centre of the block, one positioned at the top, and one at the bottom.

The shortest freezing times measured for the pseudo-fish tissue blocks at each evaporation temperature are presented in Fig. 27. At the centre of the blocks, the freezing times were 384 minutes and 560 minutes for evaporation temperatures of  $-48\text{ }^{\circ}\text{C}$  and  $-40\text{ }^{\circ}\text{C}$ , respectively. These results indicate that lowering the evaporation temperature can significantly reduce the freezing time. It is also

noteworthy that in this test, the products were packaged in thick plastic film and placed in cardboard boxes, resulting in significantly higher thermal resistance compared to packaging with thin plastic bags and stainless-steel frames.

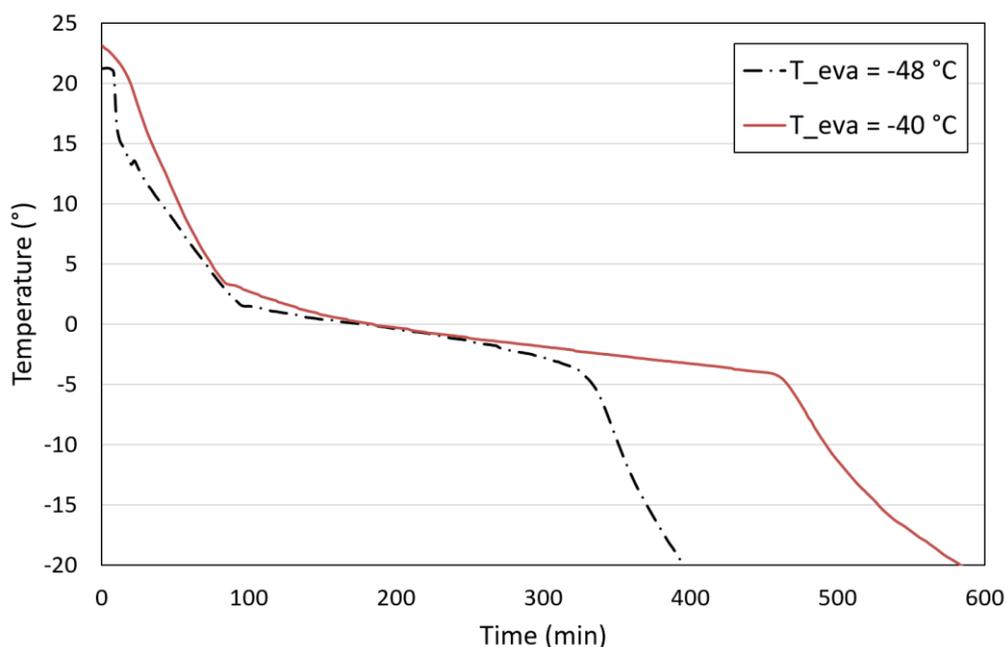


Figure 27. Evolution of the temperature at the centre of the pseudo-fish tissue block

### 7.3.1.5 Summary of the freezing time measured for different products

The freezing times measured for different types of products are summarized in Table 2, which presents the shortest freezing times recorded from each test. The results indicate that the position of the product blocks on the plate can influence freezing time due to slight variations in plate spacing caused by hydraulic pressure.

Table 2. Freezing time measured for different types of products

Product	$T_{eva}$ , °C	Start temp. °C	Target temp. °C	Product height (mm)	Freezing time (minutes)
Apple juice	-50	0	-18	133	284
Whole herring	-50	0	-18	100	222
Herring fillets	-50	0	-18	100	206
Whole mackerel	-50	5 – 10	-18	100	325
Whole herring	-50	5 – 10	-18	100	380
Herring fillets	-50	0 – 5	-18	100	205
Whole mackerel	-50	5 – 10	-18	75	178
Whole herring	-50	5 – 10	-18	75	250
Herring fillets	-50	5 – 10	-18	75	135
Salmon fillets	-40	5	-18	100	412
Salmon portions	-40	5	-16	100	540
Pseudo-fish tissue	-40	22	-18	100	560
Pseudo-fish tissue	-48	22	-18	100	384

Additionally, the packaging material and method—including the thickness and structure of the packaging layer—have a significant impact on freezing efficiency. Furthermore, the way products are packed inside the box or frame also plays a crucial role. Air gaps between individual items, such as whole fish, fillets, or portions, can reduce thermal contact and lower freezing efficiency.

### 7.3.2 Performance of the plate freezing system

The freezing load and energy consumption during the freezing of the apple juice blocks at an evaporation temperature of -50 °C, as described in Section 7.3.1.1, are presented in Fig. 28 and Fig. 29. The coefficient of performance (COP) obtained during this process is shown in Fig. 30. The freezing load was highest at the beginning of the process, when the temperature difference between the refrigerant and the product was greatest, resulting in rapid heat transfer from the product to the refrigerant. As this temperature difference decreased over time, the rate of heat transfer declined accordingly, leading to a gradual reduction in the freezing load throughout the process. The variation in energy consumption throughout the freezing process followed the same trend as the freezing load. The COP was calculated as the ratio of freezing load to energy consumption and ranged between 2.5 and 2.6 throughout the freezing process.

The cumulative COP (defined as):

$$\text{COP} = \frac{|\int \dot{Q} dt|}{\int \dot{W} dt}$$

over the entire freezing process was 2.51.

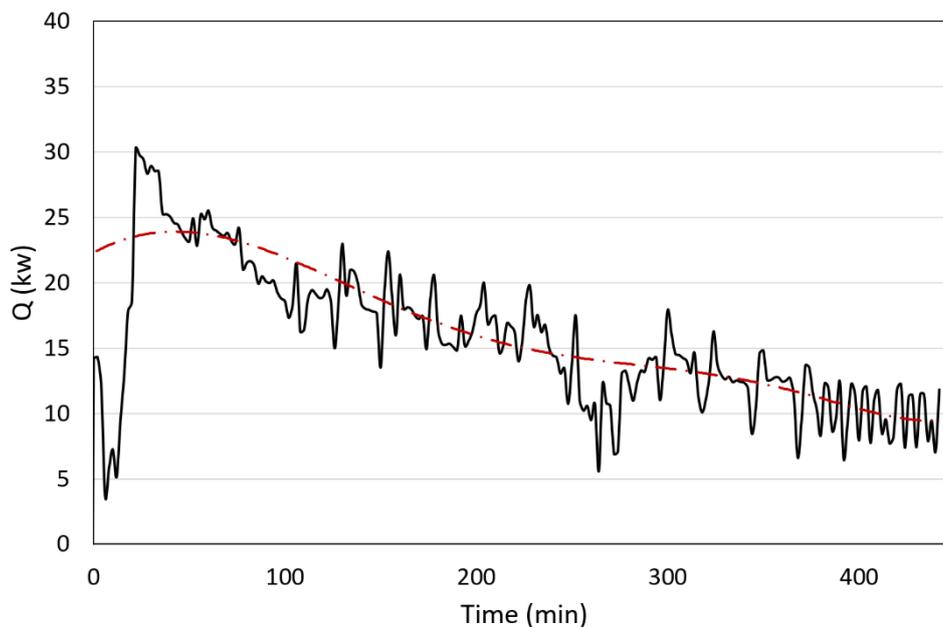
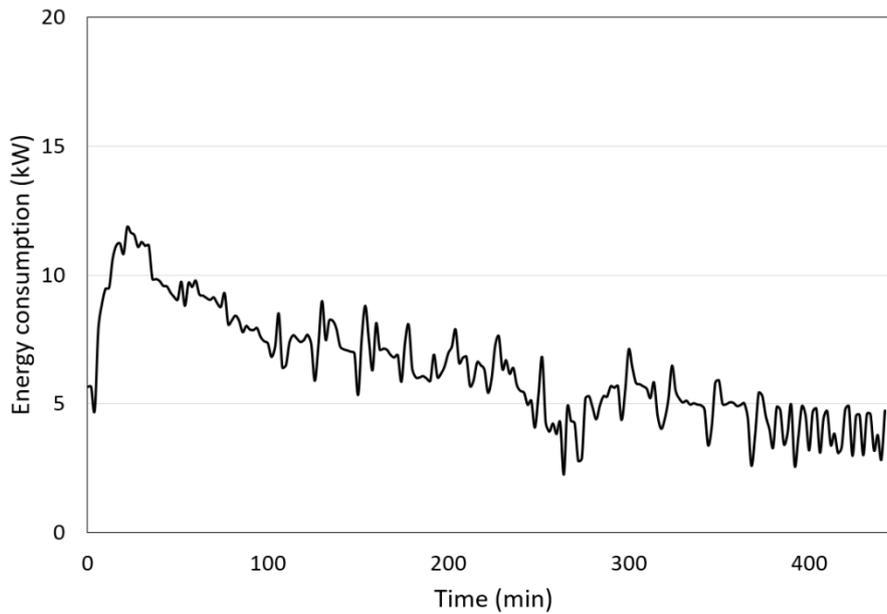
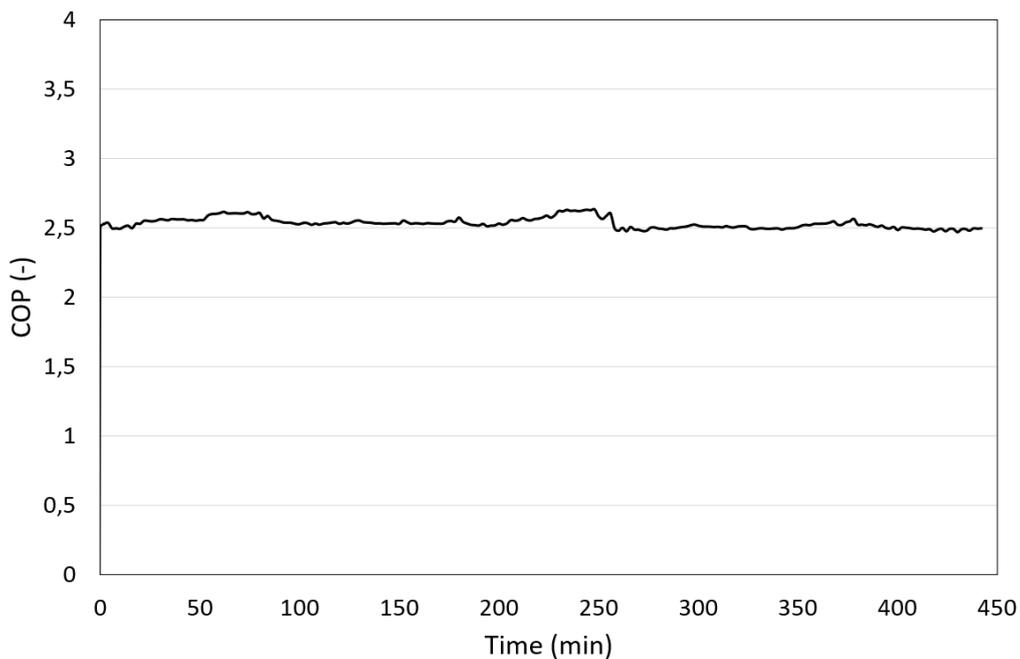


Figure 28. Evolution of the freezing load during freezing of apple juice blocks

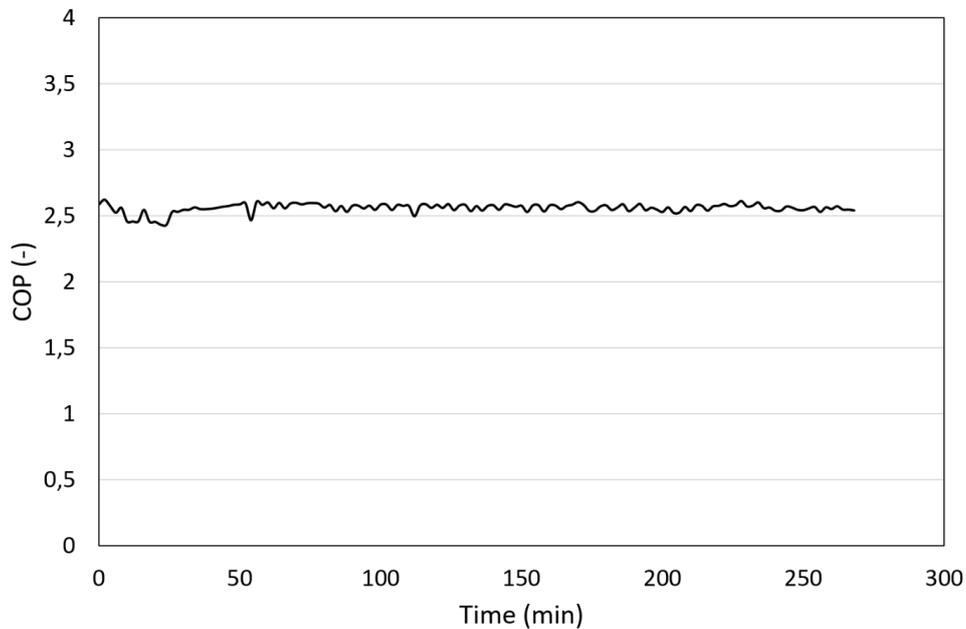


*Figure 29. Evolution of the energy consumption during freezing of apple juice blocks*



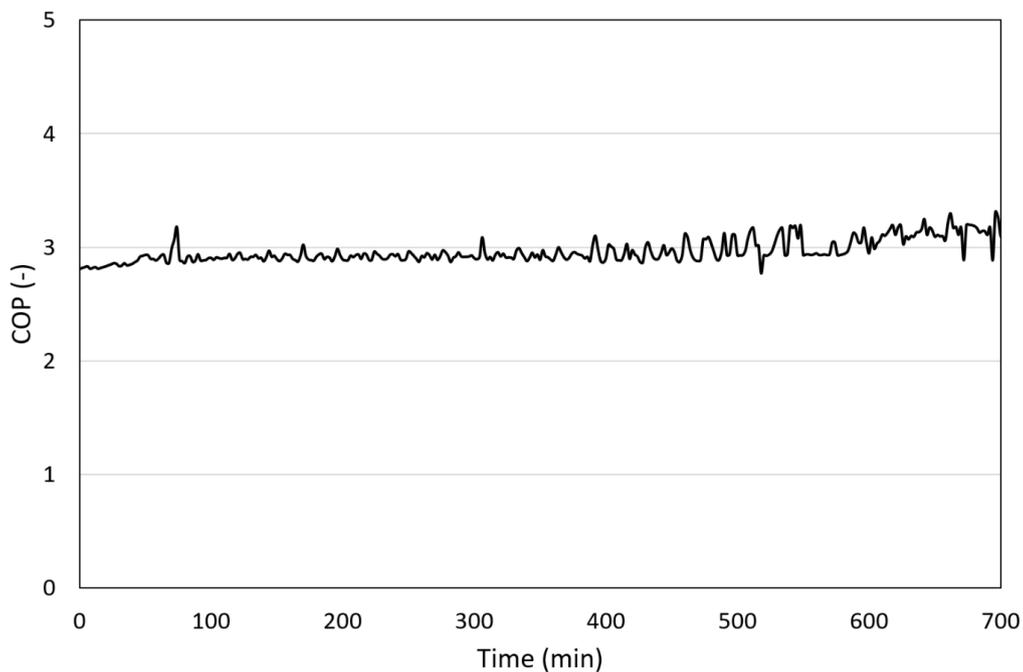
*Figure 30. Evolution of the COP during freezing of apple juice blocks*

The COP during the freezing of whole herring and herring fillets at an evaporation temperature of -50 °C, as described in Section 7.3.1.2, is presented in Fig. 31. The results were similar to those observed in the apple juice block test, with COP values ranging between 2.5 and 2.6 throughout the freezing process. The cumulative COP over the entire freezing process was 2.56.



*Figure 31. Evolution of the COP during freezing of herring blocks*

The COP during the freezing of pseudo-fish tissue blocks at an evaporation temperature of  $-40\text{ }^{\circ}\text{C}$ , as described in Section 7.3.1.5, is presented in Fig. 32. The COP ranged between 2.8 and 3.2 throughout the freezing process, slightly higher than the values observed in tests conducted at an evaporation temperature of  $-50\text{ }^{\circ}\text{C}$ . The cumulative COP over the entire freezing process was 2.86.



*Figure 32. Evolution of the COP during freezing of pseudo-fish tissue blocks*

### 7.3.2.1 Summary of the KPIs

The KPIs obtained from the different freezing tests are listed in Table 3. To investigate the GHG emissions of the plate freezing system, the CO<sub>2</sub> equivalent values for electricity were calculated based on the Norwegian (NO) and European (EU) cases, respectively. In the NO case, a CO<sub>2</sub> emission factor for electricity of 50 g CO<sub>2,eq.</sub> kWh<sup>-1</sup> is used according to the range presented by Clauß et al, 2019<sup>9</sup>). In the EU case, the CO<sub>2</sub> emission factor for electricity is 210 g CO<sub>2,eq.</sub> kWh<sup>-1</sup> on the basis of the EU energy consumption reported by the European Environment Agency (EEA, 2024<sup>10</sup>).

Freezing apple juice at an average evaporation temperature of -36 °C was used as the baseline case. The test setup was identical to that described in Section 7.3.1.1, except that a higher evaporation temperature was applied. As shown in Table 3, the shortest measured freezing time was 500 minutes, 1.76 times longer than the freezing time observed at an evaporation temperature of -50 °C. This finding is consistent with the numerical simulation results reported by Ren et al. (2024)<sup>7, 8</sup>. However, the COP was significantly higher at the elevated evaporation temperature, and as a result, the specific energy consumption was nearly the same as in the case with an evaporation temperature of -50 °C. This suggests that the improved system performance due to the higher evaporation temperature was offset by the longer freezing time.

The results published by Fernández-Seara (2012)<sup>11</sup> were used as another baseline case for comparison with the findings of the present study. In Fernández-Seara's work, a CO<sub>2</sub>-NH<sub>3</sub> cascade refrigeration system was employed to provide the necessary freezing capacity. CO<sub>2</sub> was used in the low-temperature cycle and supplied to the plate freezer. Water was used as the test product, with a total mass of 94 kg and a height of 95 mm. For the test conducted at an average evaporation temperature of -40 °C, the reported average COP was 1.34.

As shown in Table 3, the freezing time reported by Fernández-Seara (2012)<sup>11</sup> was significantly shorter than that observed in the present study, despite the use of a higher evaporation temperature. This discrepancy is because, in their study, water was directly filled into aluminium tins without any packaging, thus eliminating additional thermal resistance between the product and the freezing plates. However, real industrial applications of horizontal plate freezers typically involve freezing fish or meat products that are packed in plastic bags or cardboard boxes. Therefore, including packaging in the present measurements provides a more realistic representation of actual industrial conditions. As such, the results obtained with packaging are more relevant and useful for end users in the fish processing industry.

The COP values obtained in the present study were higher than those reported by Fernández-Seara (2012)<sup>11</sup>. The demonstrated CO<sub>2</sub> plate freezing system proved to be an energy-efficient solution, leading to significantly lower specific energy consumption and greenhouse gas (GHG) emissions. Using the demonstrated CO<sub>2</sub> plate freezing system, the specific energy consumption can be reduced up to 44% and 59% for evaporation temperatures of -40 °C and -50 °C, respectively.

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<sup>9</sup> Clauß, J., Stinner, S., Solli, C., Lindberg, K.B., Madsen, H., Georges, L. (2019). Evaluation method for the hourly average CO<sub>2,eq.</sub> intensity of the electricity mix and its application to the demand response of residential heating. *Energies*, 12 (7), 1345.

<sup>10</sup> EEA (2024). European Environment Agency: Greenhouse gas emissions intensity of electricity generation in Europe. [www.eea.europa.eu/en/analysis/maps-and-charts/co2-emission-intensity-15](http://www.eea.europa.eu/en/analysis/maps-and-charts/co2-emission-intensity-15).

<sup>11</sup> Fernandes-Seara, J., Dopazo, J.A., Uhia, F.J., Diz, R. (2012). Experimental analysis of the freezing process in a horizontal plate freezer with CO<sub>2</sub> as refrigerant in a cascade refrigeration system. *Heat transfer engineering*, 33(14), 1170-1176.

Table 3. Summary of the KPIs

Test product	T <sub>eva</sub> (°C)	Product height (mm)	Start temp. (°C)	KPIs				
				Freezing time (min)	COP	Specific energy consumption (kWh/kg)	GHG emission (g CO <sub>2,eq</sub> kWh <sup>-1</sup> kg <sup>-1</sup> )	
							NO <sub>el</sub>	EU <sub>el</sub>
Apple juice	-50	133	0	284 min	2.51	0.0644	3.22	13.53
Herring	-50	100	0	206 (Fillets) 222 (whole)	2.56	0.0767	3.83	16.10
Pseudo-fish tissue	-40	100	22	560	2.86	0.0915	4.57	19.21
Apple juice (Baseline)	-36	133	2	500	3.50	0.0649	3.24	13.62
Water (Fernández-Seara, 2012)	-40	95	14	100	1.34	0.1640	8.2	34.44

## 7.4 Impacts

The CO<sub>2</sub> plate freezer demonstrator implements a horizontal plate freezer capable of achieving a freezing temperature of -50 °C. Natural refrigerant CO<sub>2</sub> is utilized for cooling the fish product. It is environmentally friendly, has zero ozone depletion potential (ODP) and negligible global warming potential (GWP), and is non-toxic and non-explosive. These characteristics can contribute to the overall sustainability of fish processing operations.

As presented in Section 7.3, the demonstrated CO<sub>2</sub> plate freezing system proved to be an energy-efficient solution for both onshore and on-board fish freezing applications. A coefficient of performance (COP) of 2.56 was achieved at an evaporation temperature of -50 °C, 2.86 at -40 °C, and 3.5 at -36 °C. By decreasing the evaporation temperature from -36 °C to -50 °C, the freezing time was reduced by 43.2%.

The system exhibited significantly lower specific energy consumption compared to the baseline case operating at -40 °C using a CO<sub>2</sub>-NH<sub>3</sub> cascade system. Notably, it achieved up to a 59% reduction in energy consumption (kWh/kg) at -50 °C compared to the baseline case. Additionally, the reduced energy demand contributes to a significant decrease in greenhouse gas (GHG) emissions, supporting more sustainable fish processing operations. Implementing such an efficient freezing method not only enhances energy performance but also substantially extends product shelf life, thereby helping to reduce food loss and waste.

Two peer-reviewed conference papers have been published, and the technology was presented at several academic and industrial workshops.

## 7.5 Business potential

The demonstrated CO<sub>2</sub> plate freezer is well-suited for application in food processing facilities that focus on freezing large volumes of fish, meat, and other perishable products. Retail chains and wholesale distributors that require high-quality frozen goods with extended shelf life also represent significant potential customers.

In addition, industrial processors aiming to enhance the sustainability of their operations, particularly those transitioning away from synthetic refrigerants or ammonia (NH<sub>3</sub>), are likely to adopt this technology. The meat and fish processing industries, where freezing quality directly influences product value and marketability, are expected to be early adopters.

The potential revenue streams for the demonstrated CO<sub>2</sub> plate freezer technology include direct sales of freezer units to food processing plants and wholesale distributors, with an estimated annual market revenue of €190 million in Europe. Additional income can be generated through service and maintenance contracts, providing ongoing support for installed systems. Licensing the CO<sub>2</sub> refrigeration technology to other manufacturers offers another revenue opportunity, while consultation and training services, focused on system operation and energy optimisation, can further support adoption and generate value-added income.

# CONCLUSIONS

## 8 IMPACT

The ENOUGH project addresses integrated solutions to transform the food chain to become climate neutral through technological innovation and adapted process and chain management. This final report presents the outcomes of the ENOUGH project's demonstrator activities focused on the **fish sector**. The overarching aim was to reduce greenhouse gas (GHG) emissions and improve energy efficiency in food processing, reducing freezing time, all while keeping the product quality unaffected or better than alternative systems and methods.

There was demonstrated three innovative technological solutions designed to optimise freezing processes in fish processing, including **brine freezing, blast freezing, and plate freezing**. Each was assessed for its potential to reduce specific energy consumption and GHG emissions, using key performance indicators (KPIs) such as freezing time and specific energy use. The demonstrators also underscored the importance of transitioning to natural refrigerants and integrating energy-efficient technologies across the cold chain. By promoting technology transfer and providing validated, scalable solutions, the project contributes to a more climate-resilient and sustainable seafood industry.

It was achieved up to a 14 and 15% reduction in energy use for two of the freezers, and 59% for the third. The GHG emissions reduction depends on each country's electricity-mix. Reduction of freezing time makes the process more efficient and indirectly reduces the overall energy use for the production.

For the blast- and plate-freezers, design layouts for integrated vapour compression systems were developed and validated through prototype testing. The results highlighted several areas for improvement, including system dimensioning, defrosting cycle optimisation, and enhanced regulation of components to ensure more consistent energy use. These environmentally friendly refrigeration systems are suited for hotter climates.

The demonstrated freezing technologies will create most impact beyond the project horizon as they are designed to be rolled out across the food system, benchmarked against roadmaps towards 2050. Stakeholders will become by widespread communication more objectively informed allowing to bring viable solutions quicker and more widely to realisation. To maximise the impact of the demonstrators, a comprehensive dissemination and communication strategy has been implemented targeting key stakeholders across the fish processing industry. The freezing technologies are not only suited for fish, but for other food industry as well.

## 9 DISSEMINATION AND COMMUNICATION

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Demonstration of innovative solutions that are close to industrial application is key to convince all stakeholders that significant reduction of GHG emissions can be achieved without negatively impacting food security, food quality and industrial competitiveness. All three demonstration activities were performed in cooperation with relevant stakeholders like suppliers of freezing and processing industries and end-users of the technologies. For the industry to be able to see a technology working is extremely impactful and provides not only real information on how a technology is applied and used, but also reassurance that the technology is reliable and user friendly.

The aim was to provide independent assessment of the performance of the demonstrators and to not only feedback results to industry but to provide them with information on the technical issues during application and use.

Several peer-reviewed conference papers have been published, and the technologies were presented at several academic and industrial workshops.

List of technical and scientific papers:

Ahsan, M.M., Rossetti, A., Minetto, S., Fabris, F., Girotto, S., 2023. *Demonstrating Technologies Towards A Carbon Neutral Food Business Within the Enough Project. The Blast Freezing Case Study*. 20<sup>th</sup> European Conference RACHP, Milan 8-9 June.

Svendsen, E.S., Indergård, E., Bengsch, J., Widell, K.N., Köster, L., Nordtvedt, T.S. (2024). Improving energy efficiency in seafood freezing with brine technology, *IIR 8th International conference on Sustainability and the cold chain*, Tokyo, Japan. DOI: 10.18462/iir.iccc2024.1029

Ren, S., Hafner, A., Rekstad, I.H., Widell, K.N., Svendsen, E.S., Nordtvedt, T.S. (2024). Design of a CO<sub>2</sub> plate freezer test facility with -50 °C evaporation temperature, *11th IIR Conference on Compressors and Refrigerants*, DOI: 10.18462/iir.compr.2024.0640

Ren, S., Hafner, A., Rekstad, I.H., Widell, K.N., Svendsen, E.S., Nordtvedt, T.S. (2024). Design and freezing performance study of a CO<sub>2</sub> plate freezer at -50 °C evaporation temperature, *16th IIR Gustav Lorentzen Conference on Natural Refrigerants - GL2024: Proceedings. International Institute of Refrigeration*, DOI: 10.18462/iir.gl2024.1198

## 10 FUTURE OUTLOOK

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A more energy-efficient and low-carbon fish processing industry is increasingly shaped by technological innovation, policy support, and heightened environmental awareness. Future advancements will focus on integrating high-efficiency systems and methods developed to a wide range of frozen products, and renewable energy technologies to reduce reliance on fossil fuels.

Advancements in cold chain technologies will provide more precise temperature control and improved energy efficiency, especially in refrigeration and freezing, which are among the largest energy consumers in the sector.

The demonstrated technologies will be showcased to a wider range of potential end users with efforts made to increase their Technology Readiness Level (TRL) through validation in real industrial environments. Outreach to stakeholders, policymakers, and industry decision-makers will help promote broader adoption. Ongoing development will aim to further enhance performance and environmental impact, solidifying these solutions' roles in the fish processing sector. Strengthening collaboration among industry players, technology developers, and policymakers will be essential to scale up pilot successes and accelerate the implementation of best practices. The future of fish freezing processing lies in its transition to smart, sustainable, and resilient systems that not only reduce energy use and emissions but also improve product quality and overall operational efficiency.