PROJECT ACRONYM	ENOUGH
PROJECT TITLE	European Food Chain Supply to reduce GHG emission by 2050
PROJECT COORDINATOR	SINTEF OCEAN
PROJECT DURATION	2021-2025

D6.6:

Report on Meat demonstrators

PROJECT NO: 101036588

TYPE OF ACTION: IA (INNOVATION ACTION)

CALL: H2020-LC-GD-2020-4

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588

DOCUMENT INFORMATION

DELIVERABLE NO.	D6.6 Report on Meat Demonstrators
DISSEMINATION LEVEL	Public
WORK PACKAGE	6 Demonstrators
TASK	6.1 Meat demonstrators
LEAD BENEFICIARY	NTNU
CONTRIBUTING BENEFICIARY(IES)	INRAE, ARCELIK, SO
DUE DATE OF DELIVERABLE	31.07.2025
ACTUAL SUBMISSION DATE	08.08.2025

DOCUMENT HISTORY

Version	DATE	CHANGE HISTORY	AUTHOR	BENEFICIARY
1	30.07.2025		Shuai Ren, Graciela Alvarez, Hong Minh Hoang, Cihan Kaan Coskun	NTNU, INRAE, ARCELIK

QUALITY ASSURANCE, STATUS OF DELIVERABLE		
ACTION	PERFORMED BY	DATE
Reviewed	Judith Evans, Erlend Indergard	30.07.2025
Approved	Silvia Minetto	30.07.2025
Uploaded to SyGMa	Kristina N. Widell	08.08.2025

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OVERVIEW ON TASK 6.1

1 GENERAL SUMMARY

Within this task, innovative solutions aimed at improving overall sustainability(particularly through reducing greenhouse gas (GHG) emissions) in meat processing were investigated. Two demonstration activities were carried out: Demo 14 — 150 °C Absorption Compression Heat Pump (ACHP)for steam production, and Demo 17 — Superchilling.

Demo 14 – 150 °C ACHP for Steam Production focuses on utilizing an absorption-compression high-temperature heat pump (ACHP) to generate hot water and steam for meat processing. The system enables surplus heat recovery, replaces fossil fuel boilers, and significantly reduces energy consumption and GHG emissions. This demonstrator is led by NTNU, with SINTEF Ocean as a project partner.

Demo 17 – Superchilling investigates a promising method to reduce food waste and its environmental impact by extending product shelf life. By maintaining meat products just below their freezing point in a carefully controlled compartment at -2°C ± 0.2°C within a domestic refrigerator, superchilling offers a significant improvement in shelf life over traditional refrigeration. This demonstrator is led by INRAE, with ARÇELİK and LSBU as partners.

Within the ENOUGH project, demonstration facilities were established, and the technologies were validated and improved through experimental testing, numerical simulations, and an industrial case study. Key performance indicators (KPIs) were defined and assessed for each demonstrator. The technologies have been showcased to potential end users through industry and academic workshops, conferences, scientific publications, and social media.

2 RECOMMENDATIONS

The two demonstrators within this task offer sustainable solutions for hot water and steam production for meat processing as well as meat chilling and storage in domestic storage. Both demonstrated technologies have strong potential to reduce the environmental footprint of the food sector and contribute meaningfully to clim ate change mitigation. The innovative and advanced technology demonstrators reached a TRL of 7–8 by the final stage of the project, exhibiting competitive performance in energy efficiency and GHG emission reduction compared to baseline scenarios. This demonstrates their effectiveness in lowering the environmental impact across the food supply chain.

The technologies demonstrate strong potential for wide application. The objective was to take established technologies that have not yet seen widespread use, test and showcase them in real setting, and provide concrete, quantified evidence of their financial returns and benefits in terms of low-emission solutions that are currently available or close to market readiness.

Demo 14 – 150 °C ACHP for steam production

- Industrial recommendations – The absorption-compression heat pump is especially appropriate for food industry processes that depend on hot water and steam, such as sterilization, drying, cooking, and cleaning. Key target markets include companies involved in meat and fish processing, as well as dairies. Beyond the food sector, the technology could also be applied in industries requiring high-temperature heating, such as chemical production and pharmaceutical manufacturing.

- Academic recommendations – The demonstrator utilizes oil-free compression technology, which contributes to enhancing the supply temperature achievable by the ACHP. This feature presents a compelling research topic for the academic community, particularly in the context of developing high-efficiency, high-temperature heat pump systems.
- Society recommendations – The demonstrator contributes to the phase-out of fossil fuels and supports society by enabling cleaner, more efficient industrial heating, reducing greenhouse gas emissions, and enhancing both food safety and energy efficiency.
- Policy makers recommendations – EU policymakers can introduce financial incentives and subsidies for adopting this technology in the food industry and support research, development, and demonstration (RD&D) programs for further improvement of the technology.

Demo 17 — Superchilling

- Industrial recommendations – Superchilling stands out as a promising alternative to conventional freezing systems, particularly in large-scale food storage and distribution systems. Besides household users who prioritize sustainable living and reducing food waste, as well as for environmentally conscious consumers seeking innovative kitchen technologies., it is relevant also for the other chain links.
- Academic recommendations – Superchilling represents a sustainable, cost-effective, and quality-preserving method for red meat storage. Investigating how food quality evolves during and after superchilling storage, as well as under varying superchilling conditions, is a highly relevant and valuable research area for advancing energy-efficient freezing technologies. Additionally, the ability to precisely control temperatures within the superchilling compartment—ensuring accurate maintenance of target conditions through advanced cooling system algorithms—opens up further research opportunities in the development of optimized control strategies for refrigeration systems.
- Society recommendations – Superchilling technology can help society by reducing food waste, extending shelf life, and improving food safety, all while using less energy than conventional freezing methods. For consumers, it supports more sustainable living by preserving food longer and minimizing spoilage.
- Policy makers recommendations – EU policymakers can support the adoption of superchilling technology in food processing by providing targeted funding and incentives, supporting R&D to optimize performance and safety, and promoting its use through green public procurement and industry training programs.

3 DESCRIPTION OF THE SECTOR

Between 2020 and 2023, the average per capita meat consumption in the European Union (EU-27) was 67 kilograms[1], though this figure varies across member states. Countries such as Cyprus, Ireland, Portugal, and Spain report higher per capita consumption, while Germany's consumption is notably lower. In 2025, it is projected to reach 66.6 kilograms. Looking ahead, meat consumption per capita in the EU is expected to decline slightly by 1.2% over the next decade, reaching an estimated 65.4

[1] Shahbandeh, M. (2024). Per capita consumption of meat in the European Union 2020-2035. Statista.

kilograms by 2035[1]. High levels of meat consumption directly drive energy demand in both the production and processing stages.

In the UK, meat processing, including chilled, frozen, canned, sausages, and minced meat, as well as cooked poultry, accounted for approximately 7% of the total energy consumption and 8% of the greenhouse gas emissions within the entire food processing sector in 2019[2]. Emissions in the meat processing industry vary depending on processing techniques and the type of meat species handled. Moreover, strict hygiene regulations necessitate considerable energy input for cleaning and sanitation. The shift toward more complex and processed products—such as frozen or portioned meat—also contributes to higher energy consumption. Colley[3] identified that 59% of the energy in meat processing plants was associated with steam, 33% with electricity and 8% with hot water. Energy associated with different processes does vary quite considerably though.

Steam and hot water generation play a crucial role in both production and hygiene in meat processing. Steam is widely used for cooking products like sausages, hams, and ready-to-eat meals, providing uniform heat to ensure product quality and safety. It is also essential for sanitizing equipment and processing areas, pasteurizing meat, and sterilizing casings and packaging materials. However, steam and hot water production—particularly when reliant on fossil fuels—is highly energy-intensive and significantly contributes to the sector's carbon footprint.

Cooling and freezing are equally vital in meat processing, serving to maintain product integrity, extend shelf life, and uphold food safety standards. These processes are among the largest consumers of electricity in meat processing facilities, significantly influencing both operational costs and environmental sustainability.

Although the EU continues to advance its energy efficiency targets and expand the use of renewable energy sources, further improvements in energy efficiency within meat processing facilities remain essential. The ENOUGH project aims to address these challenges by offering practical solutions to reduce energy use and lower the carbon footprint of meat processing. Innovative technologies such as absorption-compression high-temperature heat pumps present a viable alternative to fossil-fuel boilers by enabling surplus heat recovery and delivering efficient, low-emission steam generation. Additionally, superchilling preserves food quality and extends shelf life by operating at higher temperatures than conventional freezing. This approach not only maintains product safety and freshness compared to regular food preservation above freezing points but also promotes more sustainable food preservation practices, contributing to global climate objectives.

4 DESCRIPTION OF THE TECHNICAL SOLUTIONS

Demo 14 — the absorption-compression heat pump uses an ammonia-water mixture as the working fluid and integrates both absorption and vapor compression heat pump technologies. It is capable of providing both heating and cooling, achieving heat sink temperatures of up to 150 °C. This technology

[2] ENOUGH (2024). D1.2 A report on energy and emissions of food chain for case study countries for 1990 and 2019.

[3] Colley, T. (2012). Heat Integration and Renewable Energy in Meat Processing Plants - a strategy for minimising the impact of a carbon price.

presents a promising solution for generating steam and hot water in meat and fish processing, as well as in dairy operations. The details of the demonstrator are described in **Section 5.1**.

Demo 17 — superchilling technology utilizes a precisely controlled compartment within a domestic refrigerator, maintained at -2 °C ± 0.2 °C, to lower the temperature of meat by 1–2 °C below its initial freezing point. This process significantly extends the product's shelf life while preserving quality. The details of the demonstrator are described in **Section 6.1**.

4.1 Definition of KPIs and benchmarks

The KPIs and benchmarks for each demonstrator in Task 6.1 were defined and are presented in

Table 1 and Table 4, respectively.

PRESENTATION OF DEMONSTRATORS

5 DEMO 14 – 150°C ACHP FOR STEAM PRODUCTION

5.1 Description

Steam (water vapor) is a naturally benign fluid and an important heat carrier with high specific energy and stable heat exchange by latent heat. Process steam and hot water are widely used in food processing for various purposes such as sterilization, drying, cooking, and cleaning. Currently, process steam is mainly produced by fossil fuel boilers, accounting for 57% of the food sector's primary fuel use[4]. At the same time, there is a large amount of unutilized low and medium-grade waste heat available from cooling processes. To achieve climate neutrality in the food sector and GHG emissions, there is an urgent need to minimize the energy consumption by improving energy efficiencies and phase out fossil fuel by renewable energies or eco-friendly steam generation technologies.

High-temperature heat pumps (HTHPs) using natural refrigerants as a working fluid are a promising solution for steam boiler replacement, which can recover low-grade waste heat and supply heat at more than 100 °C and up to 150 °C. These systems have gained particular interest in recent years due to their low global warming potential (GWP) and well-known environmental impacts[5]. The major limitations of employing HTHPs for high-temperature heat supply are the critical point of the refrigerants applied and the compressor operating constraints at high temperatures and pressures[6].

The ACHP cycle combines the technologies of an absorption and vapour compression heat pump with a mixture of ammonia and water as the natural working fluid. An outline sketch of the ACHP steam generation system is illustrated in Figure 1. The ACHP was designed based on the Osenbrück cycle [7] as a vapor compression cycle with an additional liquid circuit. Heat is extracted and released at non-constant temperature glides, and the necessary compression ratio is lower compared to conventional vapour compression heat pumps. The ACHP can combine both cooling and heating processes and achieve high heat sink temperatures of up to 150 °C, which is suitable for replacement of fossil fuel boilers. Compared with applying gas boilers, ACHPs are more economical[8]. Using an oil-free twin-screw compressor with liquid injection, the compressor discharge temperature can be decreased[9], which can ensure the safe operation of the ACHP with a high heat supply temperature.

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[4] Batouta, K. I., Aouhassi, S., & Mansouri, K. (2024). Sustainable energy transition: A steam system optimization case study from a Moroccan food industry. Results in Engineering, 24, 102944.

[5] Mateu-Royo, C., Arpagaus, C., Mota-Babiloni, A., Navarro-Esbrí, J., & Bertsch, S. S. (2021). Advanced high temperature heat pump configurations using low GWP refrigerants for industrial waste heat recovery: A comprehensive study. Energy Conversion and Management, 229, 113752.

[6] Ommen, T., Jensen, J. K., Markussen, W. B., Reinholdt, L., & Elmegaard, B. (2015). Technical and economic working domains of industrial heat pumps: Part 1–Single stage vapour compression heat pumps. International Journal of Refrigeration, 55, 168-182.

[7] Osenbrück, A. (1895). Verfahren zur kälteerzeugung bei absorptionsmaschinen. Deutsches Patent, 84084.

[8] Jensen, J. K., Ommen, T., Markussen, W. B., Reinholdt, L., & Elmegaard, B. (2015). Technical and economic working domains of industrial heat pumps: Part 2–Ammonia-water hybrid absorption-compression heat pumps. International Journal of Refrigeration, 55, 183-200.

[9] Ahrens, M. U., Tolstorebrov, I., Tønsberg, E. K., Hafner, A., Wang, R., & Eikevik, T. M. (2023). Numerical investigation of an oil-free liquid-injected screw compressor with ammonia-water as refrigerant for high temperature heat pump applications. Applied Thermal Engineering, 219, 119425.

The 150 °C ACHP for steam production at NTNU is shown in Figure 2. The system provides a flexible experimental system for the investigation and optimization of the operating parameters, conditions and components for the ACHP applications in different food processes. The TRL level of the demo at the starting point was TRL 5. The final TRL level is TRL 7, with system prototype demonstration in an operational environment.

The demonstrator serves as a starting point for further demonstration by combining theoretical approaches, possible solutions, and experimental results. The system was designed for a maximum heat capacity of 200 kW with a maximum operating pressure of 40 bar and an operational temperature ranging from -10 °C to 190 °C [10]. The test facility consists of an absorption-compression heat pump system and an auxiliary system which provides the required heat source and heat sink water circuits. A twin-screw compressor is used in the system and is equipped with multiple injection ports. This approach enables oil-free operation while effectively managing excessively high discharge temperatures[11].

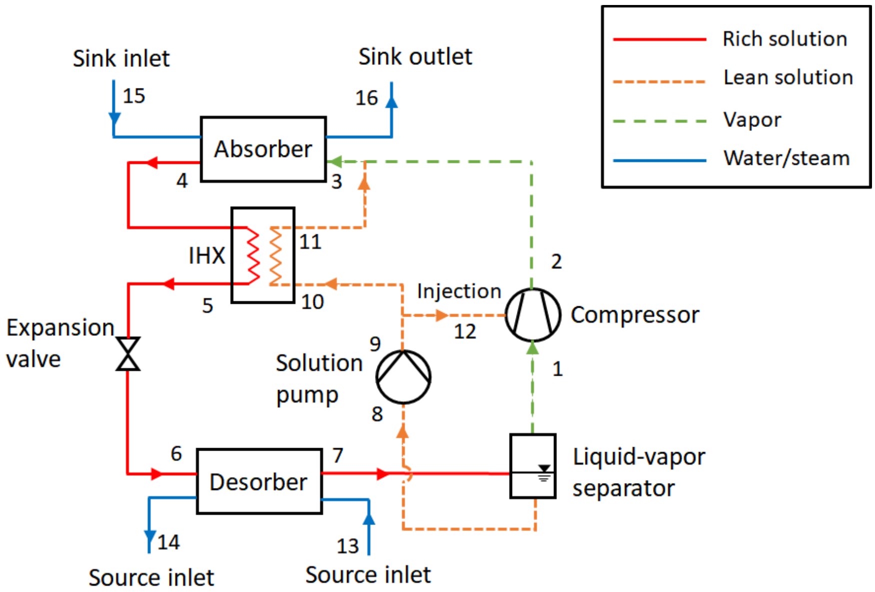


Figure 1 A principle sketch of the ACHP cycle

[10] Ren, S., Ahrens, M. U., Hamid, K., Tolstorebrov, I., Hafner, A., Eikevik, T. M., & Widell, K. M. N. (2023). Numerical investigation of an ammonia-water absorption-compression high-temperature heat pump for hot water and steam production in food processing. In Proceedings of the 26th IIR International Congress of Refrigeration: Paris, France, August 21-25, 2023-volume 4. International Institute of Refrigeration.

[11] Hamid, K., Ren, S., Tolstorebrov, I., Hafner, A., Wang, C. C., Sajjad, U., & Eikevik, T. M. (2025). Development and experimental assessment of oil free combine absorption-compression heat pump with NH_3/H_2O mixture working fluid. Applied Energy, 383, 125352.

Figure 2 The ACHP prototype in the NTNU lab

There are four different implementation approaches of the ACHP for steam production, as shown in Figure 3. The first approach (Approach A) is direct evaporation. Liquid water is first pressurized to the target steam pressure by a pump, then directly evaporated in the absorber of the ACHP. The second approach (Approach B) is low-pressure evaporation with Mechanical Vapor Recompression (MVR). The third approach (Approach C) is flashing hot pressurized water with MVR. The feeding water is first pressurized by a pump to a higher pressure and then heated up in the absorber of the ACHP. The generated hot pressurized water is throttled and partially evaporated in a flash tank at a low pressure. Then the low-pressure steam is compressed by MVR to the target pressure. The fourth approach (Approach D) is using the ACHP for sensible heating and a pentane vapor compression heat pump (VCHP) for latent heating.

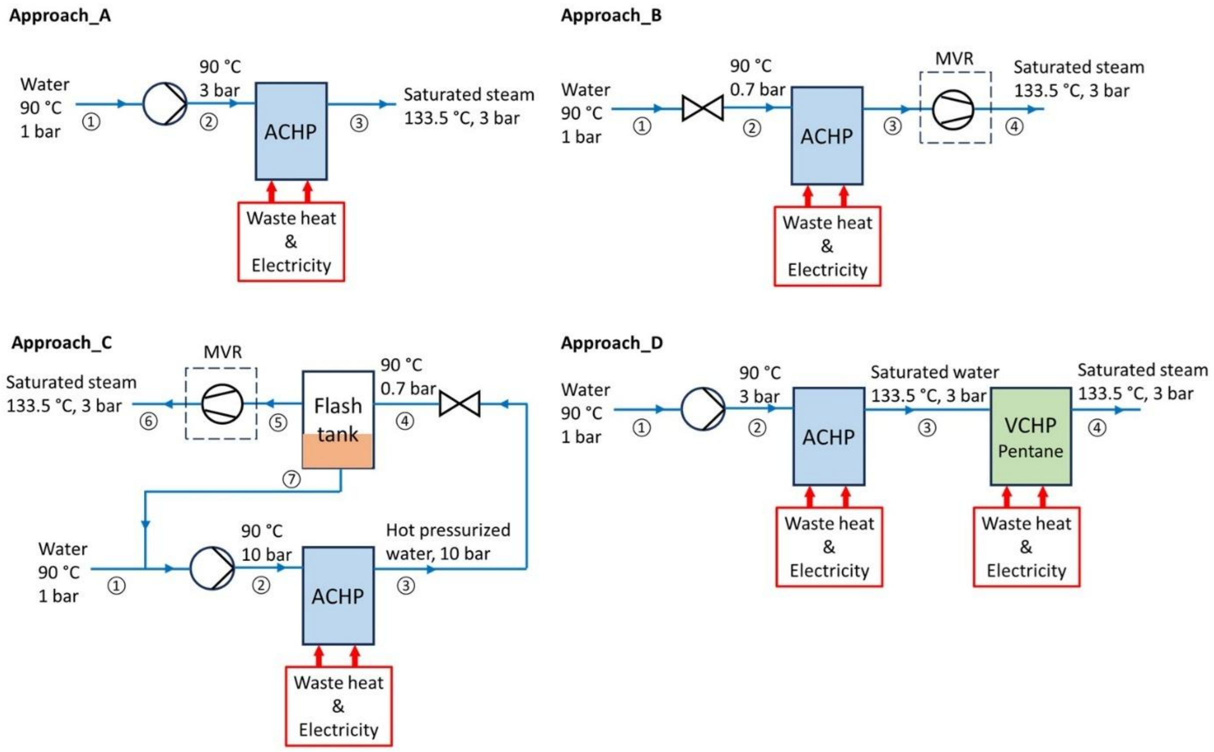


Figure 3 Schematics of different steam generation approaches using the ACHP

5.2 Application methodology and assessment

At the start of the project, an ACHP had been identified as a demonstrator. A comprehensive research plan was established. To support this, a flexible ammonia-water ACHP experimental system was designed for the investigation and optimization of the operating parameters, conditions and components for various food processing applications. Following the initial phase of system commissioning and experimentation, several modifications were implemented based on the practical performance of the test rig. The injection line was redesigned to enhance injection into the discharge-side rotors, and the compressor discharge line was modified to improve compressor efficiency. Additionally, a supplementary cold-water loop was installed upstream of the solution pump to stabilize the lean solution mass flow.

After more experimental tests were conducted, some additional modifications were implemented to enhance system performance. First, to prevent shaft seal failure at high compressor rotational speeds, a new shaft seal made of a more robust material was installed, capable of withstanding long-time operation at high temperatures. Second, to stabilize the HTHP system, the auxiliary system was modified to ensure a consistent supply of source and sink water at stable temperatures. Third, to avoid the fluctuation of the lean solution mass flow rate, the discharge pressure of the solution pump was controlled to be higher than the compressor discharge pressure by a valve downstream of the pump.

Following these modifications, additional experimental tests were carried out to obtain steady-state data for evaluating the performance of the HTHP system and its heat exchangers, in accordance with the operating procedures[11].

In parallel with the experimental work, a numerical investigation was carried out. A dynamic model of the ACHP was developed using Modelica Dymola to simulate the feasibility of implementing the ACHP for various steam production approaches and the impact of temperature glide matching. Additionally, a static model of the ACHP was developed using EES software as part of WP4.

The KPIs of the demonstrator were identified, as listed in

Table 1. Employing a gas boiler to produce the same amount of steam or hot water was identified as the baseline.

Table 1 Identified KPIs for the demonstrator

no.	Category	KPI	Unit	Description
1	ACHP	ACHP heating capacity	kW	Heating load at the absorber
2	ACHP	Sink supply temperature	°C	
3	ACHP	Waste heat share	kW/kW	Utilized waste heat/ACHP heating load
4	ACHP	Heat pump COP	-	$Q_{abs}/(W_{compressor}+W_{pump})$
5	ACHP	Efficiency index	-	Carnot & Lorenz efficiency
6	Steam generation	Steam generation rate	kg/h	
7	Steam generation	Steam generation rate per kWh power consumption	kg/kWh	Steam mass flow rate/total power cunsumption
8	Steam generation	Steam generation system COP	-	Q_{steam}/W_{system}
9	Steam generation	GHG emission per kg steam	$kgCO_{2,eq}/kg$	
10	Steam generation	GHG emission reduction per kg steam	$kgCO_{2,eq}/kg$	Baseline: gas boiler
11	Component	Compressor efficiency	-	Isentropic efficiency
12	Component	Absorber efficiency	-	

Since December 2023, the NTNU team has made several visits to the Norsk Kylling (NK) company to study its energy system and conduct a case study on the potential implementation of an ACHP for steam and hot water production. The plant is located in the municipality of Orkland, a key industrial hub in Trøndelag County, Norway. Steam is currently supplied by an electric boiler. During the week of March 3–9, 2025, the average steam demand was 370 kW, with peaks of around 2,300 kW. Although the required steam pressure is 3 bar, the current electric boiler system produces steam at 11 bar due to system constraints. The steam is then supplied to the heating processes at 6 bar from a steam accumulator. By integrating an HTHP, the steam pressure can be reduced to the required 3 bar, resulting in additional energy savings.

5.3 Results

The ACHP presents a highly energy-efficient solution for producing steam and hot water, with strong potential for significant reductions in CO_2 emissions. Experimental results demonstrated that, when both the heat source and sink inlet temperatures were maintained at 60 °C, the system could deliver pressurized hot water at 110 °C with a heating capacity of 55 kW—of which 47.3% from recovered surplus heat. Under these conditions, the calculated Carnot and Lorentz coefficients of performance (COP) were 2.2 and 2.7, respectively. This configuration enables CO_2e emission reductions of up to

87.3% and 46.8% when benchmarked against the Norwegian (NO) and European (EU) electricity grid mixes, respectively. When applied to steam generation in a Norwegian chicken processing facility, the ACHP can produce saturated steam at 3 bar with a generation rate of up to 2.96 kg/kWh. In comparison with a conventional natural gas boiler, this approach offers CO_2e emission reductions of up to 89.8% for the Norwegian grid and 57.2% for the European grid, per kilogram of steam produced. Furthermore, against real-world operational data, the ACHP system has demonstrated potential CO_2e savings of up to 75%. The technical details and performance data are provided in this section.

5.3.1 Experimental evaluation of the ACHP

The variations of heat sink outlet temperature and heat source outlet temperature with heat load are shown in Figure 4. The experimental results indicated that by maintaining the heat source and sink inlet temperature both at 60 ^{0}C, a heat sink supply temperature of 110 ^{0}C was achieved with a heating load of 55 kW. The recovered surplus heat in the desorber was around 26 kW, with a waste heat share of 47.3%.

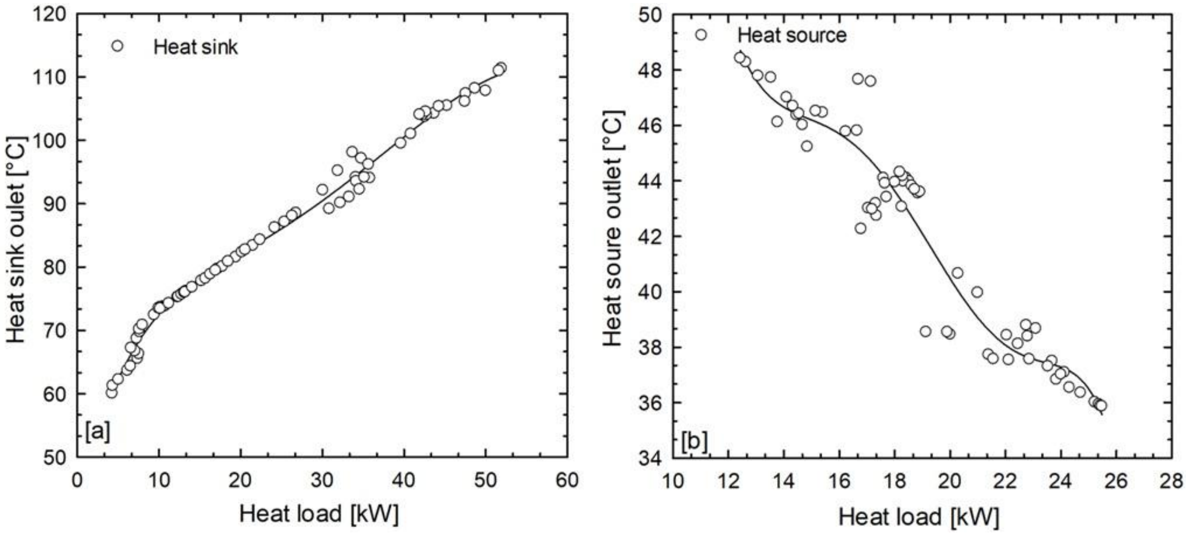


Figure 4 Variation of (a) heat sink outlet temperature and (b) heat source outlet temperature with heat load (circular points: experiment data; line: fitted trend line)

Figure 5(a) presents the variations in COPs and efficiencies with respect to the heat sink outlet temperature, under constant inlet temperatures of 60 °C for both the heat source and sink. As the heat sink outlet temperature increased from 60 °C to 110 both the Carnot and Lorentz COPs decreased, though they remained relatively stable within a range of approximately 3.9 to 2. In addition, both the Carnot and Lorentz efficiencies increased as the heat sink outlet temperature rose, reaching maximum values of 0.68 and 0.58, respectively, as shown in Figure 5(b).

Figure 6(a) illustrates the pressure ratio and temperature lift between the minimum desorption and maximum absorption temperatures. Figure 6(b) shows the variation in total power consumption with temperature lift. Similar to the pressure ratio, the total power required by the system increased as the temperature lift rose, starting from approximately 15 kW at a 10 °C lift and reaching up to 45 kW at the highest temperature lifts. This relationship indicated that the system demanded significantly more power as the temperature lift increased, which was consistent with the greater energy needed to compress the working fluid and achieve higher pressure differences. The increase in power consumption with temperature lift highlighted the typical trade-off in thermal systems: achieving greater temperature differences—and thus higher heat transfer—required substantially more input energy, which negatively impacted overall efficiency and increased operational costs.

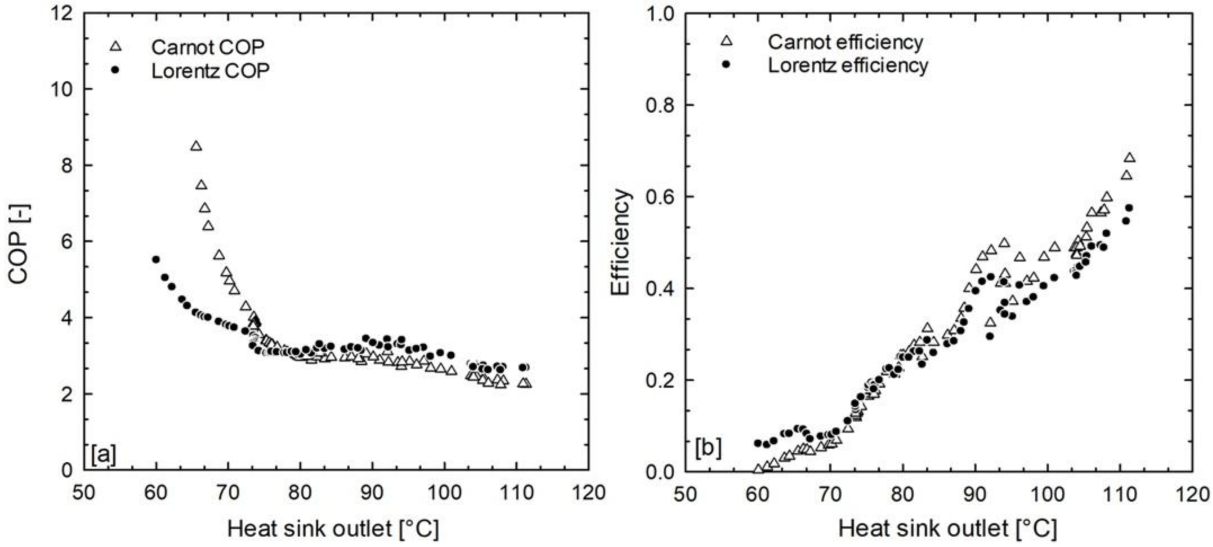


Figure 5 Variation of (a) COPs and (b) efficiencies with heat sink outlet temperature

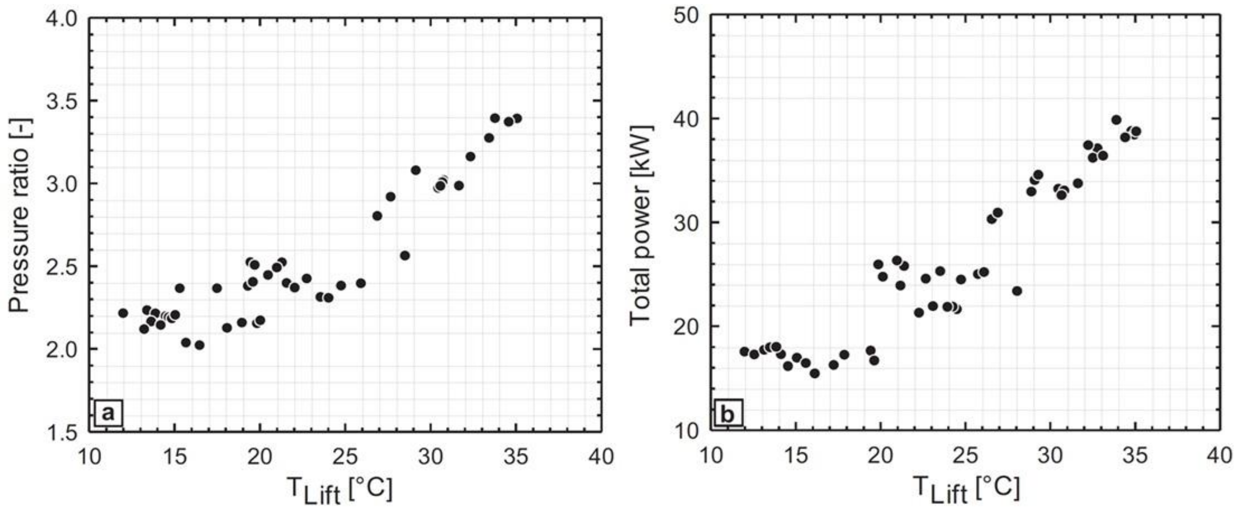


Figure 6 Variation of (a) pressure ratio and (b) power consumption with temperature lift

The KPIs obtained from the experimental evaluation of the ACHP for producing hot pressurized water, conducted under constant heat sink and source inlet temperatures of 60 °C, are summarized in Table 2. To investigate the GHG emissions of the plate freezing system, the CO_2 equivalent values for electricity were calculated based on Norwegian (NO) and European (EU) cases, respectively. In the NO case, a CO_2 emission factor for electricity of 50 g $CO_{2,eq}$. kWh^{-1} is used according to the range presented by Clauß et al.[12]. In the EU case, the CO_2 emission factor for electricity is 210 g $CO_{2,eq}$. kWh^1 on the basis of the EU energy consumption reported by the European Environment Agency[13]. The results were

[12] Clauß, J., Stinner, S., Solli, C., Lindberg, K. B., Madsen, H., & Georges, L. (2019). Evaluation method for the hourly average CO2eq. Intensity of the electricity mix and its application to the demand response of residential heating. Energies, 12(7), 1345.

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

compared with the baseline case of employing a gas boiler to supply the same amount of hot water. A CO_2 emission factor of 204 g $CO_{2,eq}$. kWh^{1} for natural gas combustion was used in the calculations[14].

Table 2 Summary of the KPIs of the ACHP

KPIs		ACHP	Gas boiler
Heating capacity (kW)		55	55
Sink supply temperature (^{o}C)		110	110
Waste heat share		47.3%	0
COP /efficiency	Carnot COP	2.2	0.95
	Lorentz COP	2.7	
ACHP efficiency index	Carnot efficiency	0.68	-
	Lorentz efficiency	0.58	-
Compressor efficiency (isentropic)		0.76	-
Absorber efficiency		0.92 (bubble mode) 0.77 (falling film mode)	-
GHG emissions (g $CO_{2,eq}$. kWh^{-1}. kg^{-1})	$NO_{,el}$	1.59	12.53
	$EU_{,el}$	6.66	
GHG emissions reduction	$NO_{,el}$	87.3%	-
	$EU_{,el}$	46.8%	-

5.3.2 Performance of ACHP-based steam generation using different strategies

The performance of implementing the ACHP with different steam generation approaches shown in Figure 3 was evaluated theoretically using Modelica Dymola. The target steam generation pressure was 3 bar, corresponding to a saturation temperature of 133.5 °C, with a steam generation rate of 155 kg/h. The feed water was at 1 bar and 90 °C. Water was used as the heat source fluid for the ACHP and pentane VCHP, with an inlet temperature ranging from 50 °C to 90 °C.

The system COPs of each steam generation approach at source inlet temperatures of 50 °C and 90 °C are illustrated in Figure 7. For comparison, the COP of the Approach A employing only a VCHP using pentane as the working fluid is also included as a reference. Approach B exhibits the best performance with the highest system COP of 3 and 1.87 for source inlet temperatures of 90 °C and 50 °C, respectively. This indicates that directly generating low-pressure steam in combination with MVR is the most energy efficient manner for steam production using a HTHP under the given operation conditions.

[14] SEAI (2024). Conversion factors for energy use in Ireland. https://www.seai.ie/data-and-insights/seai-statistics/conversion-factors.

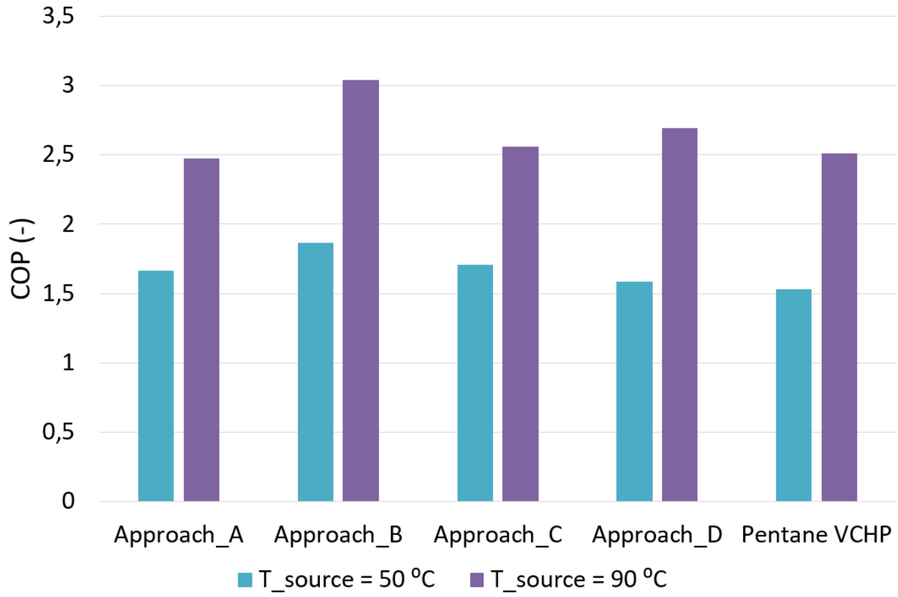


Figure 7 System COP of different steam generation approaches

5.3.3 Implementation of the ACHP in chicken processing

In the current refrigeration system, seawater from the Trondheimsfjorden serves as the heat sink for the ammonia refrigeration cycles and is also used for oil cooling. After absorbing heat, the seawater is discharged back into the fjord. This heated seawater presents a potential low-grade heat source for steam production. During the week of March 3–9, 2025, the average temperature of the incoming seawater was 8 °C, while the average temperature after heating was approximately 16 °C. The heated seawater cannot be used directly as the heat source for the ACHP system and must first be upgraded by either a bottom ammonia (NH_3) or CO_2 heat pump**Error! Bookmark not defined.**Due to the required temperature lift, a two-stage compression configuration was employed for the NH_3 cycle. For the CO_2 cycle, a transcritical configuration with an internal heat exchanger was adopted. The steam can be generated by the ACHP through different approaches shown in Figure 3.

The evaluation results were compared with actual operational energy data, as well as with a baseline scenario using a gas boiler to produce the same amount of steam. As shown in Table 3, steam generation systems incorporating a CO_2 bottom cycle outperformed those using an NH_3 bottom cycle under the conditions studied. Among the configurations, Approach B combined with a CO_2 bottom cycle achieved the highest overall COP of 1.93. Compared to a conventional gas boiler, the ACHP steam generation system can reduce CO_2e emissions by up to 89.8% and 57.2% per kilogram of steam produced for the Norwegian (NO) and European (EU) electricity grid cases, respectively. When compared with actual operational data, the ACHP system offers CO_2e emission savings of up to 75%. Notably, the ACHP steam generation system demonstrates highly competitive thermal performance in real industrial environments, even under scenarios with very low waste heat temperature levels.

Table 3 Evaluation results of implementing the ACHP for steam generation at a chicken processing plant

Steam generation approaches	COP/ efficiency			Steam generation rate (kg/kWh)	GHG emission (g $CO_{2,eq}$. kWh^{-1}. kg^{-1})		GHG emission reduction compared to gas boiler (%)		GHG emission reduction compared to actual case (%)
	COP bottom	COP top	COP total		$NO_{,el}$	$EU_{,el}$	$NO_{,el}$	$EU_{,el}$	
NH_3+ Approach A	3.42	1.99	1.55	2.37	21.1	88.7	87.3%	46.5%	68.8%
NH_3+ Approach B	3.42	2.32	1.68	2.57	19.5	81.8	88.3%	50.7%	71.2%
NH_3+ Approach C	3.42	2.05	1.57	2.41	20.8	87.2	87.5%	47.4%	69.3%
NH_3+ Approach D	3.42	2.11	1.59	2.44	20.5	86.0	87.7%	48.1%	69.7%
NH_3 + VCHP	3.42	1.97	1.53	2.35	21.3	89.4	87.5%	46.1%	68.5%
CO_2+ Approach A	4.91	1.99	1.66	2.54	19.7	82.7	88.1%	50.1%	70.9%
CO_2+ Approach B	4.91	2.32	1.93	2.96	16.9	70.9	89.8%	57.2%	75.0%
CO_2+ Approach C	4.91	2.05	1.71	2.62	19.1	80.3	88.5%	51.6%	71.7%
CO_2+ Approach D	4.91	2.11	1.75	2.69	18.6	78.1	88.8%	52.9%	72.5%
CO_2 + VCHP	4.91	1.97	1.63	2.50	20.0	83.9	88.0%	70.5%	70.5%
Electric boiler	-	-	0.99	0.74	65.58	283.83	-	-	-
Gas boiler	-	-	0.95	1.23	165.83		-	-	-

5.4 Impacts

The ACHP integrates both cooling and heating functions and is capable of delivering high heat sink temperatures of up to 150 °C, making it a viable alternative to fossil fuel boilers in the food supply chain. It uses a natural working fluid—a mixture of ammonia and water—which has negligible ozone depletion potential (ODP) and global warming potential (GWP). The system operates with temperature glides during heat extraction and release, and requires a lower compression ratio than conventional vapor compression heat pumps. The ACHP demonstrator at NTNU offers industrially relevant boundary conditions and provides the flexibility to fine-tune operating parameters, conditions, and components, supporting the adaptation of ACHP technology across various food processing applications.

The experimental investigation showed that, with both the heat source and sink inlet temperatures maintained at 60 °C, the ACHP was capable of supplying pressurized hot water at 110 °C with a heating load of 55 kW, including 47.3% recovered surplus heat from the heat source. The corresponding Carnot and Lorentz COPs were 2.2 and 2.7, respectively. Under these conditions, the ACHP can reduce CO_2e emissions by up to 87.3% and 46.8% for the Norwegian (NO) and European (EU) electricity grid scenarios, respectively.

By implementing the ACHP in a chicken processing plant in Norway for steam generation, a steam generation rate of up to 2.96 kg/kWh can be achieved to produce saturated steam of 3 bar. Compared to a conventional gas boiler, the ACHP steam generation system can reduce CO_2e emissions by up to 89.8% and 57.2% per kilogram of steam produced for the Norwegian (NO) and European (EU) electricity grid cases, respectively. When compared with actual operational data, the ACHP system offers CO_2e emission savings of up to 75%.

The ACHP offers a thermally efficient solution for steam and hot water production and can significantly reduce CO_2e emissions. In addition, the ACHP steam generation system delivers strong thermal performance in real industrial environments, maintaining high efficiency even under conditions with very low waste heat temperatures. As a viable replacement for fossil fuel boilers, the ACHP presents an effective pathway to lowering the carbon footprint in meat processing operations.

5.5 Business potential

The demonstrated ACHP is well-suited for food processing applications that require hot water and steam, such as sterilization, drying, cooking, and cleaning. The primary market includes industrial companies within the food supply chain, such as meat processing facilities, fish processing plants, and dairies. Secondary markets could include other high-temperature industrial heating applications, such as chemical processing and pharmaceuticals.

The technology has been promoted through direct partnerships with industrial food supply chain companies, including Norsk Kylling AS and Tine AS. It has also been showcased at the experimental facility at NTNU, as well as presented at both industry and academic conferences, and through scientific publications. In the future, the technology will be further demonstrated to end users and the general public through trade shows and targeted online marketing campaigns aimed at relevant sectors.

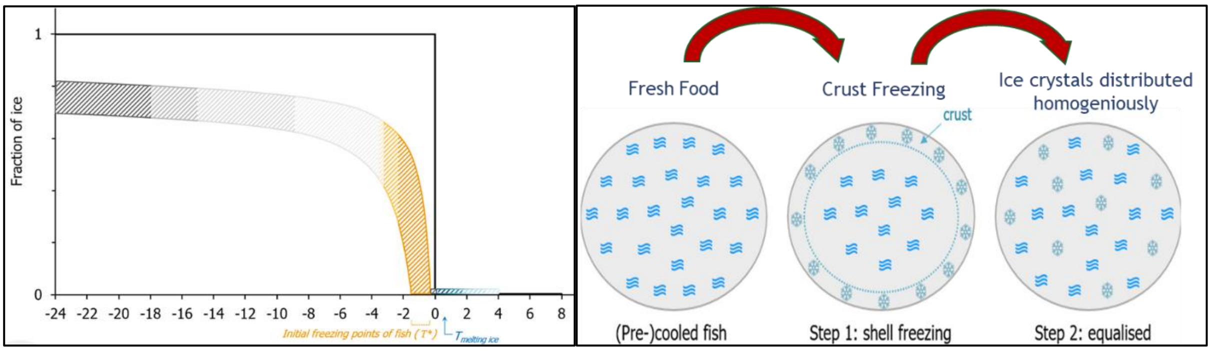
Early adopters of this technology are likely to be innovative companies in the food processing sector that are actively pursuing sustainable heating solutions, reducing reliance on fossil fuels, and striving to meet increasingly stringent environmental regulations.

Potential revenue streams for the ACHP technology include direct sales of ACHP units to customers in the food processing and related industries, delivery of custom-designed high-temperature heat pump systems and consulting services, and provision of post-installation maintenance and support services. By employing an ACHP integrated with an NH_3 bottoming cycle, capable of supplying 1.8 tons of steam per hour with a heating capacity of 1.3 MW, the estimated total capital investment is €610.8k. The projected net present value is €1,557k, with a payback period of 3.16 years and annual operating and maintenance cost of €122.6k.

6 DEMO 17 - SUPERCHILLING

6.1 Description

Superchilling technology can double the shelf-life compared to storage at traditional refrigeration temperatures. The objective of the superchilling demonstrator is to show how a well-designed and carefully controlled temperatures (-2°C +/- 0.2) compartment in a domestic fridge enables the storage life of meat to be dramatically extended. Superchilling (partial/crust/shell freezing) is the reduction the food product's temperature 1–2°C below its initial freezing point. In current practice superchilling means reducing the food temperature until 42% of the total water content of the food is frozen.



(a) (b)

Figure 8 (a) Fraction of ice and temperature relationship, and (b) ice distribution in superchilling process

Figure 8(a) shows the relationship between ice fraction and temperature. Accordingly, when a meat reaches -2°C, the ice fraction rate is between 40% and 60%. This rate varies from foods and can vary depending on their freezing points and ingredients. Figure 8(b) shows the most common superchilling process and how ice molecules are distributed in the tissues of foods. In the superchilling process, freezing is first achieved on the outer shell of the food, while in the next stage, the temperature is equalized in all parts of the food through heat exchange and the ice fraction distribution becomes homogeneous.

6.2 Application methodology and assessment

All experimental procedures were conducted in a precisely controlled superchilling environment. For this purpose, a specialized compartment within a cooling system was designed and developed specifically to facilitate the superchilling process (Figure 9). This compartment was engineered to maintain stable and customizable temperature settings, ensuring that the desired target conditions could be accurately achieved. Functioning as an isolated zone within the cooling system, the compartment incorporated components governed by a fully automated air-controlled algorithm. This autonomous control mechanism enabled the compartment to independently regulate its internal temperature and other environmental conditions, separate from the main cooling unit.

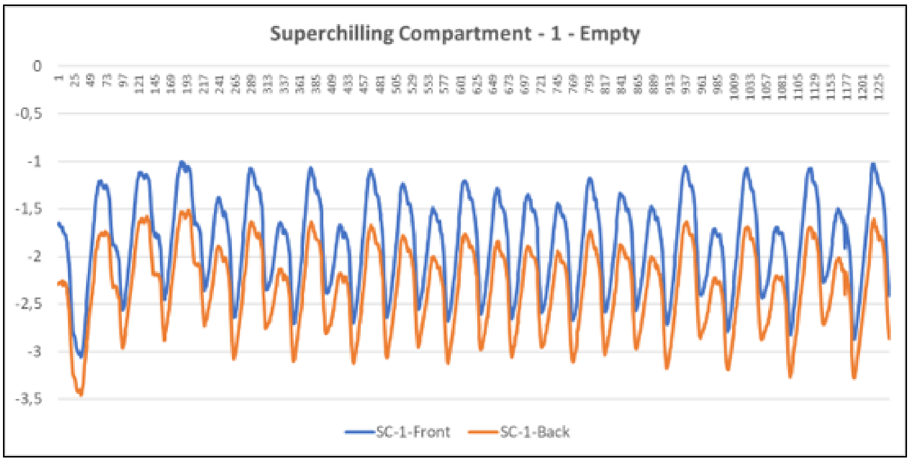
Figure 9 Refrigerator and the compartment in red that was designed for superchilling application

Temperature monitoring was carried out using calibrated thermocouples, which delivered real-time and highly accurate readings +/- 0.1°C. Thermocouples were placed in the geometrical center of the compartment, at the front middle and the back middle of the compartment. These measurements were continuously recorded via a data acquisition system, allowing consistent observation and subsequent analysis of thermal behavior. This setup ensured precise documentation of temperature variations and facilitated a comprehensive assessment of thermal consistency within the compartment.

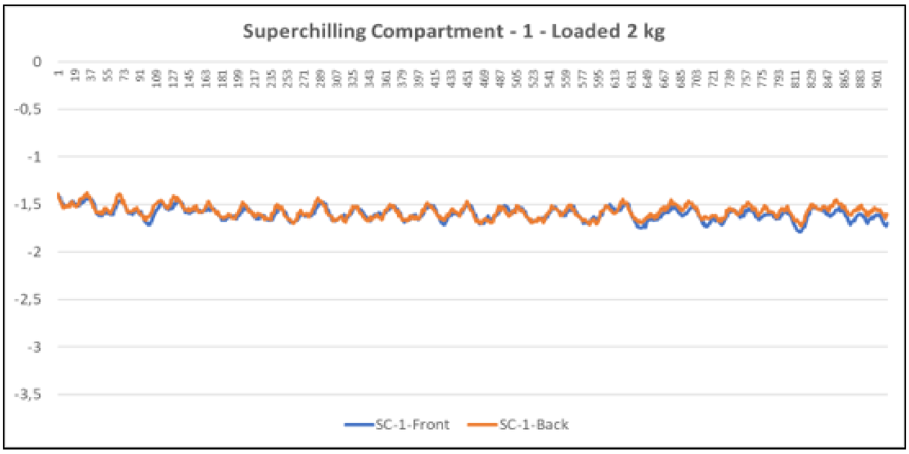
During the superchilling process, the average temperature was maintained at approximately -2.5°C, with a fluctuation range of ±0.8°C (Figure 10). To mitigate the detrimental effects of freeze-thaw cycles inherent in superchilling applications, efforts were made to minimize temperature deviations using the control algorithm of the cooling system. As a result, the temperature fluctuations remained below 1°C. In contrast, conventional chilling was applied at +0.5°C with a minimal variation of ±0.1°C in a separate refrigerator that does not have superchilling cooling system.

The experimental study utilized beef tenderloin (M. *psoas major*) and lamb loin (*longissimus dorsi*) muscles as test materials. These fresh meat cuts were procured from a local butcher in Istanbul. Each sample was trimmed to dimensions of 10.0 × 4.0 × 4.0 cm and weighed approximately 150 grams. Samples were individually wrapped in transparent cling film and placed into either the superchilling or chilling environments. Sampling was performed on days 0, 2, 5, 7, 9, 12, 14, and 16. For each time point, analyses were conducted in triplicate. Sample placement followed the predefined layout shown in Figure 11, with equal spacing maintained between each sample within the compartment.

Sensory evaluations were carried out based on a modified version of the quantitative descriptive analysis (QDA) method. On designated sampling days, six trained panelists participated in the sensory analysis. These panelists were instructed to evaluate the appearance (specifically redness), odor, and overall acceptability of the meat samples.



(a)



(b)

Figure 10 Superchilling compartment temperatures (a) air temperatures when compartment is empty, (b) meat geometrical center temperatures when the compartment is loaded with 2 kg meat

Figure 11 Beef samples stored in a superchilling compartment

Table 4 Identified KPIs at the beginning of the project

Identfied KPIs	
Temperature requirements of compartment	1-2°C below food's initial freezing point
Temperature fluctuation	Max. ±0.2°C
Ice fraction of raw meat	Max. 42%
Maintaining quality	Drip loss after thawing ≤ 2%, nutrient loss should be controlled
Extending shelf life	Extending raw meat's more than 1.5 times according to conventional chiller (2-4°C)
CO2 emmissions/Food waste	Calculations needs to be done after shelf life analysis done and energy consumption measured

Microbiological assessments were carried out in accordance with the method described by Argyri et al. (2010)[15].

All microbiological analyses were performed in triplicate with three parallel samples. The microbial counts were expressed as log cfu per gram (log cfu g^{-1}). Enumeration of microorganisms was calculated using the following formula:

Microorganism count (cfu)

$$Microorganism\ count\ (cfu) = a \times b \div c$$

a: Microorganism colony count in petri dish

b: Dilution factor

c: Amount of planted in petri dish (ml)

Thiobarbituric acid (TBA) analysis was performed to assess the extent of lipid oxidation in the meat samples, based on the reference method described by Pikul et al. (1989)[16]. Each analysis was performed in triplicate with three parallel samples to ensure reliability.

Quality assessment and microstructure were investigated by INRAE within the National Agency of Research (ANT) granted project SUPERSHIELD. Findings are described to support developments achieved within ENOUGH.

[15] Argyri AA, Panagou EZ, Tarantilis PA, Polysiou M and Nychas GJ (2010) Rapid qualitative and quantitative detection of beef fillets spoilage based on Fourier transform infrared spectroscopy data and artificial neural networks. Sensors and Actuators B: Chemical, 145(1), 146-154.

[16] Pikul J, Leszczynski DE and Kummerow FA (1989) Evaluation of three modified TBA methods for measuring lipid oxidation in chicken meat. Journal of Agricultural and Food Chemistry, 37(5), 1309-1313.

In that project INRAE developed a methodology that was described in two papers[17,18].

INRAE assessed the quality and micro-structure of the meat samples. Beef samples were first pre-frozen in a blast freezer at -30°C for 9 minutes and then stored at different temperatures: -5°C, -4°C, -2.8°C, and -1.8°C; and two positive temperatures 2°C, 6°C without pre-freezing for 21 days. Samples were analyzed every 7 days. The temperature dependence of selected beef quality parameters was adequately modelled with the Arrhenius-type equation; the model parameters were identified for drip loss, firmness, TBARS, TVB-N, and colour change, respectively. The kinetic models were validated using experimental data at intermediate temperatures and comparative data from the literature. Material methods and results analysis are reported in papers[17,18].

For the same temperatures and times, INRAE analyzed the meat microstructure using frozen X-ray microtomography to visualize and measure ice crystal development, including volume, size, number, and distribution. While full description is reported in Mwakosya et al. (2025)[18], in the following a brief summary is presented; Beef samples were partially frozen in an air blast freezer with a heat transfer coefficient of 112 W/m^2K, air temperature of –32 °C, for 2 minutes following storage at –1.8 °C, –2.8 °C, –4 °C and –5 °C for 21 days.

6.3 Results

The effectiveness of superchilling and conventional chilling treatments was evaluated based on lipid oxidation levels, microbial growth, ice crystal formation, and sensory quality. Over a 16-day storage period, superchilling was found to significantly slow down both lipid oxidation and microbial development in beef and lamb, thereby extending their shelf life. Specifically, the microbial load in beef stored under superchilling exceeded the safety threshold at least 10 days later than in samples stored under standard chilling. Additionally, sensory evaluation revealed that beef and lamb retained acceptable quality for more than 16 days under superchilling, compared to only 4.5 and 6.0 days under chilling, respectively. Nonetheless, microscopic analysis of ice crystals and cellular structure over 4 days indicated that superchilling could cause some structural damage to the tissue.

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[17] Mwakosya, A. W., Alvarez, G., & Ndoye, F. T. (2025). Effects of Partial Freezing and Superchilling Storage on the Quality of Beef: A Kinetic Modelling Approach. *Foods*.

[18] Mwakosya, A. W., Alvarez, G., & Ndoye, F. T. (2025) "Investigating the effects of superchilling storage on the microstructure of beef meat" 7th Edition of Euro Global Conference on Food Science and Technology, Valence Spain.

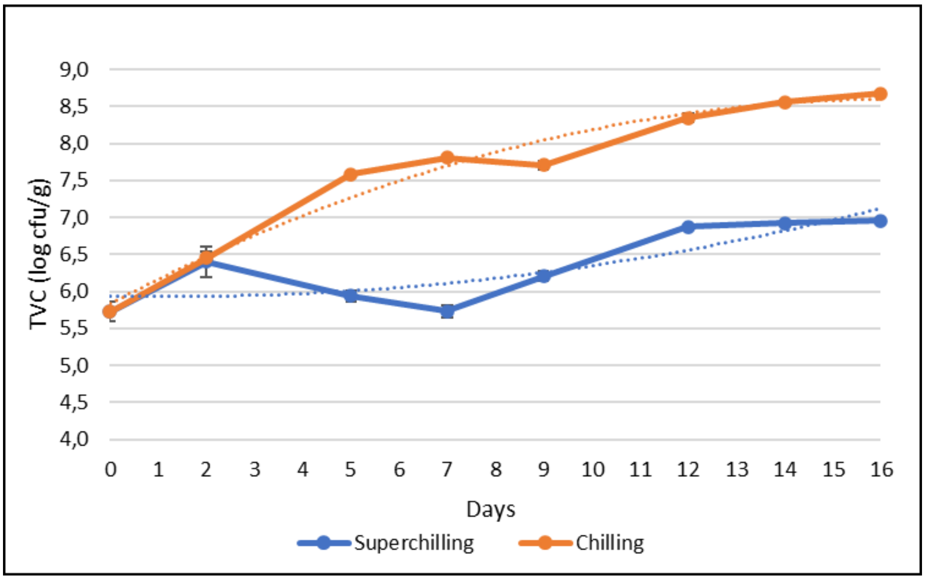
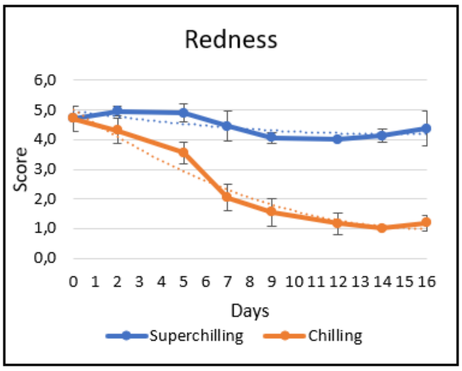
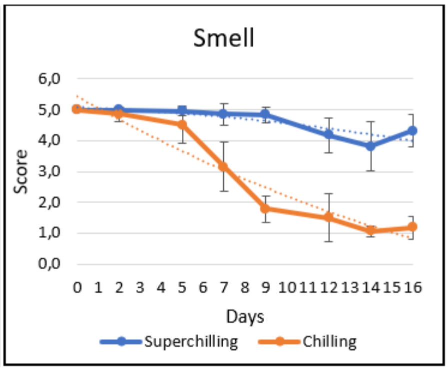


Figure 14 TVC analysis results of raw beef samples preserved for 16 days in different conditions (log cfu/g)

According to Turkish Food Codex Regulation of Microbiological Criteria, this limit is 6.7 log cfu/g and the values of TVC of beef slices preserved in chilling condition exceeded this threshold limit by day 2.8 according to Figure 14. TVC was above 6.7 log cfu/g on day 13.1 for the samples stored in superchilling condition while TVC was around 8.3 log cfu/g in beef samples preserved in chilling conditions.



(a)



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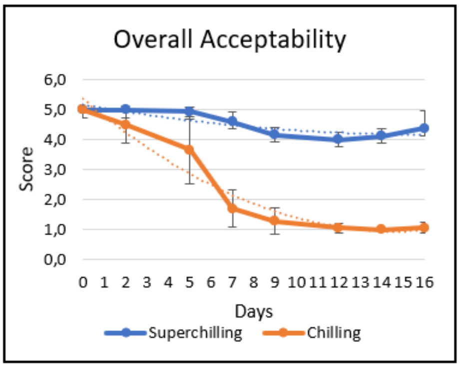

(c)

Figure 15 Sensory evaluation scores of beef samples preserved at superchilling and chilling conditions (0-5 range)

As a conclusion of sensory evaluations for raw beef samples preserved in superchilling and chilling conditions for 16 days, overall acceptability scores of samples in chilling condition decreased faster than superchilling condition in Figure 15. According to the results, raw beef had above 3.0 overall acceptability score for 5 days for chilling, more than 16 days for superchilling condition. In conclusion, when sensory evaluation results were investigated for raw beef, shelf life prolongs more than 4 times by superchilling storage.

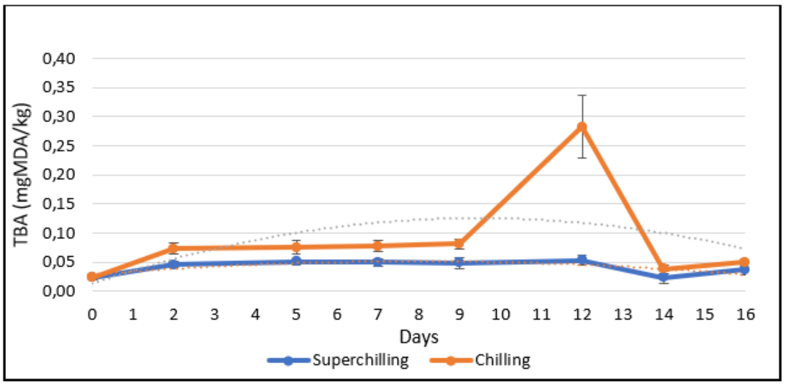

Figure 16 The results for lipid oxidation of raw beef for 16 days storage during superchilling and chilling compartments

While there is no officially established legal limit for TBA values, a concentration of 1 mg MDA/kg of meat is generally considered the threshold above which rancid flavor becomes detectable by human senses[19]. At the beginning of the storage period, both beef and lamb samples exhibited low TBA values, approximately 0.02 mg MDA/kg meat. As illustrated in Figure 16, TBA values in beef samples increased significantly within the first two days under both chilling and superchilling conditions. After the second day, oxidation levels stabilized; however, beef samples kept under standard chilling consistently showed higher TBA values than those stored under superchilling conditions throughout the entire storage duration.

The findings clearly demonstrated that superchilling offers significant benefits in maintaining the quality and freshness of beef and lamb. It effectively delays lipid oxidation and extends the microbiological shelf life more than conventional chilling. However, further research is needed to understand how ice crystal formation during superchilling may contribute to drip loss and potential nutrient degradation. This should involve comparing drip loss and nutritional content with conventional chilling, where ice crystallization is absent.

For the same temperatures and times, we analyzed at INRAE the meat microstructure using frozen X-ray microtomography to visualize and measure ice crystal development, including volume, size, number, and distribution. . Results show that, recrystallization rate was strongly correlated with all quality kinetic rates ($R^2 > 0.9$). In addition, this study highlights the significance value of X–ray micro–CT in monitoring microstructure evolution of partially frozen beef during superchilled storage. This will lead to a better control of quality and safety of food throughout the cold chain.

6.3.1 Key Performance Indicators (KPIs)

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19 Limbo S, Torri L, Sinelli N, Franzetti L and Casiraghi E (2010) Evaluation and predictive modeling of shelf life of minced beef stored in high oxygen modified atmosphere packaging at different temperatures. Meat science, 84(1), 129-136.

Shelf-Life Extension:

Beef and lamb shelf life extended from ~4.5–6 days (chilling) to >16 days (superchilling), representing a >150% increase in storage duration under acceptable quality and safety conditions.

Products retained acceptable sensory properties (appearance, odour, texture) for over 16 days, validated via panel evaluations.

Temperature Stability:

Superchilling compartment maintained a mean air temperature of -2.5°C ± 0.8°C, with meat core temperatures closely aligned.

Temperature fluctuation kept below ±1°C, minimizing freeze–thaw stress.

Microbial Load Reduction:

Delay of at least 10 days in reaching critical microbial (total flore) thresholds under superchilling compared to chilling.

Oxidative Stability:

Slower progression of lipid oxidation markers, suggesting improved retention of freshness and nutritional value of meat included.

Energy Savings Potential:

Compared to freezing at -18°C, superchilling at -2 to -3°C reduces cooling load, with estimated energy savings of 30–50% depending on usage profile and the insulation efficiency of the compartment.

6.3.2 General Impacts

Food Waste Reduction:

The extended shelf life directly contributes to lowering meat spoilage rates in household and retail settings, addressing a critical component of post-purchase food waste. Eriksson et al. (2014)[20] reported that the application of superchilling can lead to up to a 20% reduction in food waste in the retail sector, primarily due to the extended storage time and delayed spoilage.

Sustainability and Climate Impact:

Reduced energy consumption in refrigeration leads to a lower carbon footprint, supporting international climate objectives (e.g., SDG 12 – Responsible Consumption and Production, and SDG 13 – Climate Action).

Technology Scalability:

The use of superchilling compartment design demonstrates high potential for integration into commercial and domestic refrigerator models, increasing market feasibility.

Consumer Health and Satisfaction:

Improved preservation of freshness, flavour, and nutritional quality enhances consumer satisfaction and supports healthier food consumption practices with reduced reliance on preservatives or additives.

Economic Value:

[20] Eriksson, M., Strid, I., & Hansson, P. A. (2014). Waste of organic and conventional meat and dairy products—a case study from Swedish retail. Resources, Conservation and Recycling, 83, 44–52.

Superchilling enables cost savings in logistics, cold chain management, and retail, by reducing product losses, extending sale periods, and minimizing the need for emergency deep freezing.

6.3.3 General conclusions

This study has comprehensively demonstrated that superchilling technology, when applied under precisely controlled thermal conditions, can significantly extend the microbiological and sensory shelf life of fresh meat products such as beef tenderloin and lamb loin. By maintaining the product temperature at approximately -2.5 °C—just below the initial freezing point—without inducing complete solidification, superchilling effectively delayed lipid oxidation and microbial proliferation compared to traditional chilling conditions at +0.5 °C. The integration of a specially designed compartment with automated, algorithm-controlled air circulation ensured minimal temperature fluctuations (±0.8 °C), thereby mitigating the adverse effects typically associated with freeze–thaw cycles and heterogeneous ice formation. The experimental results revealed that meat stored under superchilling conditions remained microbiologically safe and organoleptically acceptable for more than 16 days, whereas standard chilling failed to preserve these qualities beyond 4.5 to 6 days.

Moreover, although microscopic analysis indicated some degree of structural damage in muscle tissue due to extracellular ice crystal formation, particularly in the outer layers, the process remained within acceptable limits for quality preservation. Advanced imaging methods such as microtomography are recommended for future studies to better characterize these changes and to optimize superchilling parameters for different food matrices.

In addition to its quality preservation advantages, superchilling presents significant implications for food system sustainability. By reducing spoilage rates and extending product shelf life, it directly contributes to the mitigation of food waste across the supply chain—from producers to end consumers. Furthermore, unlike conventional freezing, which requires storage temperatures around -18 °C, superchilling operates within a narrower thermal window (typically between -1 °C and -3 °C), thereby reducing energy consumption during both the cooling and storage phases. This reduced energy demand translates not only into lower operational costs but also a decreased carbon footprint associated with refrigeration systems.

In conclusion, the findings underscore the dual potential of superchilling: enhancing food safety and quality while simultaneously supporting broader environmental and economic goals. To maximize its benefits, future work should focus on refining the thermal control mechanisms, quantifying nutrient retention under varying superchilling regimes, and evaluating long-term impacts on sensory perception, drip loss, and consumer acceptance. The widespread adoption of superchilling technology could play a vital role in developing more efficient, sustainable, and resilient cold chains in the face of growing global demand for fresh and minimally processed foods.

6.3.4 Future outlook

The application of superchilling technology aligns directly with the project's overarching objectives by offering a low-energy alternative to conventional freezing and an advanced solution for food preservation with minimized spoilage and waste.

In the coming years, the development and scaling of superchilling systems is expected to play a critical role in building climate-friendly cold chains and reducing the environmental footprint of food storage. The ability to preserve perishable products at temperatures just below their freezing point—without complete solidification—not only reduces microbial spoilage and quality degradation, but also minimizes the need for deep freezing systems that consume substantially more energy (e.g., at -18 °C or lower). In addition, drip loss and product thickness are important factors that should be considered in future optimization efforts. As a result, superchilling supports lower electricity demand, reduced carbon emissions, and extended product shelf life, all of which contribute to the long-term sustainability goals of the ENOUGH initiative.

Moving forward, future work should focus on:

- Integrating superchilling compartments into commercial and household refrigeration units, enabling wider adoption of energy-efficient storage.
- Enhancing system intelligence through AI-supported control algorithms to maintain precise temperature profiles for different food types under varying usage conditions.
- Conducting life cycle assessments (LCA) to quantify carbon savings and environmental impacts compared to traditional chilling and freezing methods.
- Developing product-specific protocols and validating them under real-world conditions to ensure food safety, nutritional preservation, and minimal quality loss.
- Creating regulatory frameworks and market strategies to facilitate the introduction of superchilled foods into mainstream retail with proper labelling and consumer awareness.
- Encouraging cross-sector collaboration among appliance manufacturers, food producers, research institutions, and policymakers to accelerate innovation and implementation.

In line with the ENOUGH project's vision the superchilling technology represents a promising tool for decarbonizing the food sector while enhancing food security and consumer satisfaction. Its future lies in interdisciplinary R&D, sustainable design, and smart integration into global cold chains. With continued progress, superchilling can become a cornerstone of next-generation refrigeration strategies that meet both climate and food system resilience targets.

6.4 Impacts

The superchilling technique, which involves lowering the temperature of food products to just below their initial freezing point without complete solidification, offers a promising alternative to conventional freezing in terms of energy efficiency and environmental impact. Compared to freezing, which requires maintaining storage temperatures around -18°C or lower, superchilling typically operates at approximately -1°C to -3°C, significantly reducing the energy demand for both the chilling process and long-term storage. This temperature difference translates into lower electricity consumption and reduced operational costs, particularly in large-scale food storage and distribution systems. Furthermore, the decreased energy usage directly contributes to a reduction in GHG emissions associated with refrigeration. By maintaining food quality and extending shelf life while operating under milder conditions than freezing, superchilling not only ensures product safety and freshness but also supports more sustainable food preservation practices aligned with global climate goals.

6.5 Business potential

The superchilling project is a technology that has positive effects on the food quality, food waste and environment and has positive effects on user experiences. It will be put into mass production with cost and manufacturability studies.

Potential customers for the superchilling technology include household users who are interested in sustainable living and reducing food waste, as well as environmentally conscious consumers looking for innovative kitchen technologies. Early adopters are likely to be eco-conscious families, tech-savvy individuals, and those who frequently experience food spoilage. These groups are motivated by both environmental concerns and a desire to preserve food freshness, making them ideal candidates for adopting superchilling solutions.

The superchilling technology can be marketed directly through e-commerce platforms, supported by targeted digital advertising and informative content such as demonstration videos and customer testimonials. Collaboration with home appliance stores and eco-friendly shops can help feature the superchilling units, with trained staff available to explain the product benefits to potential buyers. Additionally, showcasing the technology at home and technology expos, as well as eco-fairs, will allow direct customer interaction and live demonstrations. To further raise awareness, concise educational content—including blogs and infographics—can be produced and distributed via the company's website and through environmental and tech news outlets.

Revenue streams for the superchilling technology include direct sales of the refrigerator units, licensing the technology to major refrigerator manufacturers, and offering post-sale maintenance and service contracts to ensure ongoing customer support.

CONCLUSIONS

7 IMPACT

In this task, two innovative technologies were demonstrated to address the primary energy-consuming processes in the meat processing industry—steam generation and food cooling/freezing—with the aim of reducing energy consumption and GHG emissions.

Both demonstrators offer significant emission-saving potential, leading to substantial reductions in GHG emissions compared to baseline practices. In addition, the ACHP employs a natural refrigerant and enables efficient recovery of surplus heat for steam generation, minimizing environmental impact and energy waste. Meanwhile, superchilling enhances food safety and freshness and reduces food waste by extending shelf life and preserving product quality. Together, these technologies support more sustainable meat production and preservation, in line with global climate and environmental goals.

8 DISSEMINATION AND COMMUNICATION

To maximize the impact of the two demonstrators, a comprehensive dissemination and communication strategy has been implemented targeting key stakeholders across the meat processing industry. Both the ACHP (Demo 14) and the superchilling (Demo 17) technology have been actively promoted through multiple channels to reach potential end users, industry experts, policymakers, and technology providers. The results from both demonstrators also helped optimize solutions in WP7 and WP8.

The results and benefits of the ACHP system, particularly its enhanced thermal efficiency and notable CO_2e emission reductions, have been showcased in technical workshops, industry and academic conferences, and specialized webinars. The results have been published in scientific journals, industrial magazines, and newsletters. Case studies from the chicken processing plant in Norway illustrates real-world operational performance and environmental gains, fostering confidence in technology adoption. The related publications are listed below:

1. Hamid, K., Ren, S., Tolstorebrov, I., Hafner, A., Wang, C. C., Sajjad, U., & Eikevik, T. M. (2025). Development and experimental assessment of oil free combine absorption-compression heat pump with NH3/H2O mixture working fluid. Applied Energy, 383, 125352.
2. Hamid, K., Ren, S., Tolstorebrov, I., Hafner, A., Sajjad, U., Arpagaus, C., ... & Eikevik, T. M. (2025). Experimental optimization of an absorption-compression heat pump with wet compression for large temperature glide industrial applications. Renewable Energy, 243, 122531.
3. Hamid, K., Wang, C. C., Tolstorebrov, I., Hafner, A., & Eikevik, T. M. (2025). Experimental study on ammonia/water mixture desorption heat transfer for vapor absorption-compression heat pump. International Journal of Heat and Mass Transfer, 246, 127114.
4. Ren, S., Ahrens, M., Hamid, K., Tolstorebrov, I., Hafner, A., Eikevik, T., & Widell, K. (2023). Performance modelling of an ammonia-water absorption-compression heat pump for steam generation in food processing. Presented at the 10th IIR Conference on Ammonia and CO2 Refrigeration Technologies April 27-29, 2023, Ohrid.
5. Ren, S., Ahrens, M. U., Hamid, K., Tolstorebrov, I., Hafner, A., Eikevik, T. M., & Widell, K. M. N. (2023). Numerical investigation of an ammonia-water absorption-compression high-

temperature heat pump for hot water and steam production in food processing. In Proceedings of the 26th IIR International Congress of Refrigeration: Paris, France, August 21-25, 2023-volume 4. International Institute of Refrigeration.

6. Ren, S., Ahrens, M. U., Hafner, A., & Widell, K. N. (2022). Performance evaluation of high-temperature heat pump systems for hot water and steam generation in food processing. In 15th IIR-Gustav Lorentzen Conference on Natural Refrigerants-GL2022-Proceedings-Trondheim, Norway, June 13-15th 2022. International Institute of Refrigeration.
7. Hamid, K., Ren, S., Tolstorebrov, I., Hafner, A., & Eikevik, T. M. (2024). Experimental investigation of oil free absorption-compression heat pumps with liquid injection screw compressor for high temperature applications. Presented at the 16th IIR Gustav Lorentzen Conference on Natural Refrigerants, August 11-14, 2024, Maryland, USA.
8. Hamid, K., Ren, S., Tolstorebrov, I., Hafner, A., & Eikevik, T. M. (2024). Experimental assessment of oil free liquid injection twin screw compressor for high temperature industrial applications. Submitted to the IIR Conference on Compressors and Refrigerants, Sep. 9 – 11, 2024, STU Bratislava.
9. Ren, S., Ahrens, M., Hafner, A. (2022). The Applications of Ammonia-Water Absorption-Compression High-Temperature Heat Pumps in European Food Industry. Presented at High-Temperature Heat Pump Symposium 2022, Copenhagen.
10. Hafner, A., Ahrens, M. U., Hamid, K., Ren, S. (2022). Untersuchungen einer NH3-H2O Hybrid-Wärmepumpen-Testanlage. DKV Deutsche Kälte- und Klimatagung , Magdeburg 2022-11-16 - 2022-11-18.
11. Dano, T. (2023). Experimental investigation of a high-temperature heat pump for food processing applications (Master's thesis, NTNU).
12. Ahmed, R. (2024). Investigation on hot water production and steam generation heat pump for energy efficiency in meat processing, Master thesis, NTNU.

The ACHP technology is also applicable to steam and hot water production in dairies, where thermal heat demand is typically high. As part of the HighEFF project[21], an ACHP system was implemented in a greenfield dairy facility in Norway for hot water production[22]. Within the ENOUGH project, the potential of implementing an HTHP in a Norwegian dairy (Demo 2) was analyzed and several HTHP configurations were evaluated in Task 6.3. Additionally, ACHP findings supported the development of a web-based software tool for efficiency and emissions assessment along the food supply chain within WP4.

Similarly, the superchilling technology has been highlighted for its energy savings, extended shelf life, and ability to preserve meat quality. Findings have been disseminated through workshops, conferences, webinars, scientific journals, and industry publications, emphasizing its role as a sustainable alternative to traditional freezing, highlighting both environmental and economic benefits.

1. P. Collin, M. Darsonval, O. Rué, 3F. Ndoye, G. Alvarez, F. Dubois-Brissonnet (2025) Superchilling storage of salmon (Salmo salar) reduces bacterial diversity and increases shelf-life. Submitted to Food Research International, Manuscript number FOODRES-D-25-09325
2. P.Collin, M. Darsoval, F Ndoye, G Alvarez, F Dubois-Brissonnet (2023) Diversity of bacterial communities on Fresh salmon when preserved by refrigeration of superchilling . ISEKI Food.
3. P.Collin, M. Darsoval, F Ndoye, G Alvarez, F Dubois-Brissonnet(2024) Impact of superchilling technique on the microbiological quality of fresh salmon . Food Micro

[21] HighEFF, https://www.sintef.no/projectweb/higheff/.
[22] Ahrens, M. U., Foslie, S. S., Moen, O. M., Bantle, M., & Eikevik, T. M. (2021). Integrated high temperature heat pumps and thermal storage tanks for combined heating and cooling in the industry. Applied thermal engineering, 189, 116731.

4. Anjelina William Mwakosya, Graciela Alvarez, Fatou Toutie Ndoye (2025) Effects of partial freezing and superchilling storage on the quality of beef: A Kinetic Modelling Approach. Foods Vol 15 In press.
5. Anjelina William Mwakosya, Graciela Alvarez, Fatou Toutie Ndoye (2025) "Investigating the effects of superchilling storage on the microstructure of beef meat" 7th Edition of Euro Global Conference on Food Science and Technology, Valence Spain.
6. Anjelina William Mwakosya, , Fatou Toutie Ndoye, Graciela Alvarez (2025) Study on superchilling technology on Investigating the effects of superchilling storage conditions on the microstructure of beef meat and its impact on quality submitted to IJR Special issue

Communication efforts also include the development of technical brochures, posters, and multimedia content distributed through online platforms and social media to engage a broader audience. Collaboration with industry associations and regulatory bodies ensures that the knowledge generated is aligned with market needs and regulatory frameworks, supporting faster technology uptake.

Moving forward, the Technology Readiness Level (TRL) of both systems will be advanced through further demonstrations in diverse operational environments. Ongoing stakeholder engagement and dissemination activities will continue to build awareness and facilitate the scaling of these innovative solutions across the meat processing sector, ultimately driving energy efficiency and greenhouse gas emission reductions industry-wide.

9 FUTURE OUTLOOK

The path toward a more energy-efficient and low-carbon meat processing industry is increasingly shaped by technological innovation, policy support, and heightened environmental awareness. Future advancements will focus on integrating high-efficiency systems such as heat pumps, superchilling, and renewable energy technologies to reduce reliance on fossil fuels. Waste heat recovery, intelligent process control, and real-time energy monitoring will play a crucial role in optimizing operations and minimizing energy loss across production lines.

As electricity grids continue to decarbonize, the electrification of thermal processes—particularly steam and hot water generation—will offer a major opportunity to lower greenhouse gas (GHG) emissions. Simultaneously, with continued progress, superchilling can become a cornerstone of next-generation refrigeration strategies, enabling more precise temperature control and greater energy efficiency while supporting both climate goals and food system resilience.

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 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 meat processing sector.

Looking ahead, additional energy consumption bottlenecks will be identified, and new solutions will be proposed and tested to address them. Strengthened collaboration among industry players, technology developers, and policymakers will be essential to scale up pilot successes and accelerate the implementation of best practices. Continued investment in research, development, and demonstration will help overcome technical and economic challenges, paving the way for wider deployment of clean technologies.

Ultimately, the future of meat 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.