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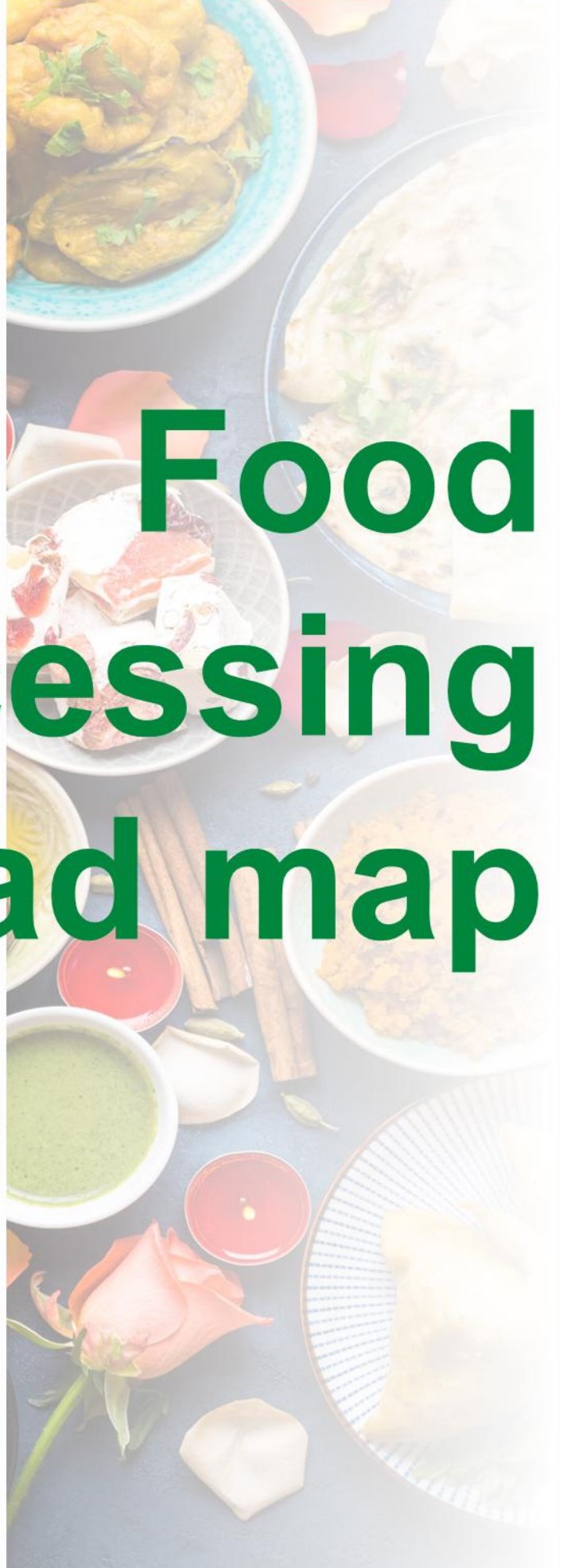
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Food processing road map



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ENOUGH

EUROPEAN FOOD CHAIN SUPPLY
TO REDUCE GHG EMISSIONS BY 2050

NOMENCLATURE

AD	Anaerobic Digestion
AI	Artificial Intelligence
AIS	Active insulation system
AMF	Alternating magnetic field
BAT	Best available technology
CaCl ₂	Calcium chloride
CAGR	Compound annual growth rate
CAS	Cell alive system
CBAM	Carbon Border Adjustment Mechanism
CCAR	Closed cycle air refrigeration
CCS	Carbon capture and storage
CFD	Computational fluid dynamics
CHP	Combined Heat and Power
CHTC	Convective heat transfer coefficients
CIP	Cleaning-in-place
CNC	Carbon nanocomposites
CO	Carbon monoxide
COP	Coefficient of Potential
COSP	Coefficient of system performance
COVID	Coronavirus disease
CO ₂	Carbon dioxide
CPO	Crude palm oil
CSC	Clean smoke coalition
CTES	Cold thermal energy storage
DM	Dry matter
DSR	Demand side response
DSR	Demand side response
DX	Direct expansion
ECA	European Chemicals Agency
ECL	European Climate Law
EF	Electrostatic field
EFSA	European Food Safety Authority
EPBT	Energy payback time
EPS	Expanded Polystyrene
ESOS	Energy Savings Opportunity Scheme
ETS	Emissions Trading System
ETS	Emissions trading system
EU	European Union
EUMOFA	European Market Observatory for fisheries and aquaculture products

F&V	Fruit and vegetables
FAO	Food and Agriculture Organisation of the United Nations
FAOSTAT	Global Food and Agriculture Statistics of FAO
FBD	Fluidised bed dryer
FCC	Federal Communications Commission
FFA	Free fatty acid
FO	Forward osmosis
FUI	Fuel use intensity
GB	Great Britain
GHG	Greenhouse gas
GWP	Global warming potential
HFC	Hydro fluorocarbon
HFO	Hydrofluoro-olefins
HPH	High-pressure homogenisation
HPP	High pressure processing
HSP	High shear mixer
HTHP	High-temperature heat pump
HTST	High-temperature short time
HV	High viscosity
HVAC	Heating, ventilation, and air conditioning
ICE	Integrated cogeneration engine
IEA	International Energy Agency
INP	Ice nucleation proteins
IoT	Internet of Things
IQF	Individual quick freezers
IR	Infrared
IRENA	International Renewable Energy Agency
ISO	International Standards Organisation
KPI	Key performance indicator
LCA	Life cycle assessment
LCC	Life cycle costing
LN	Liquid nitrogen
LNG	Liquid nitrogen gas
LPG	Liquified petroleum gas
LPR	Low pressure receiver
LTLT	Low-temperature long time
LULUCF	Land use, land-use change, and forestry
LWE	Live weight equivalent
MAP	Modified Atmosphere Packaging
MATS	Microwave-Assisted Thermal Sterilisation
MD	Membrane distillation

MEE	Multi-effect evaporation
MGO	Marine gas oil
MMt	Million metric tons
MRF	Magnetic reasoning field
MRR	Material-removal rates
Mt	Million tonnes
MTES	Medium temperature energy storage
MVR	Mechanical vapour recompression
MW	Microwave
NDC	Nationally determined contribution
OD	Osmotic dehydration
ODP	Ozone depletion potential
ORC	Organic Rankine Cycle
PCM	Phase change materials
PEF	Pulsed electric field
PFA	Per and Polyfluorinated Substances
PFAD	Palm fatty acid distillate
PGPR	Polyglycerol polyricinoleate
PID	Proportional–Integral–Derivative
PLC	Programmable Logic Controllers
POME	Palm oil mill effluent
PV	Photovoltaic
PVT	Pulsed vacuum treatment
RBDPO	Refined, bleached, and deodorised palm oil
RF	Radio frequency
RO	Reverse osmosis
RORC	Regenerative Organic Rankine Cycles
RPM	Revolutions per minute
RRM	Rest raw materials
RSPO	Roundtable for Sustainable Palm Oil
RSW	Refrigerated seawater
RTE	Ready-to-eat
SCF	Supercritical fluid extraction
SEC	Specific energy consumption
SECR	Streamlined Energy Carbon Reporting
SEE	Single-effect evaporators
SEF	Specific emission factors
SJ	Steam-jacketed
SME	Small to medium sized organisations
SSF	Solid-state fermentation
TABE	Thermally anisotropic building envelope

TEEI	Total energy efficiency index
TEG	Thermoelectric generators
TES	Thermal energy system
TRL	Technology readiness level
TVR	Thermal vapor recompression
UF	Ultrafiltration
UH	Ultrasonic homogeniser
UHT	Ultra-high temperature
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
USDA	US Department of Agriculture
VAR	Vapour Absorption Refrigeration
VFD	Variable frequency drives
VI	Vascular infusion
VOC	Volatile organic compounds
VP	Vascular perfusion
VRTP	Variable retort temperature profile
VSD	Variable Speed Drive
WNA	World Nuclear Association

EXECUTIVE SUMMARY

In this roadmap we question how the food processing sector can decarbonise and rapidly reach net zero. As part of the work, we provide independent reviews of 54 different technologies/strategies that processing companies could apply to reduce greenhouse gas (GHG) emissions and energy consumption. Scope 1 and 2 emissions are covered which encompass emissions from leakage of refrigerants and emissions from direct fuel use (e.g. gas) and indirect emissions from the electrical grid.

The potential to reduce emissions in the meat, fish, dairy and further processing food sectors are assessed through identifying the best technologies/strategies and modelling the impact on typical processing operations. The most appropriate technologies/strategies with the most potential to reduce GHG emissions were selected from the reviews. Only technologies with a high technology readiness level (TRL) were considered as we wanted to assess what was feasible today. GHG emissions from many lower TRL technologies were often difficult to quantify and many had very varied application times and the claimed savings often varied widely.

Results from the reviews and modelling identified routes for the food processing sector to reduce emissions and enabled the creation of a roadmap through to 2050. In all sectors there was considerable potential to reduce GHG emission by 2050. In the meat, fish and dairy sectors it was possible to reduce GHG emissions by almost 100%. In the prepared meals sector for the foods examined (fish fingers and beef casserole) it was possible to reduce emissions by up to 91%. Decarbonisation was very dependent on application of low carbon technologies and moving away from fossil fuels.

Technologies that were identified as being of most relevance were:

In all sectors:

1. Efficient cooling processes and in some cases novel technologies such as hot boning in the meat sector or brine or plate freezing in the fish sector.
2. Heat pumps to replace fossil fuels used for space heating and domestic water heating. In the near future applying high temperature heat pumps that will be capable of achieving temperatures of up to 160°C for high and low pressure steam.
3. Heat reclaim technologies.
4. Efficient air compressors or improving the efficiency of currently installed air compressors.
5. Use of biogas or potentially hydrogen if from low carbon sources.
6. Use of solar PV to provide electricity (potentially integrated with energy storage).

In all cases it is recommended to compare process performance to key KPIs and metrics (see section 6: Performance of food processing sectors). Auditing, good maintenance and ongoing monitoring are essential tools to ensure energy and carbon savings. A summary of the main recommendation is shown in the diagram below

Recommendations



FOOD PROCESSING ROAD MAP

1 ABOUT THIS ROAD MAP

Globally, GHG emissions from the food chain are estimated to account for 33% of the total GHG emissions¹. Emissions from the food chain can emanate from direct or indirect sources. Emissions related to post farm gate (post-harvest/slaughter), which are the focus of the ENOUGH project, are thought to account for around 20% of total emissions.

This road map focuses on the food processing sector. Almost all food undergoes some form of primary processing to cool or cook it. Foods are then often further processed (secondary processing) to create a range of products and meals. The main emphasises of this road map is to assess the potential for food processors to reduce carbon emissions.

The road map presents quantified evidence on the levels of GHG emissions that could be saved, the technologies and strategies that could be applied and looks forward to 2050 to predict how near a zero-carbon cold storage sector is feasible.

The road map covers primary processing for 3 food types that have high GHG emissions and further (secondary processing). The following sectors are covered:

Meat processing:

The sector covers large slaughterhouses and companies who further process meat products. Many of these are owned by international conglomerates who process the majority of meat products by mass. There are also a large number of small to medium sized (SME) organisations that process meat into specialist products.

In the road map we focus on red meat (beef and pork) and white meat (poultry) as example products. The road map tends to focus on larger facilities but many of the technologies evaluated would also be appropriate for smaller facilities.

Fish processing:

This roadmap focuses on the processing of pelagic fish, specifically primary processing of Atlantic mackerel caught, landed, and processed in Norway. Beyond this, the sector covers a diverse range of seafood products and processes, including aquaculture, whitefish processing, fishmeal and oil production, and traditional products such as stockfish and salted cod. While these traditional products represent lower volumes, they are high-value commodities in international trade.

Dairy processing – milk and cheese:

The European dairy sector includes a diverse range of activities, from primary milk production and processing into basic products such as butter and milk powder, cheese, yogurt, ice cream, and a growing range of value-added products. In this roadmap we focus on pasteurised and ultra-high temperature (UHT) drinking milk as well as secondary processing into cheese. This includes iconic varieties like Cheddar, Roquefort, and Parmesan, reflecting the rich culinary traditions across the continent.

Secondary processing to produce composite products:

¹ Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N. and Leip, A.J.N.F., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature food*, 2(3), pp.198-209.

Secondary processing in the food industry combines multiple ingredients to create composite products, each with distinct environmental impacts. By analysing the sub-processes involved in producing items like beef casserole and breaded fish fingers, we can identify key sources of GHG emissions, from ingredient sourcing to final packaging. Optimising energy use, reducing waste, and selecting low-impact pre-processed ingredients offer significant opportunities to lower emissions across these production stages.

2 INTRODUCTION

2.1 The market

2.1.1 Meat processing

The European Union (EU), United Kingdom (UK) and Norwegian market for meat products is dominated by pork, poultry and beef meats (94% of the meat market in 2021 according to Food and Agriculture Organisation Corporate Statistical Database (FAOSTAT²) (Figure 1).

Almost 55% of meat products consumed are produced within the EU, UK and Norway. Approximately 19% (by mass) of meat is imported into and 27% exported out of the EU, UK and Norway (Figure 2).

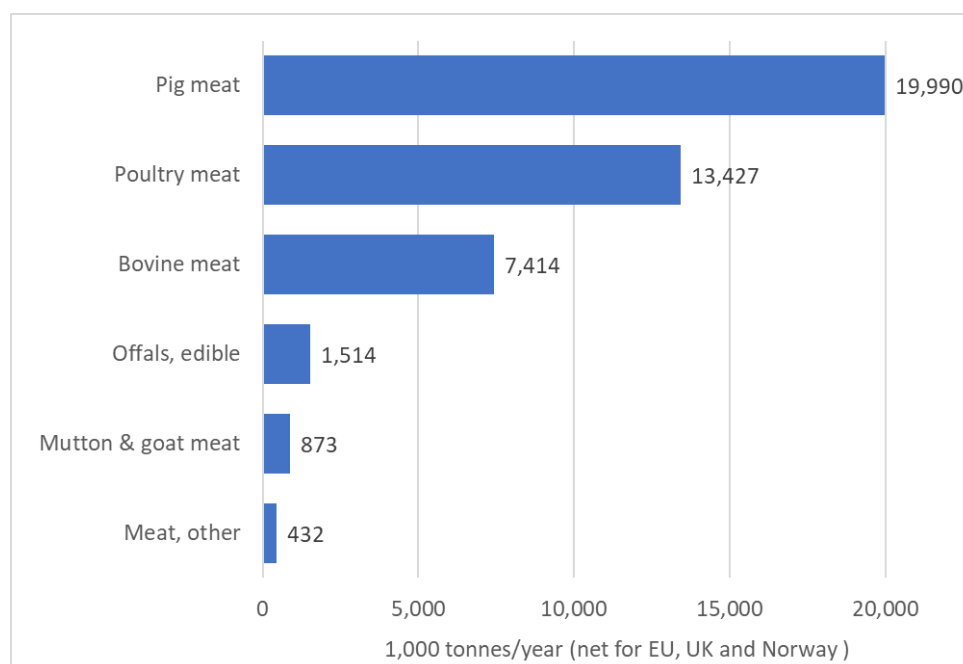


Figure 1. Net mass of meat products in the EU, UK and Norwegian markets in 2021 (from FAOSTAT).

² <https://www.fao.org/faostat/en/#data/FBS>.

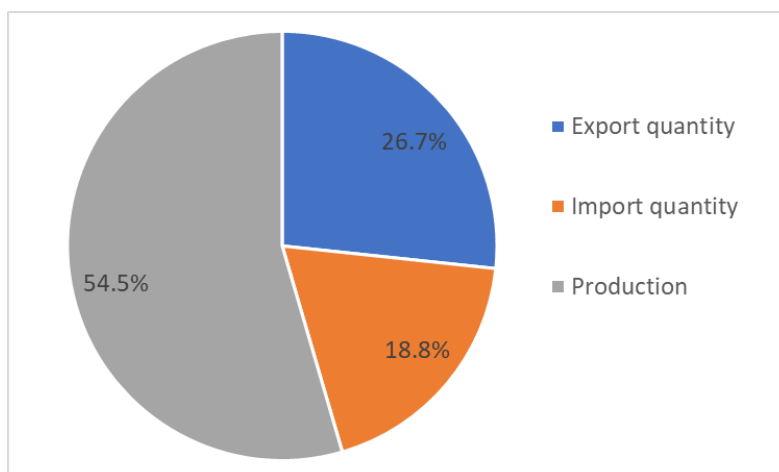


Figure 2. Percentage of exports, imports and home production for meat products in the EU, UK and Norwegian markets in 2021 (from FAOSTAT).

Figure 3 presents the mass of meat available per capita per year in the EU³. The per capita mass of poultry available for consumption has increased since the 1990's whereas at the same time the per capita mass of beef has decreased. Overall, the total mass of meat available for consumption per capita decreased between the mid 1980's and mid 1990's. Since the 1990's the available mass per capita has increased and had been relatively stable through the 2020's. In 2021 pork and poultry were the meats most available for consumption followed by beef. Sheep and goat meat and other meats had relatively low consumption compared to beef, poultry and pork.

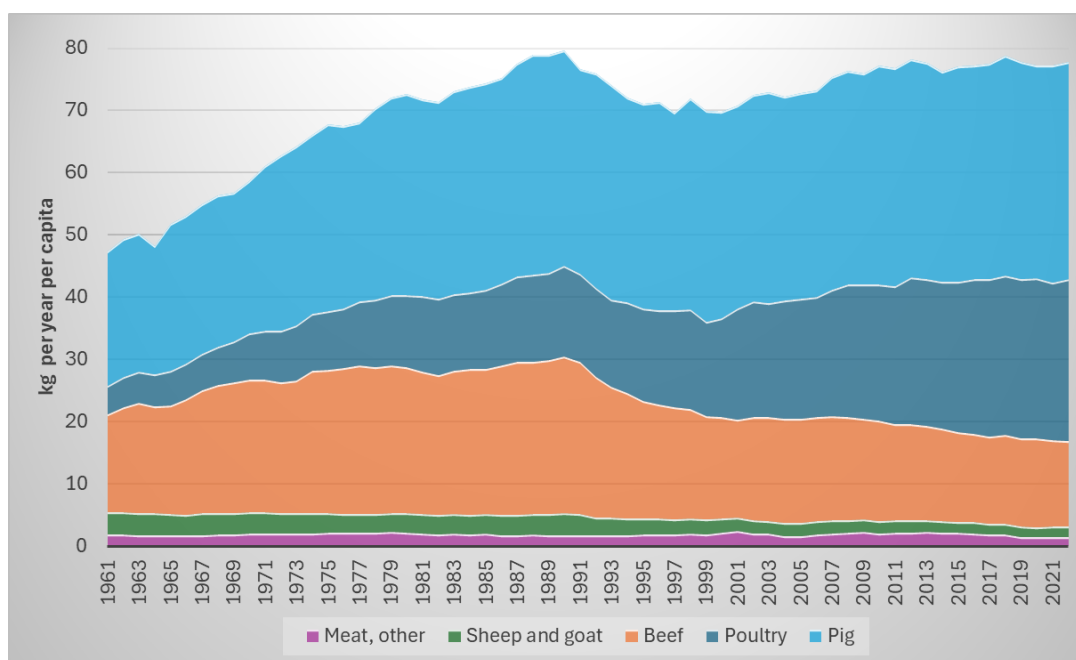


Figure 3. Meat available for consumption per capita in the EU (from FAOSTAT).

³ Food and Agriculture Organization of the United Nations (2024) – with major processing by Our World in Data. “Per capita consumption of poultry meat – FAO” [dataset]. Food and Agriculture Organization of the United Nations, “Food Balances: Food Balances (-2013, old methodology and population)”; Food and Agriculture Organization of the United Nations, “Food Balances: Food Balances (2010-)” [original data].

In terms total number of animals slaughtered for meat production in the EU (which does not include those used primarily for dairy or egg production which are not eventually used for meat) the production of chicken completely dominates the market (Figure 4)⁴. Since 2000 the numbers of chicken slaughtered has increased by approximately 70% whereas the numbers of other animals have reduced or remained stable.

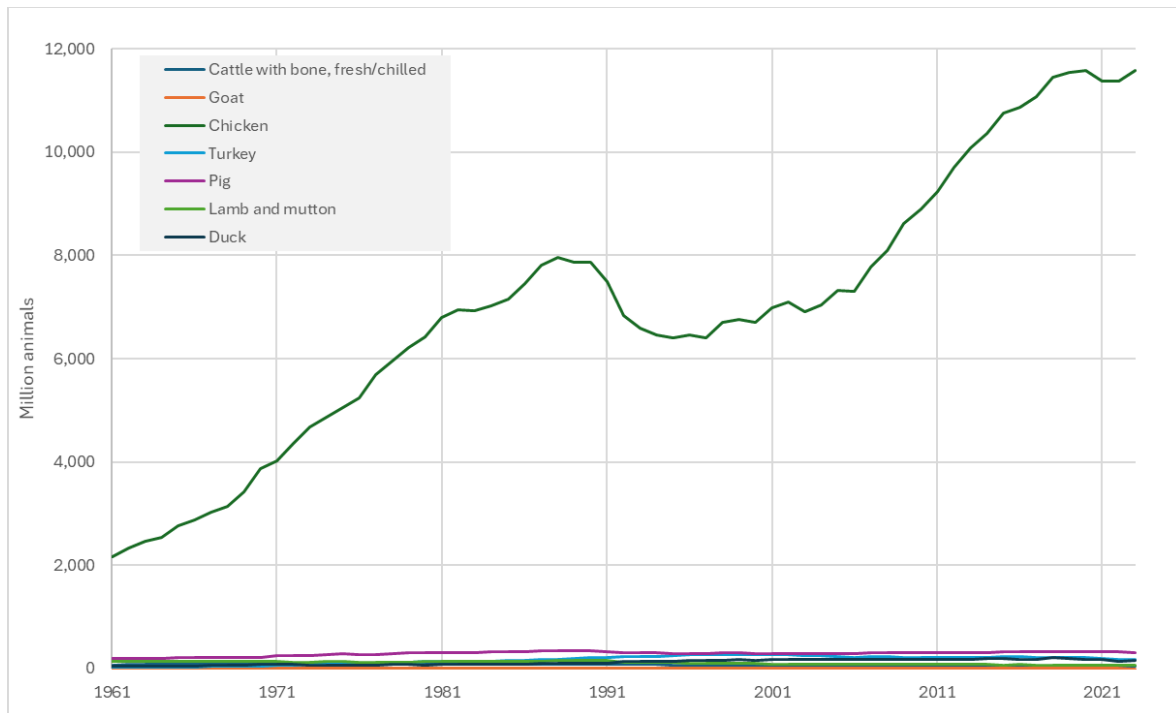


Figure 4. Total number of animals slaughtered for meat production in the EU (from FAOSTAT).

2.1.2 Fish processing

Globally, aquaculture and fishery production reached 223.2 million tonnes (Mt) live weight equivalent (LWE), in 2022 with aquaculture accounting for nearly 59% and capture fisheries for 41%. China dominated global production, followed by Indonesia and India (Figure 5)⁵**Error! Reference source not found.**

The EU is one of the largest players in the world seafood processing and trade market, handling vast amounts of both domestically caught and imported fish. The industry is shaped by strong internal trade, including close ties with Norway, and high consumer demand. In 2022, the total supply of aquaculture and fishery products to the EU was 12.71 Mt LWE, of which 8.78 Mt LWE was imported (Figure 6), valued at €32 billion. This high level of trade reflects the importance of processing activities, where fish is often imported, processed and then redistributed within the EU or exported globally. For example, Norway remains a net exporter, shipping 3.1 Mt of fish while importing 1.2 Mt. Much of Norway's seafood, particularly salmon, is exported gutted whole to EU processing hubs, such as Poland and Denmark, where it is filleted, portioned, and packaged before being re-exported or sold

⁴ Food and Agriculture Organization of the United Nations (2025) – with major processing by Our World in Data. “Number of cattle slaughtered for meat – FAO” [dataset]. Food and Agriculture Organization of the United Nations, “Production: Crops and livestock products” [original data].

⁵ FAO. 2024. FishStat: Global production by production source 1950-2022. [Accessed on 29 March 2024]. In: FishStatJ. Available at www.fao.org/fishery/en/statistics/software/fishstatj. Licence: CC-BY-4.0.

domestically (European market observatory for fisheries and aquaculture products (EUMOFA), 2023⁶, 2024⁷).

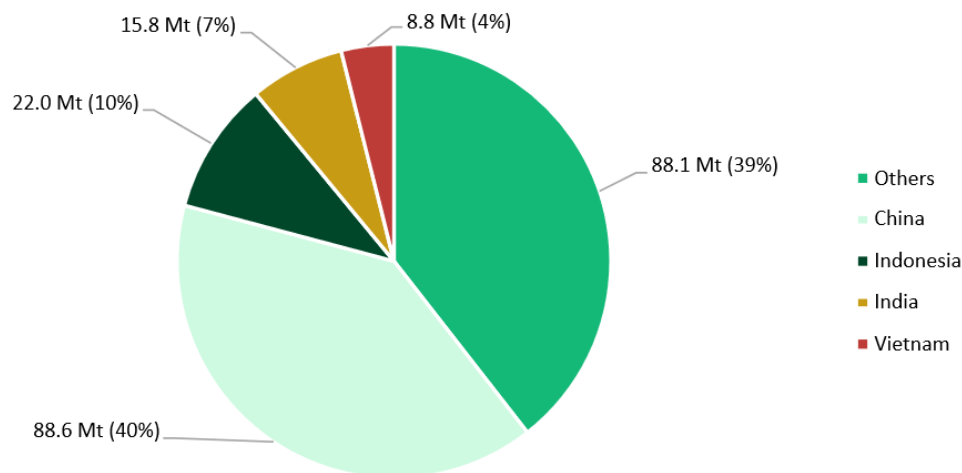


Figure 5: Global aquaculture and capture fishery production by selected countries. Figures in million tonnes LWE. Based on data from EUMOFA (2023).

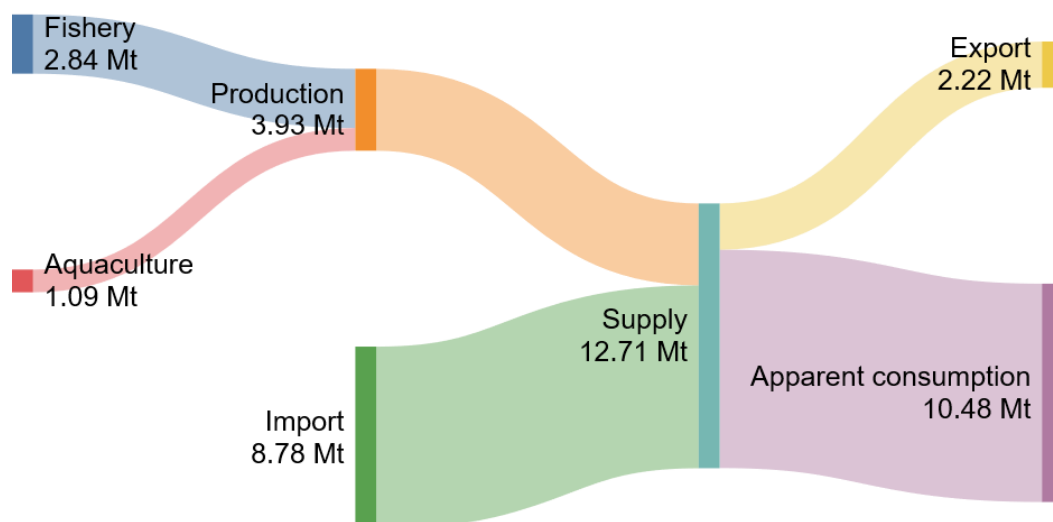


Figure 6: Supply balance in the EU for 2022. Figures in million tonnes LWE. Based on data from EUMOFA (2024⁷)

Seafood consumption in the EU reached 10.5 Mt in 2022, averaging 23.5 kg per capita per year. However, there are significant variations across member states: Portugal leads with 54.4 kg per capita, while Czechia has the lowest consumption at 5.9 kg per capita⁷. The per capita consumption in Norway was 54.8 kg. When it comes to consumer preferences, household expenditure data shows a clear preference for fresh or chilled fishery products, which account for 48% of fishery products spending, compared to 20% for frozen seafood (remaining 32% is dried, salted, smoked, preserved). Despite this,

⁶ European Commission: Directorate-General for Maritime Affairs and Fisheries, The EU fish market: 2023 edition. Publications Office of the European Union; 2023. Available from: doi/10.2771/38507.

⁷ European Commission: Directorate-General for Maritime Affairs and Fisheries, The EU fish market: 2024 edition. Publications Office of the European Union; 2024. Available from: doi/10.2771/9420236.

fishery products make up less than 1% of total household expenditure, whereas meat accounts for 3.6% (EUMOFA, 2024⁷).

In terms of species, salmon has been the most consumed fish over the past decade, although in recent years, tuna (various species) has taken the top spot. Another notable shift is that Alaska pollock has surpassed cod in consumption rankings. Interestingly, while pelagic fish dominate EU landings, including herring, sprat, blue whiting and mackerel, the most consumed fish species are primarily imported, highlighting the EU's reliance on external seafood supply chains (Table 1).

Table 1: Top apparent consumption and landed species in EU by volume in 2022. Figures in Mt. Based on data from EUMOFA (2024⁷).

Consumption and landings in EU, 2022, by volume per species (Mt)			
Top consumption (Mt)		Top landings (Mt)	
Tuna	1.33	Herring	0.46
Salmon	1.13	Sprat	0.34
Shrimps	0.75	Blue whiting	0.32
Alaska pollock	0.75	Mackerel	0.24
Cod	0.73	Sardine	0.17

The fish processing industry in Europe is highly interconnected, with many products undergoing processing in multiple countries before reaching the final consumer. For example, cod caught and landed in Norway might be exported to Poland for processing into consumer-ready meals, which are then distributed across Europe. This interconnected nature stems from a combination of economic factors and the structure of supply and demand. Coastal countries such as Norway and Iceland are natural hubs for landing wild-caught fish due to their proximity to rich fishing grounds, while aquaculture production has developed as an extension of established maritime traditions. However, the processing of seafood—particularly for labour-intensive tasks such as filleting, portioning, and breasting—has increasingly shifted to countries with lower labour costs. Despite advancements in automation, many processing steps still require manual precision, making labour costs a significant factor in the distribution of production activities across Europe.

2.1.3 Dairy processing to produce milk and cheese

According to Eurostat 2015 the EU is a major player in the global dairy industry, with over 12,000 dairy processing sites and approximately 300,000 direct jobs. Five of the world's top ten dairy companies are European, and the industry contributes significantly to the EU's trade balance, generating over €9.3 billion euros. For **2025**, EU milk production is forecasted to decline by 0.2% to 149.4 million metric tons (MMT), from an estimated 149.6 MMT in 2024. This contrasts with the 164.8 million tonnes produced in 2014.

In 2014, EU-28 farms produced around 164.8 million tonnes of milk, with cow's milk accounting for the vast majority (96.8%). The remaining 3.2% came from sheep, goats, and buffaloes. Most of this milk was delivered to dairies for processing, while a smaller portion was used on the farms themselves. Between 2013 and 2014, cow's milk production in the EU-28 increased by 3.8%, reaching 159.6 million tonnes. The EU-28's dairy herd of 23.6 million cows had an average yield of 6,777 kg per cow per year.

In 2024-and 2025 cow's milk continues to account for most of the total milk production in the EU. While specific recent percentages for other species are not as readily available for the whole EU-27, the trend of cow's milk being dominant persists.

Dairy Herd Decline: A key driver for the projected milk production decline is a shrinking dairy cow herd. EU dairy cow populations are projected to fall to 19.219 million head in 2025 from 19.912 million in 2023. This is a significant decrease from the 23.6 million cows in 2014. This trend is driven by factors such as low farmer margins, environmental regulations (e.g., related to the EU Green Deal's methane reduction targets), and disease pressures.

Germany and France were the leading milk-producing countries in the EU-28 in 2014. Germany accounted for 21.2% of all cow's milk collected, followed by France with 17.1%. While most EU countries primarily relied on cow's milk, Greece stood out with a higher volume of milk from other species than from cows. Italy and France also collected significant quantities of milk from other animals, but cow's milk remained their primary source.

In 2025 Germany and France are still typically the leading milk-producing countries in the EU. However, they are also experiencing declines. For instance, Germany's milk production is expected to decrease by 2.3% in 2025, while France's is projected to drop by 1.8%.

The milk delivered to dairies is processed into various fresh and manufactured dairy products. In 2014, approximately 68.8 million tonnes of raw milk in the EU-28 were used to produce primarily cheese, drinking milk, milk powder, butter, skimmed milk, and buttermilk.

The United Kingdom, despite accounting for only about 10% of the EU-28's milk production, contributed nearly 25% of the drinking milk produced in the region. Similarly, Germany, France, Italy, Netherlands, and the Poland of the 5.5 million tonnes of cheese produced across the EU-28 in 2014, highlighting their specialisation in specific dairy products (Figure 7).

In some EU Member States, like Italy, dairy installations often specialise in producing multiple subcategories of raw milk, including market milk, milk and milk derivatives, yogurt, vegetables, cheese (both soft and hard), and butter.

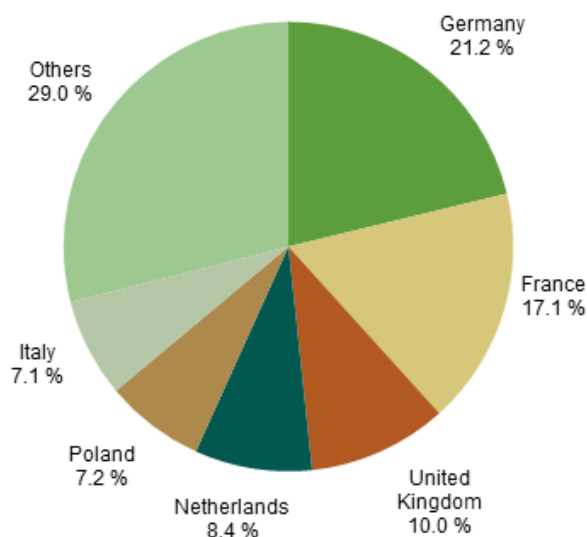


Figure 7. Collection of cow milk by dairies.

The milk collected by dairies is transformed into a variety of fresh and processed dairy products. In 2014, approximately 68.8 million tonnes of raw milk in the EU-28 were used to produce primarily cheese, drinking milk, milk powder, butter, skimmed milk, and buttermilk.

In 2025 the milk delivered to dairies is still processed into a diverse range of products. However, there's a notable strategic pivot towards cheese production due to strong domestic demand and export opportunities (Figure 8).

Cheese production is forecast to rise by 0.6% to 10.8 million metric tons (MMT) in 2025. This is a significant increase from the 5.5 million tonnes produced in 2014. Conversely, butter production is forecast to drop 1% to 2.1 MMT in 2025, and powdered milk (non-fat dry milk and whole milk powder) production is expected to fall by 4% and 5% respectively in 2025, as milk is prioritised for cheese. This indicates a shift from the trends seen in 2014 where milk powder and butter accounted for a larger share of processed milk.

Countries like Germany, Italy, and the Netherlands continue to be major players in cheese production. The UK's contribution to drinking milk production, while still significant, is now viewed in the context of its exit from the EU-28.

In summary, the EU dairy industry in the 2020-2025 period is characterised by a slight contraction in overall milk production driven by herd reduction, but a strategic focus on higher-value products like cheese. The sector remains economically vital, adapting to environmental pressures and evolving market demands.

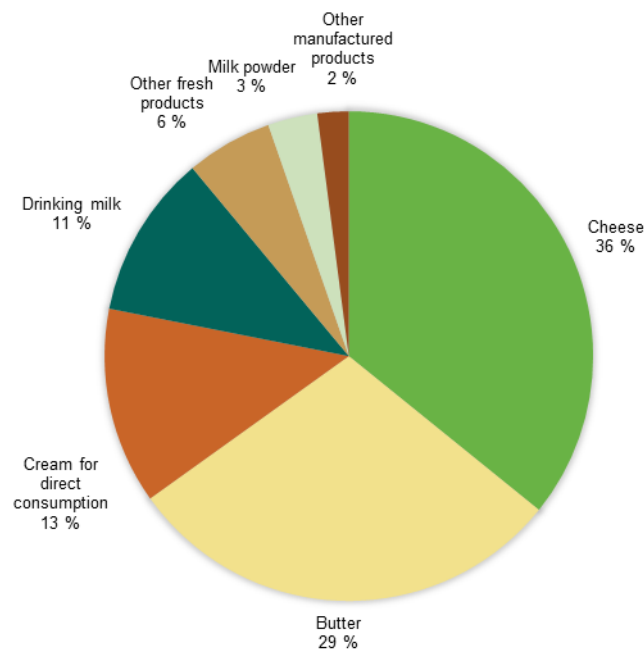


Figure 8. Utilisation of the whole milk in the EU-28 in 2014 (source Eurostat 2015).

2.1.4 Secondary processing to produce composite products

Prepared and semi-prepared products, such as pre-marinated meats and pre-cut vegetables, are gaining popularity due to their convenience. The semi-finished food market is experiencing steady growth, driven by changing consumer lifestyles and technological advancements in food processing. These products cater to busy consumers and food service providers, offering time savings and consistency in taste and quality.

The secondary processing of meat, fish, and dairy products in the EU encompasses a wide range of activities, including the production of ready-made dishes, prepared, and semi-prepared products for home cooking and catering. The processed meat market in Europe has been growing steadily, with revenues expected to reach over €155 billion by 2029⁸. Sausage sales alone were estimated at over

⁸ European Commission (2023). "EU Agricultural Outlook for Markets and Income 2023-2030."

€45 billion in 2024. The meat processing industry in Europe is substantial, with a market size of €330.2 billion in 2025. Despite challenges such as inflation and rising eco-consciousness, the industry is projected to grow annually by 4.65% from 2025 to 2030.

The fish processing market in Europe was valued at €5.6 billion in 2023 and is expected to reach €8.4 billion by 2030. This market is anticipated to expand at a compound annual growth rate (CAGR) of 5.9% between 2024 and 2030. The global fish fingers market size is anticipated to have a CAGR of 6.5% from 2023 to 2033⁹.

The dairy market in Europe is also significant, with a projected market size of €185 billion in 2025¹⁰. Milk remains a dominant product, with the EU producing 160 million tonnes of raw milk in 2022. This market is expected to grow to €230 billion by 2030, at a CAGR of 4.42%. The convenience store segment in the dairy market showed a 2.9% increase in sales value in 2022. Online channels are emerging as the fastest-growing segment in the dairy market, with cheese representing 66.3% of the online retail value share in 2022.

The EU's focus on sustainability and responsible sourcing practices is influencing the secondary processing industry. Reports from NGOs highlight the environmental impact of meat and dairy production, urging for stricter regulations and sustainable practices. Trade associations and industry reports provide valuable insights into market trends, consumer preferences, and the economic impact of secondary processing in the EU.

The growth in secondary processing of meat, fish, and dairy products in the EU has several implications. Firstly, the increasing demand for convenience foods is driving innovation in product development and packaging, leading to a more diverse range of products available to consumers. This trend is also pushing companies to invest in advanced processing technologies to improve efficiency and product quality.

Secondly, the emphasis on sustainability and responsible sourcing is prompting the industry to adopt more eco-friendly practices. This includes reducing waste, improving energy efficiency and GHG emission reduction, and sourcing raw materials from sustainable sources. These efforts are not only beneficial for the environment but also enhance the industry's reputation and appeal to eco-conscious consumers.

Lastly, the slow drifting of retail to online channels is changing the way consumers purchase processed food. The convenience of online shopping is likely to continue driving growth in this segment despite the challenges of a chilled supply chain. The last mile delivery of chilled processed foods is crucial for maintaining product quality and freshness¹¹. Efficient cold chain logistics and advanced route optimisation are essential to ensure timely and safe delivery to consumers.

2.2 Market drivers

In June 2021, the EU adopted a European Climate Law (ECL) which aims to reach net zero GHG emissions in the EU by 2050. In addition, the EU has a goal of reducing emissions by at least 55% below 1990 levels by 2030 (including land use, land-use change, and forestry (LULUCF)). This is implemented through the 'Fit for 55' package which is a set of policy proposals by the European Commission to

⁹ Spherical Insights LLP (2023) "Global Fish Fingers Market Size is Anticipated to Hold a Significant Share By 2033" Available at: www.sphericalinsights.com/press-release/fish-fingers-market.

¹⁰ European Dairy Association (2023). "Annual Report 2023." Available at: euromilk.org.

¹¹ Food Infotech (2025) 'Last-Mile Delivery: Challenges and Solutions in the Food Industry' Food Infotech, 9 January.

achieve the 55% reduction target. To achieve this target the EU has proposed a number of measures which include:

- the strengthening of the emissions reduction targets for each Member State;
- a Carbon Border Adjustment Mechanism (CBAM), putting a carbon price on imports of iron and steel, cement, aluminium, fertilisers and electricity.
- an increase of the target for renewable energy production to 40% by 2030;
- an update of energy efficiency targets for each Member State to 36-39% by 2030;
- a revision of the EU Emissions Trading System (ETS), and a new ETS for road transport and buildings;
- a revision of the Energy Taxation Directive, introducing an EU-wide minimum tax rate for polluting aviation and shipping fuels;
- higher carbon dioxide (CO₂) emission standards for cars and vans, requiring average emissions of new cars to come down by 55% from 2030 and 100% from 2035 compared to 2021 levels;
- an obligation for fuel suppliers at EU airports to blend increasing levels of sustainable aviation fuels in jet fuel through the ReFuelEU Aviation Initiative;
- a maximum limit on the GHG content of energy used by ships calling at European ports through the FuelEU Maritime Initiative;
- the introduction of an overall EU target for carbon removals by natural sinks, equivalent to 310 million tonnes of CO₂ emissions by 2030; and
- a new EU Forest Strategy, setting out a plan to plant three billion trees across Europe by 2030.

All this impacts the food cold chain which has significant emissions of GHGs. In particular the food processing sector in Europe generates carbon emissions and so has a role to play in the aimed for 55% reduction target. Information from the ENOUGH work package 1 indicates that 23% (range according to country evaluated of 12-35%) of emissions originate from food manufacture.

3 FOOD PROCESSING TYPES

3.1 Food processes

The food industry applies a wide range of processes which cover a range of temperature and other conditions. Figure 9 presents typical process temperatures conditions for cooling, heating and other thermal processing operations (created from internal data and Arpagaus et al¹²).

Cooling processes are almost entirely driven by grid electricity heating processes by fossil fuels. Data presented by FoodDrinkEurope indicates that the energy used and GHGs emitted from electrical and heating processes for different foods vary a great deal (Figure 10, Figure 11). For example, the energy/GHG for feed is many times greater than that for dried fruit/veg. On average 38% of the energy is used for electricity and 62% for heating.¹³ The division in terms of carbon is similar with 37% associated with electricity and 63% with heat.

¹² Arpagaus, C., Bless, F., Paranjape, S., Bertsch, S. S., 2023. Integration of high-temperature heat pumps in Swiss food processes. In: Proc. 26th IIR International Congress of Refrigeration (ICR 2023). Paper 367. Paris, France, August 24-30. International Institute of Refrigeration. DOI: 10.18462/iir.icr.2023.0367.

¹³ Decarbonisation road map for the European food and drink manufacturing sector. A report for FoodDrinkEurope. 2021. https://fooddrink europe.eu/wp-content/uploads/2021/09/Decarbonising-the-European-food-and-drink-manufacturing-sector_v2.pdf

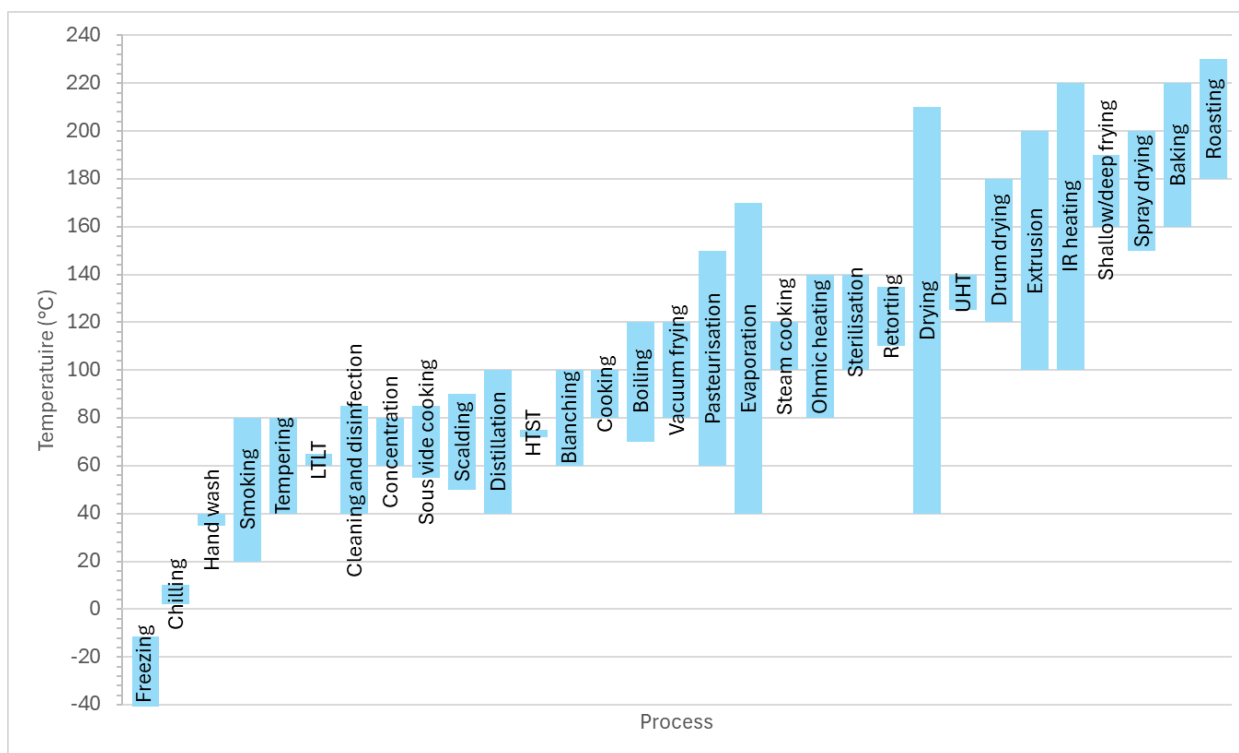


Figure 9. Temperatures typically applied across a range of food processes.

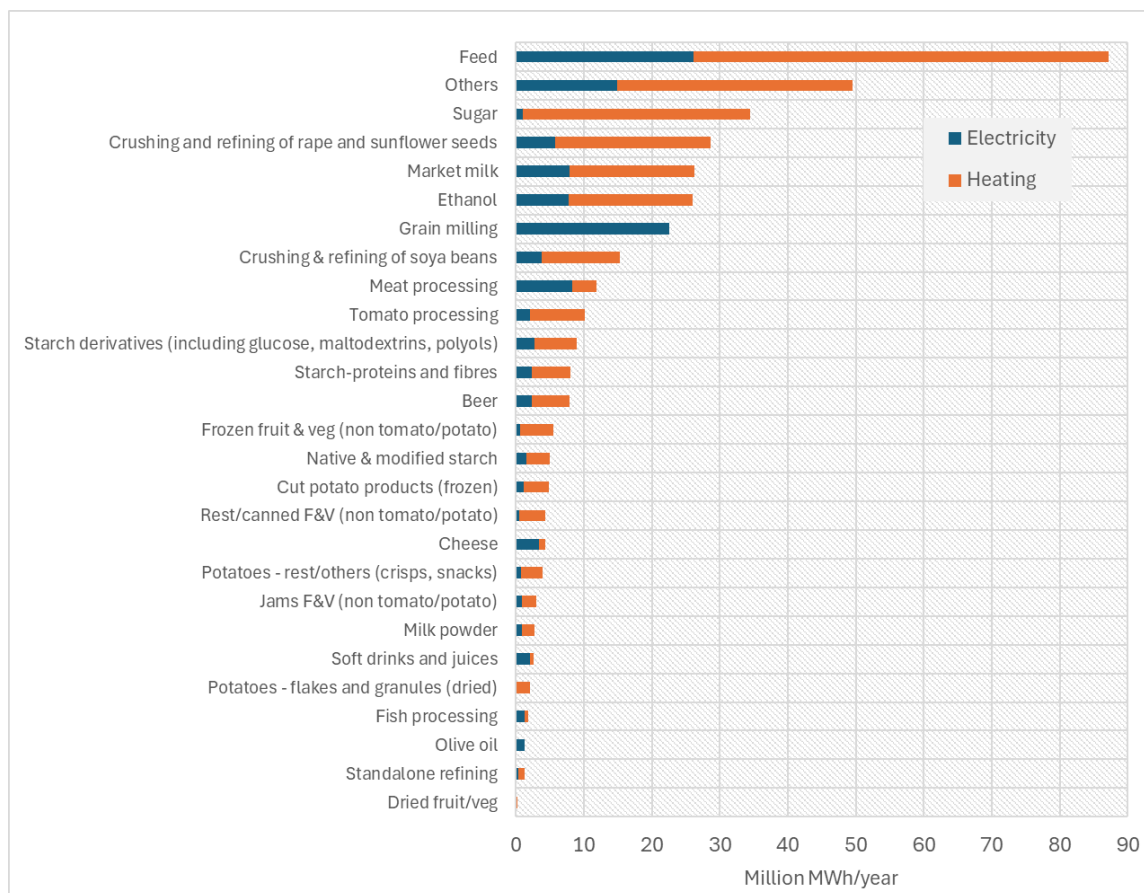


Figure 10. Energy used by electricity and heat for a range of food types¹³.

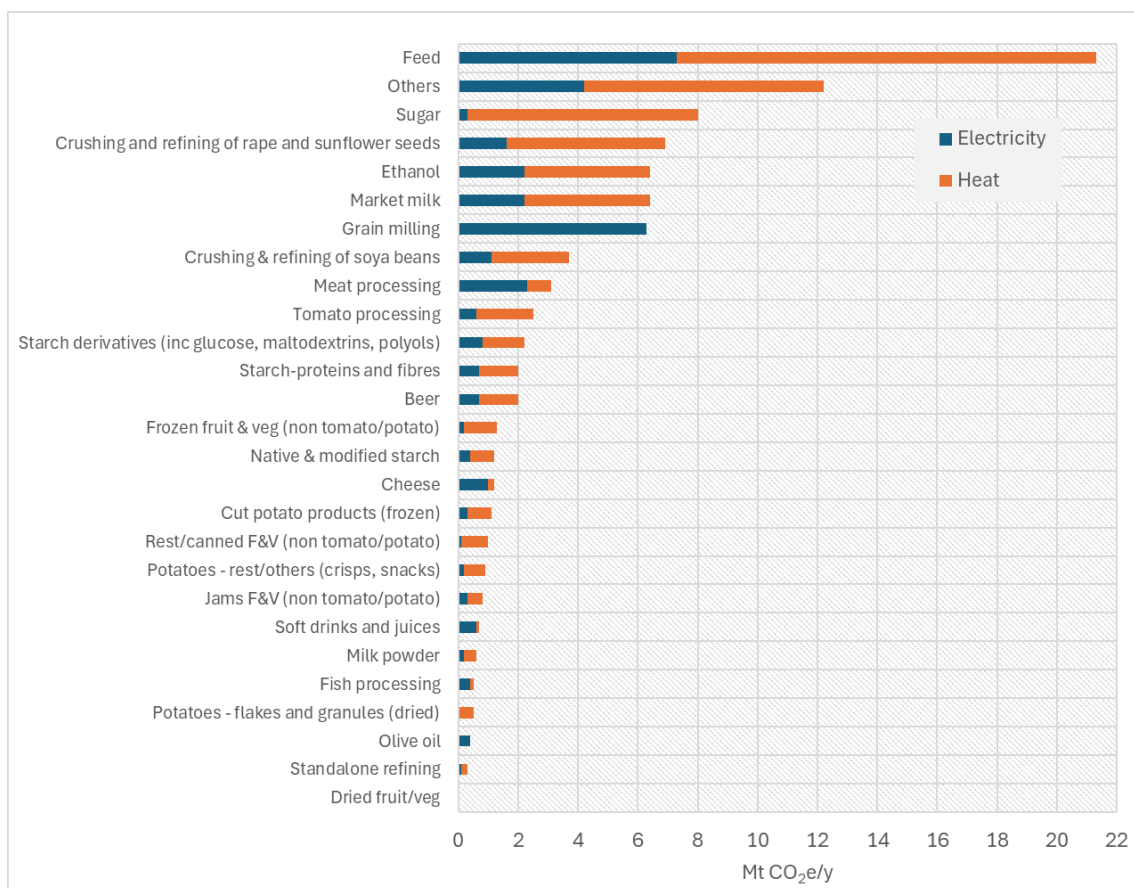


Figure 11. GHG emissions from electricity and heat used by a range of food types¹³.

3.2 Cooling processes

A range of processes are applied in food cooling (Table 2).

Table 2. Typical current cooling processes and where they are applied in food processing.

Process	Meat	Fish	Fruit	Vegetables	Milk
Carton/box freezer	✓	✓	✓	✓	
Evaporative and spray cooling	✓	✓	✓	✓	
Freeze drying	✓	✓	✓	✓	✓
Fluidised bed freezer			✓	✓	
Immersion chilling/freezing	✓	✓	✓	✓	
Liquid nitrogen (LN)	✓	✓	✓	✓	
Plate freezing	✓	✓			
Scraped surface heat exchanger					✓ (ice cream)
Spiral freezer/chiller	✓	✓	✓	✓	
Tunnel/belt chilling/freezing	✓	✓	✓	✓	
Vacuum cooling			✓	✓	✓

3.2.1 Primary chilling/freezing

Following harvest or slaughter, most food products will be chilled or frozen to minimise growth of microbial spoilage and/or food poisoning bacteria, reduce enzymatic or chemical changes and to minimise dehydration and mass transfer from the food. The time between harvest/slaughter and chilling/freezing for foods is often a critical factor for the ultimate quality of the food. After slaughter meat carcasses are at a temperature that is close to the optimum growth temperature for many microorganisms. Chilling is therefore vital to reduce the temperature of the meat to a value that limits microbiological and quality changes before the meat can be processed or distributed.

Most produce has a very limited life after harvest if held at ambient harvest temperatures. Post harvest cooling rapidly removes field heat, allowing longer storage periods. Proper post-harvest cooling can reduce respiratory activity and degradation by enzymes, reduce internal water loss and wilting, slow or inhibit the growth of microorganisms that causes decay and reduce the production of the natural ripening agent, ethylene.

Vegetable and herb production is characterised by its seasonal and highly perishable nature, with extremely rapid deterioration in quality at ambient temperatures after harvesting. A number of works have studied the problems of deterioration of flavour, texture, colour and vitamin in vegetables. Favell (1998)¹⁴ stated that the deterioration in vitamin C in peas, green beans, broccoli, carrots and spinach that occurs after harvest is accelerated by temperature and will continue until the product is blanched or frozen. Delays in elapsed time between harvesting and processing, pre-freezing treatments, freezing procedures, etc. can dramatically deteriorate the quality and safety of the products.

Most systems used to chill or freeze food use air because it is flexible, hygienic and is relatively non-corrosive to equipment. Air chilling or freezing produces much lower rates of heat transfer than contact or immersion technologies. However, this may not be a major issue for larger products sizes since conduction within the product often is the rate-controlling factor (

¹⁴ Favell, D.J. (1998). A comparison of the vitamin C content of fresh and frozen.

Table 3).

Heat transfer rates can be increased by raising the velocity (although increasing velocities above 10 m/s is rarely economic) or reducing the temperature of the air moving over the product. However, many chilled products are damaged at low temperatures (i.e. those below their initial freezing point) and reducing the air temperature is therefore not an option for all products. Where slower rates of chilling or freezing are acceptable evaporation from the surface of unwrapped products is often a problem. Excessive dehydration caused by slow chilling or freezing is an economic loss and reduces product quality.

Table 3. Raw material and primary chilling and freezing methods used.

Raw material	Primary chilling method(s)	Primary freezing method(s)
Meat	Forced air	Forced air Immersion
Fish	Packing in ice Refrigerated sea water (RSW) Ice/water slurry	Forced air Ice/water slurry Plate
Fruit	Forced air (rapid) Room cooling (slow) Hydrocooling	Forced air Fluidised bed
Vegetables	Forced air Hydrocooling Vacuum cooling Icing	Forced air Fluidised bed
Milk	Liquid cooling	n/a

The process selected to chill or freeze products depends on a number of factors including product quality requirements, available space for the process, cost for equipment, required cooling rates and practicality. A number of chilling/freezing methods are available currently and are broadly contact, air/gas or immersion methods. Contact systems (general freezers) have high heat transfer rates, faster cooling rates (often 1-5 hours dependent on operating temperature and product size^{15,16}, but generally require uniform blocks of product for easy handling. Heat transfer rates in plate freezers are suggested to be in the range of 50-500 W/m²K from different sources¹⁶ dependent on good contact between plates and product and freezing temperature.

Air systems are versatile for large product quantities. The cooling time of the product depends on the air temperature and velocity, as well as on how the products are stacked and the extent to which the room design permits a proper and even distribution of the air. Air systems include various designs such as tunnel systems, fluidised bed systems, and individual quick freezers (IQF), each offering different advantages.

ENOUGH DEMONSTRATOR: BLAST FREEZING

An ultra-low temperature CO₂ direct expansion unit for food blast freezing was developed. This was suitable for use in freezing tunnels, conveyor/tunnel bases freezers and spiral freezers. Fast freezing was achieved by applying an extremely low evaporation temperature and high air velocities. State-of-the-art technologies were applied for optimal use of heat transfer surface, capacity control, compressor and lubricant, defrosting and unit control.

A 120 KW (@-42°C evaporation temperature) blast freezer was installed near Milan- North Italy. The unit used to freeze pastry products. After modifications and improvements were applied the system demonstrated an improvement in energy efficient rate of about 15% compared to similar single stage HFC/HFO units.

¹⁵ Verpe, Espen H., Ignat Tolstorebrov, and Alexis Sevault. 2019. 'Cold Thermal Energy Storage with Low-Temperature Plate Freezing of Fish on Offshore Vessels'. Proceedings of the 25th International Congress of Refrigeration. <https://hdl.handle.net/11250/2670748>.

¹⁶ Kolbe, E., and D. Kramer. 2007. Planning for Seafood Freezing. Vol. 5040.

Air blast systems may cause moisture loss and increase energy consumption due to high fan loads (due to the need to distribute large volumes of air around the cooling chamber). Energy consumption linked to freezing processes is greater than for chilling processes, mainly because the compressors in the refrigeration system work across a higher-pressure range. The scientific literature contains examples of studies in which efforts have been made to boost the energy efficiency of such systems, such as by optimising compressor operation using variable frequency drives (VFDs) rather than slide regulation¹⁷, optimising air flow distribution¹⁸ and the use of variable air flow¹⁹. It therefore should be noted that optimisation of current systems is always a possibility that should be considered before changing to new systems.

3.2.2 Secondary processing

Most processes that occur after initial freezing or chilling are likely to cause the product to gain heat and consequently rise in temperature. Examples of secondary processes include cutting, packing, cooking and further treatments such as curing or smoking. This can range from a few degrees in a packing operation, to over 100°C in a cooking or pasteurisation operation. To maintain product quality, it is often important to remove this added heat as rapidly as possible after this operation has been completed. Industrial cooking processes cannot be guaranteed to eliminate all pathogenic organisms and if cooling rates are slow, microbial spores that survive the cooking process may potentially germinate and grow. Systems that produce a rapid reduction in the temperature of the food will retard microbial growth and consequently extend shelf life. This is especially important when chilling cooked products that will eventually be consumed cold or in a warm reheated state.

3.2.3 Batch systems

Batch chilling and freezing systems are generally best suited to larger, irregular shaped product or product that has been wrapped or palletised. Large individual items such as meat carcasses are hung from overhead rails, smaller products are placed either unwrapped or in cartons on racks, pallets, or large bins. Generally, products are placed in the chiller or freezer for relatively long periods of time and are handled in batches that fit into the working pattern of the factory (e.g. a 24 or 48 hour working cycle for meat chilling).

Most batch systems are based around an insulated room where air is distributed from an evaporator or evaporators. On occasions this room may be a store room where the air flow is often uneven and slow. Although not recommended, chamber freezing is often carried out due to availability of space to freeze product. When chamber freezing or chilling care needs to be taken that the temperatures of food at the centre of large pallets does not remain at a level where microbial growth can occur. For

¹⁷ Widell, Kristina Norne, and Trygve Magne Eikevik. 2010. 'Reducing Power Consumption in Multi-Compressor Refrigeration Systems'. *International Journal of Refrigeration* 33 (1): 88–94. <https://doi.org/10.1016/j.ijrefrig.2009.08.006>.

¹⁸ Alonso, Maria Justo, Trond Andresen, Frode Frydenlund, and Kristina Norne Widell. 2011. 'Improvements of Air Flow Distribution in a Freezing Tunnel Using Airpak'. *Procedia Food Science* 1 (January):1231–38. <https://doi.org/10.1016/j.profoo.2011.09.183>.

¹⁹ Kristófersson, Jóhannes, Lars Reinholdt, Kenneth Kramer, Alexander Rosenvinge Lindholm Bork, and Nis Peter Reinholdt. 2018. 'Energy Optimization of Batch Freezing Tunnel for Meat'. *Refrigeration Science and Technology*, 935–42. <https://doi.org/10.18462/iir.gl.2018.1328>.

example, Wanous et al. (1989)²⁰ found that sausages at the centre of a pallet required 6 to 7 days to achieve -15°C from a starting temperature of 7°C.

The main advantage of batch freezers and chillers is the flexibility to be able to chill or freeze a range of products. In practice, air distribution is often a major problem, often overlooked by the system designer and the operator. As the freezing time of the product is reduced as the air speed is increased, an optimum value exists between the decrease in freezing time and the increasing power required to drive the fans to produce higher air speeds. This optimum value can be as low as 1.0 m/s air speed when freezing beef quarters to 15 m/s plus for thin products.

Bulk product is often split up to enable faster freezing. For example, pallets often have spacer ('egg crates') inserted throughout the load to enable air to be distributed throughout the load. Although this results in thinner product layers it is vital to ensure that there is good air flow between each layer. This can only be achieved by blocking the free area around the pallet and forcing the air through the spacers (Figure 12).

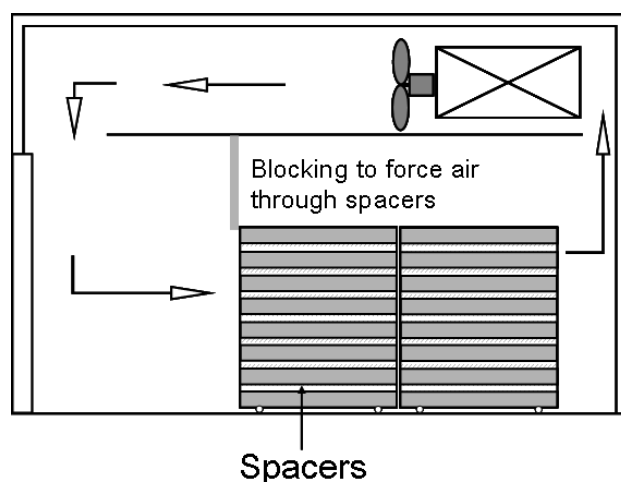


Figure 12. Batch pallet freezer.

Most chilling or freezing processes are single stage systems where the air temperature and velocity remain constant throughout the chilling or freezing process (single stage system). An alternative is a two-stage system where the air temperature and/or air velocity are changed at some point in the process. This can be especially advantageous when chilling as a low initial temperature can be used to rapidly reduce the surface temperature to a value just above its freezing point. The air temperatures can then be raised to prevent surface freezing. When freezing product, the air speed can be high in the initial stage to rapidly reduce surface product temperatures to close to the air temperature and can then be reduced in a second stage. Once the surface temperature of a large product is close to the air temperature conduction will be the major heat transfer mechanism and therefore high air velocities are no longer necessary. In addition, lowering the air velocity will reduce the fan heat load on the room and reduce energy consumption. Data presented by James and Bailey (1990)²¹ for a range of two-stage chilling systems for beef showed that chilling times to below 7°C could be achieved in under 18 hours

²⁰ Wanous, M.P., Olson, D.G. and Kraft, A.A. (1989). Pallet location and freezing rate effect on the oxidation of lipids and myoglobin in commercial fresh pork sausage. *Journal of Food Science*. Vol. 54:3, pp. 549-552.

²¹ James, S.J. and Bailey, C. (1990). Chilling of beef carcasses. In *Chilled Foods - The State of the Art*, Elsevier Science, 159-181.

and that weight loss was reduced by up to 1.37%. Likewise for pork James et al (1983)²² and Gigiel and James (1984)²³ have shown that all the initial peak heat load can be extracted from a carcass by a rapid initial chilling procedure followed by a slowed second stage. Weight loss was reduced by half compared to controls.

Weight loss from product is not only a quality issue but an economic loss. In a survey of beef slaughterhouses carried out in 1989 by Gigiel and Collett²⁴ they found that the cost of weight loss was 20 times that of the energy used in the chilling process (it should be noted that this would be less if applying current energy costs). Apart from two-stage processes another method to reduce weight loss is the use of ice bank chillers. These provide a high humidity air stream created from a bank of ice built up in a tank. The air from the room is cooled and humidified by direct contact with the cold water from the ice bank. Ice banks are commonly used for cooling fruit and vegetables but have also been used experimentally for meat cooling. In work carried out by Gigiel and Badran (1988)²⁵ pork carcasses lost 0.4% less weight when chilled, and an additional 0.9% less when stored, in an ice bank when compared to conventionally chilled controls.

3.2.4 Vacuum cooling

Vacuum cooling can be considered as a type of evaporative cooling, where the pressure is reduced to enhance evaporation of water from the product surfaces. Although this is widely claimed to offer more rapid cooling rates than for example air blast cooling, it also by its nature means that more water is lost from the product. This can be prohibitively costly for expensive products such as cooked meats. While initial capital costs for vacuum equipment are high, Feng et al 2012²⁶ for example pointed out that payback times would be expected to be medium to short as a result of increased throughput and lower energy consumption.

Vacuum cooling has been applied to various products, including meat (reviewed by Feng et al 2012²⁶), fruits and vegetables (reviewed by Rennie 2006²⁷). Although most publications focus on cooling rates and weight losses, some include comparative energy consumptions. Chen (1986)²⁸ claimed that vacuum cooling has the lowest energy cost per unit of cooled product compared to air cooling and hydrocooling. For fruits and vegetables, Thompson and Chen (1988)²⁹ compared the energy consumption of different cooling by means of an energy efficiency coefficient (cooling work/electricity use). The highest energy coefficient, indicating better efficiency, was obtained for vacuum cooling (1.8), followed by immersion cooling (1.4), water spray vacuum cooling (1.1), and air blast (0.4). Wang

²² James, S.J., Gigiel, A.J. and Hudson, W.R. (1983). The ultra rapid chilling of pork. *Meat Sci.* 8, 63-78.

Market Transformation Programme – <http://www.mtprog.com/>.

²³ Gigiel, A.J. and James, S.J. (1984). Electrical stimulation and ultra-rapid chilling of pork. *Meat Sci.* 11, 1-12.

²⁴ Gigiel, A. and Collett, P. Energy consumption, rate of cooling and weight loss in beef chilling in UK slaughter houses. *J Fd Eng*, 10 (1989), 255-273.

²⁵ Gigiel, A.J. and Badran, R.J. (1988). Chilling and storage of pig carcasses using high humidity air as produced by an ice bank cooler. *Int. J. Refrig.* 11, 100-104.

²⁶ Feng, C., Drummond, L., Zhang, Z., Sun, D.W. and Wang, Q., 2012. Vacuum cooling of meat products: current state-of-the-art research advances. *Critical reviews in food science and nutrition*, 52(11), pp.1024-1038.

²⁷ Rennie, T.J., 2006. Vacuum cooling for the fruit and vegetable industry. *Stewart Postharvest Review*, 1(7).

²⁸ Chen, Y. L. (1986). Vacuum cooling and its energy use analysis. *Journal of Chinese Agricultural Engineering*, 32, 43-50.

²⁹ Thompson, J.F. and Chen, Y.L., 1988. Comparative energy use of vacuum, hydro, and forced air coolers for fruits and vegetables. *ASHRAE Transactions*, 92, pp.1427-1433.

and Sun (2001)³⁰ claimed that to vacuum cool one tonne of lettuce, the energy consumption would be 0.56 kWh for a 1°C reduction in temperature, compared to 3.7 kWh for the same temperature change with hydro cooling. The coefficient of system performance (COSP) for the vacuum cooler would be 2.65 whereas for the hydro cooler it would be 1.2 and forced air cooling would be 0.52. Chen (1986)²⁸ however, stated that COSPs vary considerably according to the type of product and load within the cooling chamber.

Zhu et al 2019³¹ reviewed some factors and methods which can improve vacuum cooling performance, including pre-spraying of water, immersion vacuum cooling and optimisation of final pressure. They also claimed that vacuum cooling is far more energy efficient than options such as air blast cooling, although limited information was presented to validate this.

3.2.5 Continuous systems

Continuous chilling and freezing systems are generally suited to smaller products with shorter chilling or freezing times. Generally, products tend to be uniform in shape and the system is designed specifically for certain product types. Therefore, such systems have a limited flexibility and cannot often chill or freeze a large range of product sizes. In a continuous system product is often conveyed through a tunnel or room by an overhead conveyor or on a belt. This overcomes the problem of uneven air distribution since each item is subjected to the same velocity/time profile. The time spent in the chiller or freezer (residence time) is generally low to reduce the amount of floor space required for the equipment.

3.2.5.1 Carton/box freezer

Carton freezers are used for freezing small cartons such as those containing ice cream. Box freezers are used for freezing boxed product such as meat, fish and poultry. The cartons or boxes are loaded automatically onto an upper track and are hydraulically pushed through a freezer. Tracks are placed at many levels and the product is lowered between each level to the exit (Figure 13). Freezing is usually accomplished in 3 to 24 hours.

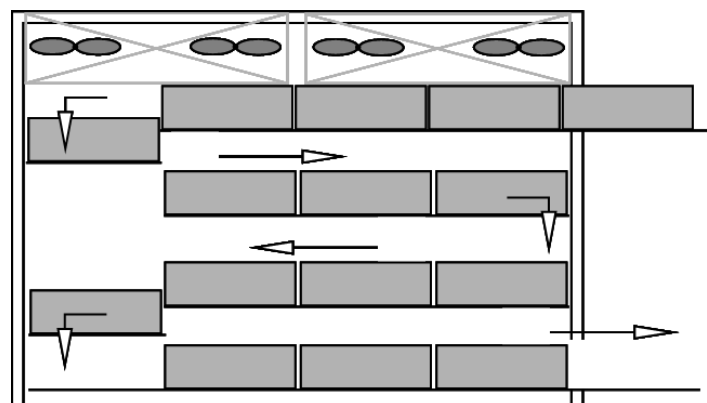


Figure 13. Carton/box freezer.

³⁰ Wang, L. And Sun, D-W. (2001). Rapid cooling of porous and moisture foods by using vacuum cooling technology. Trends in Food Science and Technology 12 (2001) 174–184.

³¹ Zhu, Z., Geng, Y. and Sun, D.W., 2019. Effects of operation processes and conditions on enhancing performances of vacuum cooling of foods: A review. Trends in food science and technology, 85, pp.67-77.

3.2.5.1.1 Tunnel/belt

Product is conveyed through a tunnel usually by an overhead conveyor or on a belt. Most commonly air is directed across the product (Figure 14) but may be directed at the product from above when a belt is used to convey product. The product should be evenly spaced so uniform air flows around the product can be achieved. Generally, most chillers/freezers are restricted to one product size and shape so that product loading can be optimised. However, often racks or trolleys are used to enable a range of products to be processed.

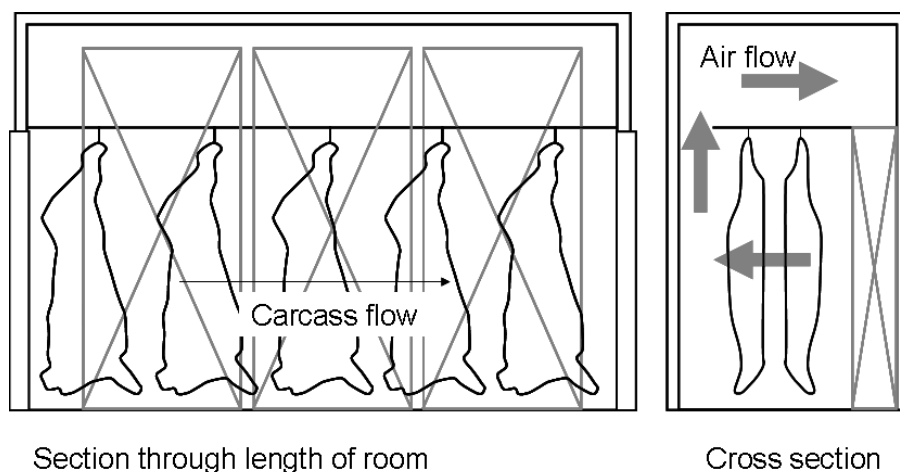


Figure 14. Tunnel freezer.

The temperature of the freezing media used in freezing tunnels is typically between -35°C and -52°C ³². The freezing time of the product depends on the air temperature and velocity, as well as on how the products are stacked and the extent to which the room design permits a proper and even distribution of the air.

The optimal operation and design of freezing tunnels are key to achieving significant energy savings and reducing GHG emissions, which are vital for both economic efficiency and environmental sustainability. In 2004, it was estimated that 20-30% of the total energy used in a blast freezer could be saved³³, a figure that remains relevant for older systems. Field measurements and Modelica modelling of a fish batch freezing system in Norway were conducted, revealing a potential energy efficiency improvement of 10%³⁴.

³² Dempsey, Patrick, and Pradeep Bansal. 2012. "The art of air blast freezing: Design and efficiency considerations." *Applied Thermal Engineering* 41: 71-83. Accessed 10 1, 2024. <https://sciencedirect.com/science/article/pii/S1359431111007101>.

³³ James, Stephen J., and Christian James. 2004. "Improving energy efficiency within the food cold-chain." In *Encyclopedia of meat sciences*.

³⁴ Bjurhult, Thomas Helleland. 2024. Performance analysis of industrial refrigeration systems for freezing tunnels. Master Thesis, Trondheim: NTNU.

Walnum et al.³⁵ and Widell et al.³⁶ analysed the operation of fans in freezing tunnels and demonstrated theoretically that energy usage could be reduced by up to 33% by lowering fan revolutions per minute (RPM) or turning off the fans towards the end of the freezing cycle, if a longer freezing period was acceptable. By introducing baffles to direct the flow to where it is needed and reducing the air flow further down whilst still maintaining the required final product temperature, Kramer and Kristofersson³⁷ identified even greater potential, predicting energy savings of up to 93%.

3.2.5.2 Liquid nitrogen (LN)

In air based cryogenic systems, a cryogen (usually liquid nitrogen) is either sprayed directly onto product in a tunnel or is expanded in a heat exchanger which is used to cool air blown around a tunnel. In these systems the cryogen is generally 'lost' to atmosphere after the freezing process and so a large store of the cryogen that is regularly refilled is required for operation. Cryogenic systems generally achieve very fast freezing rates (it has been reported by Rodezno et al 2013³⁸ that compared to blast freezing that cryogenic freezing can be 3 times faster), but the high operational costs restrict their use to high value products.

Cryogenic freezing involves the use of liquid nitrogen (at -195.8°C) or liquid CO₂ (at -78.5°C), which are either dispersed across the products or used as immersion media. Freezing using this method is very fast but incurs much higher operating costs than established mechanical freezing. Cryogenic freezing results in some product freeze damage, although this can be reduced by precooling or by reducing the temperature difference between the product and the freezing media^{39;40}.

Cooper (1980)⁴¹ collated and compared the costs for a number of freezing operations. When freezing beefburgers the overall operating costs (investment, fixed costs and variable costs) to freeze using liquid nitrogen or carbon dioxide were almost double those required for freezing a conventional spiral freezer. Although operational costs for the liquid nitrogen and carbon-dioxide plants were more than the spiral freezer, if the costs of evaporative weight loss was taken into account the overall differences between operating costs between the 3 systems was considerably less (Figure 15). In a more recent

³⁵ Walnum, Harald T., Trond Andresen, and Kristina N. Widell. 2011. "Dynamic simulation of batch freezing tunnels for fish using Modelica." International Congress of Engineering and Food. Athens, Greece: Procedia Food Science. 698-705.

³⁶ Widell, Kristina N., and Trygve Eikevik. 2012. "The effect of reduced air fan speed on freezing time and energy consumption in a freezing tunnel." Gustav Lorentzen Conference. Delft, The Netherlands.: International Institute of Refrigeration.

³⁷ Kramer, Kenneth Rugholm, and Johannes Kristofersson. 2018. Energy optimization of batch freezing tunnel for meat. Project report, Danish Technological Institute.

³⁸ Rodezno, L.A.E., Sundararajan, S., Solval, K.M., Chotiko, A., Li, J., Zhang, J., Alfaro, L., Bankston, J.D. and Sathivel, S., 2013. Cryogenic and air blast freezing techniques and their effect on the quality of catfish fillets. LWT-Food Science and Technology, 54(2), pp.377-382.

³⁹ Dalvi-Isfahan, Mohsen, Piyush Kumar Jha, Javad Tavakoli, Amir Daraei-Garmakhany, Epameinondas Xanthakis, and Alain Le-Bail. 2019. 'Review on Identification, Underlying Mechanisms and Evaluation of Freezing Damage'. Journal of Food Engineering 255:50–60. <https://doi.org/10.1016/j.jfoodeng.2019.03.011>.

⁴⁰ Mulot, Violette, Hayat Benkhelifa, Didier Pathier, Fatou Toutie Ndoeye, and Denis Flick. 2019. 'Measurement of Food Dehydration during Freezing in Mechanical and Cryogenic Freezing Conditions'. International Journal of Refrigeration 103:329–38. <https://doi.org/10.1016/j.ijrefrig.2019.02.032>.

⁴¹ Cooper, T. J. R. Engineering Development Report, September 1980.

example, Chourot et al 2003⁴² compared cryogenic freezing of strawberries with air blast and immersion freezing. Both the overall process costs and electrical energy costs were considerably higher for the cryogenic process, although energy consumption figures were not directly presented.

It is difficult to directly compare the energy consumptions for the three systems as the energy consumption for production of the cryogens should be included. This varies considerably (a new cryogen plant may consume half the energy of an older less efficient one) and is not widely reported by the cryogenic industry. Production of cryogens is however very energy intensive, so cryogenic freezing is unlikely to save energy compared with most conventional freezing processes.

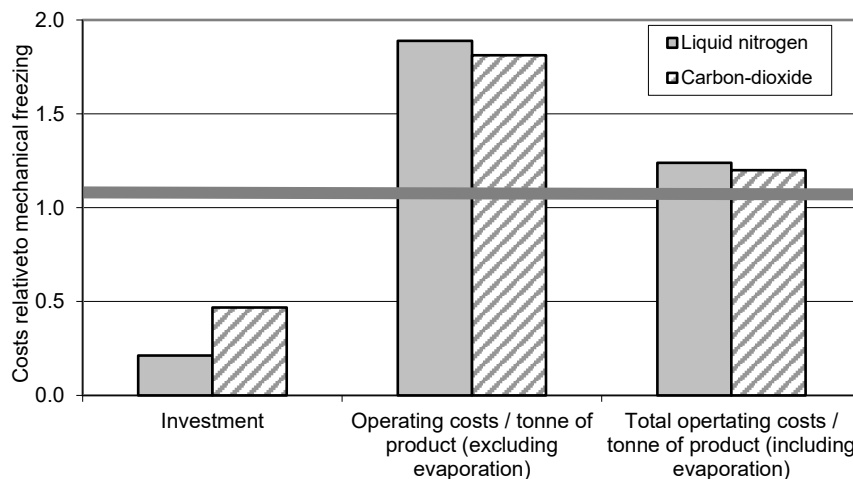


Figure 15. Costs of freezing burgers in nitrogen and carbon-dioxide relative to mechanical freezing (from Cooper, 1980).

3.2.5.3 Fluidised bed

Fluidised beds are usually used to freeze small IQF product such as small fruits or vegetables, meat mince or prawns. The product travels through a tunnel on a mesh belt and air is blown from underneath the belt onto the product. Air velocities are sufficient to partially fluidise the product and therefore product does not clump together, and each item is frozen individually. Product is fed in at one end of the freezer and overflows from the exit (Figure 16). Often the bed is angled or shaken to assist product flow. High heat transfer coefficients are achieved due to localised high air velocities over the surface and therefore freezing times are short. Due to the small product and the short freezing time these systems can be compact.

IQF, in particular, is efficient for rapid freezing at a lower cost than cryogenic methods. A performance analysis on the IQF technology suggests that processing times are markedly lower than compared with conventional belt tunnel freezers and on par with that of cryogenic freezing, but at a noticeably lower operating cost (Salvadori and Mascheroni 2002⁴³).

⁴² Chourot J M., Macchi H, Fournaison L and Guilpart J (2003), Technical and economical model for the freezing cost comparison of immersion, cryomechanical and air blast freezing processes, *Energy Conservation and management*, 44, 559-571.

⁴³ Salvadori, Viviana O., and Rodolfo H. Mascheroni. 2002. 'Analysis of Impingement Freezers Performance'. *Journal of Food Engineering* 54:133-40. [https://doi.org/10.1016/S0260-8774\(01\)00198-4](https://doi.org/10.1016/S0260-8774(01)00198-4).

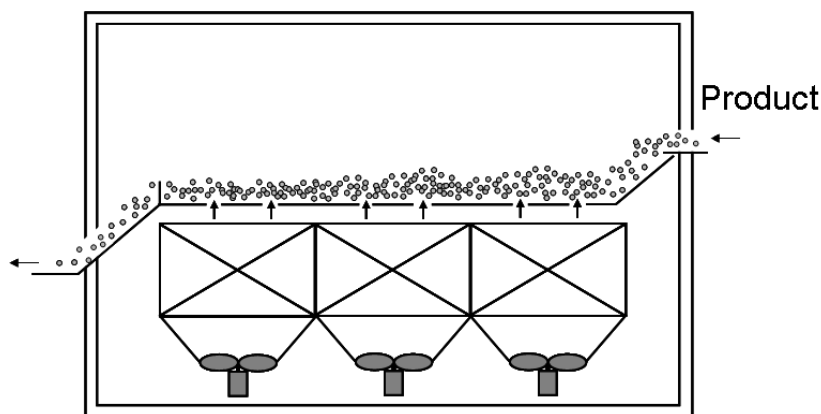


Figure 16. Fluidised bed freezer.

3.2.5.4 Spiral freezer/chiller

Spiral chiller/freezers generally require a smaller footprint than tunnel chiller/freezer but tend to be taller. They are constructed on a belt that is stacked in a spiral of up to 50 layers (Figure 17). Therefore, they allow a long belt to be used in a small area of the production plant. Air flow can be either horizontally through the stacks or vertically through the belt.

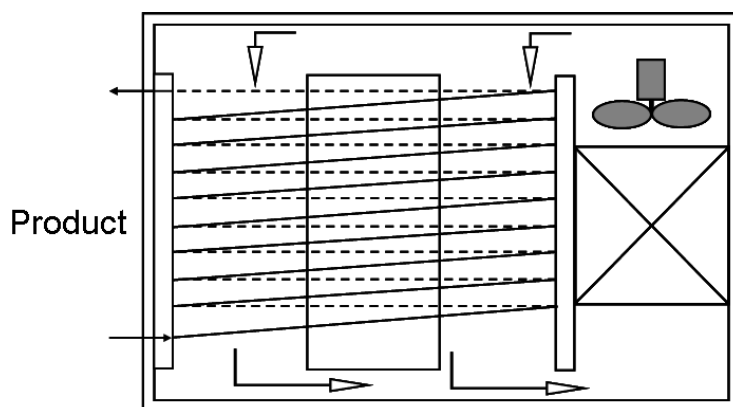


Figure 17. Spiral freezer/chiller.

3.2.5.5 Evaporative and spray cooling

Evaporating water from the surface of foods has a cooling effect. However, water loss affects yield, eating quality and sales value. Spray chilling can be used to replenish surface water during chilling to maintain an evaporative cooling effect and avoid surface drying. Spray chilling is common in poultry

chilling⁴⁴ and is used for other meat products like beef⁴⁵), lamb⁴⁶ and pork⁴⁷. It also has applications for other foods, particularly storage of fruits and vegetable as reviewed by Lal Basediya et al⁴⁸.

For all these food types undergoing primary chilling, the focus of research has been on savings in evaporative weight loss, impact on quality and safety. Potentially the faster cooling times can reduce energy usage, although this has received little attention, probably as the reductions in cooling time are relatively small. For storage applications with various fruits and vegetables however, reductions of up to 70% in cooling energy were claimed by Lal Basediya et al⁴⁸.

3.2.5.6 Batch or continuous systems

Some systems can be configured as either batch or continuous systems. These include the following systems.

3.2.5.7 Immersion chilling/freezing

Immersion systems are often batch systems but can also be designed as continuous cooling systems. Liquid cooling media offer high surface heat transfer coefficients in comparison with air blast cooling (agitated or impinging liquids can produce heat transfer coefficients over 500 Watt per square meter per Kelvin [$\text{Wm}^{-2}\text{K}^{-1}$], a factor of 10 or more higher than air). Such heat transfer coefficients enable rapid cooling of small, high surface area products but are less effective for large, thick products which are limited by conduction of heat from the inside. Such products need to be reduced in size before immersion, for example by hot cutting of carcasses or portioning of bulk food items. Additionally, in many food applications the foods must be wrapped in sealed packaging such as vacuum packs to prevent transfer of the cooling medium into the food.

ENOUGH DEMONSTRATOR: BRINE FREEZING OF FISH

Brine freezing has good heat transfer properties that can improve the energy efficiency of this process, however, but is not widely used. The demonstration activities explored the implications of introducing brine freezing into different seafood production chains, focused on potential reductions in energy consumption, quality attributes and practical aspects.

The demonstration activity evaluated brine freezing as an alternative to other freezing methods for:

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

The work found that brine freezing could reduce the freezing time of fish by up to 50%. Energy consumption could be reduced by up to 14%.

⁴⁴ Klose, A.A., 1975. Perspective on evaporative chilling of poultry. Poultry Science, 54(6), pp.1889-1893.

⁴⁵ Allen, D.M., Hunt, M.C., Filho, A.L., Danler, R.J. and Goll, S.J., 1987. Effects of spray chilling and carcass spacing on beef carcass cooler shrink and grade factors. Journal of Animal Science, 64(1), pp.165-170.

⁴⁶ Brown, T., Chourouzidis, K.N. and Gigiel, A.J., 1993. Spray chilling of lamb carcasses. Meat Science, 34(3), pp.311-325.

⁴⁷ Jones, S.D.M., Murray, A.C. and Robertson, W.M., 1988. The effects of spray chilling pork carcasses on the shrinkage and quality of pork. Canadian Institute of Food Science and Technology Journal, 21(1), pp.102-105.

⁴⁸ Lal Basediya, A., Samuel, D.V.K. and Beera, V., 2013. Evaporative cooling system for storage of fruits and vegetables-a review. Journal of food science and technology, 50, pp.429-442.

An example of the above factors was studied by Brown et al⁴⁹ who immersion chilled hot cut pork primals which were vacuum packed prior to chilling. Weight loss during chilling was reduced by 1.9 percentage points in immersion chilled samples compared to air chilled samples, and chilling times were between 2.3 and 3.5 hours less than conventional treatments. Energy input to the chilling systems was not measured, but the faster chilling can offer reductions in energy consumption. Pump power for circulating the liquid must be considered, as this is likely to exceed the fan power used in air blast cooling.

Immersion is widely used for poultry chilling, with significant numbers of publications. James et al⁵⁰ reviewed many of these up to that date. However, the focus of most of the publications is on bacterial and quality impacts of the process and no measured data on energy consumption is presented. In a more recent study Ren et al⁵¹ chilled and froze beef muscles and compared quality with air blast frozen beef. Temperature reduction curves showed that immersion was far quicker than air blast. For some other products Lucas and Raoult-Wack⁵² presented a review of fluids and conditions used in previous studies and included limited comments on energy use (for example 25% energy was saved by immersion of small pieces of vegetables rather than air blasting them).

Other authors have looked at immersion chilling of small products, such as strawberries. For example, Chourot et al⁵³ developed a model to compare freezing costs that included product parameters, refrigeration system characteristics and costs for operation as well as investment. Costs for freezing strawberries using mechanical, immersion freezing and cryomechanical freezing were compared. The results indicated that immersion freezing was the cheapest process and cryomechanical the most expensive. The electrical energy costs for the processes were similarly ranked, with those for immersion appearing (on a chart) to be approximately half those for air blast (Figure 18).

Brine freezing, used less frequently today, offers high heat transfer and energy efficiency but faces practical challenges such as brine spillage and equipment corrosion. The term 'brine' may include glycols and other similar liquids, but usually refers to solutions containing salts such as sodium chloride (NaCl) or calcium chloride (CaCl₂), which have their eutectic points at -21°C and -55°C, respectively¹⁶. Brine freezing has the potential to provide refrigeration with both high heat transfer and high energy efficiency. It should be noted however that the practical operating temperatures of the brines must be higher than their eutectic points, due to issues with ice formation in the heat exchangers and the fact that high viscosities at low temperatures require high levels of pumping power.

⁴⁹ Brown, T., Giegel, A.J., Veronica, M., Swain, L. and Higgins, J.A., 1988. Immersion chilling of hot cut, vacuum packed pork primals. *Meat Science*, 22(3), pp.173-188.

⁵⁰ James, C., Vincent, C., de Andrade Lima, T.I. and James, S.J., (2006). The primary chilling of poultry carcasses—a review. *International Journal of Refrigeration*, 29(6), pp.847-862.

⁵¹ Ren, W., Yuan, G., Lin, X., Guo, X. and Wang, Z., 2021. Comparison of the immersion chilling and freezing and traditional air freezing on the quality of beef during storage. *Food Science and Nutrition*, 9(12), pp.6653-6661.

⁵² Lucas, T. and Raoult-Wack, A.L., (1998). Immersion chilling and freezing in aqueous refrigerating media: review and future trends. *International Journal of Refrigeration*, 21(6), pp.419-429.

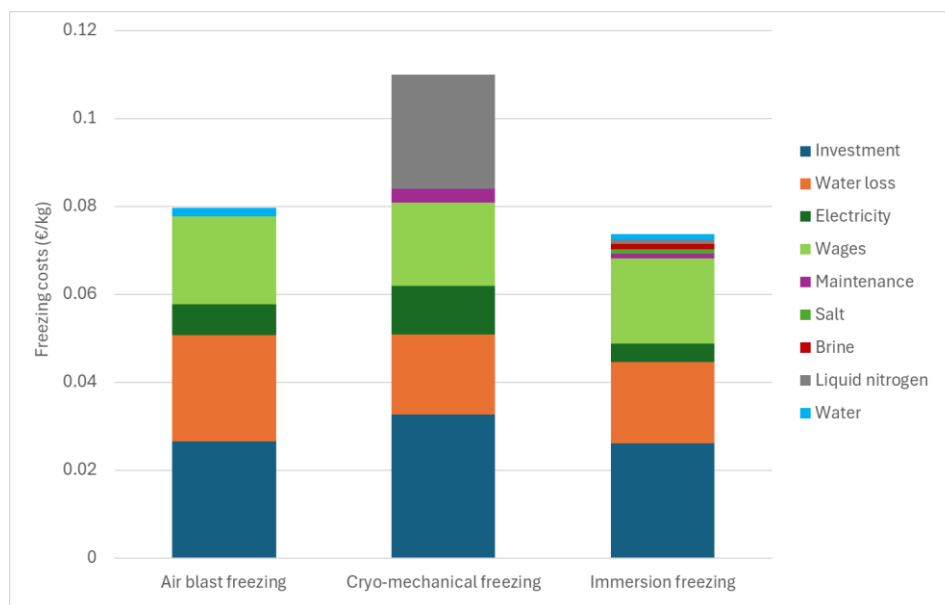


Figure 18. Comparison of the distributed costs of three freezing techniques (strawberries, 0.61 €/kg, 500 kg/h, 2000 h/year) (Chourot et al, 2003⁵³).

For bulk produced products such as sauces, few publications relate to immersion colling. However, Ketteringham and James, 1999⁵⁴ used experiments and mathematical modelling to study immersion chilling of sealed trays of several food slurries (beef chilli, Bolognese sauce, beef curry and ‘chicken Italian’). They found substantial reductions in cooling times but presented no data on energy use.

3.2.5.8 Plate freezing

Plate freezers use flat metal plates through which coolant (often refrigerant) is passed. Multiple plates are arranged either vertically or horizontally, with vertical being suited to loose, flexible products like fish (e.g. Svendsen et al⁵⁵) and offal (e.g. Creed and James⁵⁶) which can take up the shape of the gap between plates, while horizontal are more appropriate for packaged blocks of foods like deboned meat. The direct contact between the plates and product can result in energy efficiency compared with systems such as air blast freezing.

⁵³ Chourot J M., Macchi H, Fournaison L and Guilpart J (2003), Technical and economical model for the freezing cost comparison of immersion, cryomechanical and air blast freezing processes, Energy Conservation and management, 44, 559-571.

⁵⁴ Ketteringham, L. and James, S., (1999). Immersion chilling of trays of cooked products. Journal of food Engineering, 40(4), pp.259-267.

⁵⁵ Svendsen, E.S., Widell, K.N., Tveit, G.M., Nordtvedt, T.S., Uglem, S., Standal, I. and Greiff, K., 2022. Industrial methods of freezing, thawing and subsequent chilled storage of whitefish. Journal of Food Engineering, 315, p.110803.

⁵⁶ Creed, P.G. and James, S.J., 1985. Heat transfer during the freezing of liver in a plate freezer. Journal of Food Science, 50(2), pp.285-288.

Work by De Jong⁵⁷ comparing air blast and plate freezing of beef cartons in New Zealand showed that the power consumed per carton of beef for plate freezing was lower than two alternative air blast freezing processes (Figure 19). This was corroborated by Visser⁵⁸ who demonstrated that freezing times could be reduced from 47 to 18 hours and energy costs reduced by 24% when plate freezing rather than air blast freezing of meat.

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The horizontal plate freezing developed applied a CO₂ heat pump with a flooded evaporator. The unit developed can provide ~100 kW of cooling capacity at evaporation temperatures between -30 and -50°C. products such as apple juice, herring, mackerel and salmon were tested in the system

Results showed that the system exhibited significantly lower specific energy consumption compared to the baseline case operating at -40°C using a CO₂-NH₃ cascade system. 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. It achieved up to a 59% reduction 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%.

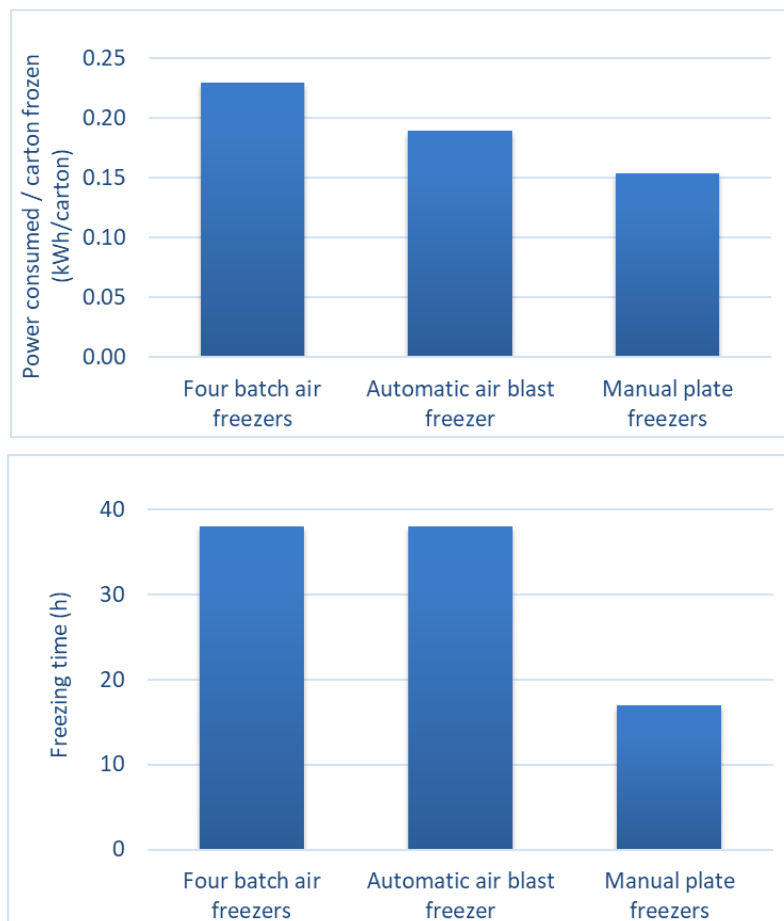


Figure 19. Energy required for freezing and freezing time for cartons of beef (from De Jong, 1994).

⁵⁷ De Jong, R S (1994), Plate freezing technology and economics applied to the meat industry, Proceedings IRHACE Technology Conference, Paper 11.

⁵⁸ Visser K (1996), The design and operation of large automatic plate freezers, Proceedings of the 19th International Congress of Refrigeration, Vol. 3a, 699-706, The Hague.

3.2.5.9 *Scraped surface heat exchanger (freezing of ice cream)*

Scraped surface freezers are essential in ice cream production. Their effectiveness lies in their ability to freeze viscous and sticky mixtures efficiently. The process involves direct contact between the product and a cold wall, with scraper blades constantly removing the frozen layer to ensure uniform freezing. This method results in a high heat transfer rates, leading to a superior quality ice cream (small ice crystals). The versatility of scraped surface freezers makes them a popular choice in the food industry.

The process of making ice cream involves two main steps: creating the mix and freezing it. The specific steps vary depending on the size of the factory. Making the mix includes blending the ingredients, pasteurizing and homogenizing it, cooling it, and then aging it. After the mix is made, it is frozen and then hardened.

The first stage of freezing ice cream is called dynamic freezing, where the mix is stirred and air is added. This is the most important part of making ice cream because the ice crystals form during this process. Air bubbles are dispersed and fat globules are rearranged. Dynamic freezing is done in a scraped surface heat exchanger or freezer. After that, the ice cream is hardened in a very cold environment. The ice cream is usually hardened to -18°C , but ideally it should be hardened to -25 to -30°C .

Ice cream is a thick product that can stick to the surface of traditional heat exchangers. Many different freezers have been invented for making ice cream, but scraped surface heat exchangers are the most commonly used in the food industry.

The type of heat exchanger that is used depends on the product that is being processed. To reduce the resistance caused by the formation of a film, the liquid film should be as thin as possible and should be constantly renewed. This is not possible with traditional tubular and plate heat exchangers. Scraped surface heat exchangers or freezers have scraper blades and a beater assembly. The scraper blades continuously scrape the frozen film off of the cylinder wall, mix it back into the mixture, and carry it from one end of the freezer to the other for uniform cooling and unloading.

There are two types of scraped surface freezers: batch and continuous. Batch freezers freeze a set amount of ice cream mix at a time, while continuous freezers constantly feed the ice cream mix into one end of the freezer and take the frozen ice cream out of the other end.

Batch freezers are mostly used in very small ice cream factories. For the same amount of ice cream, batch freezers are much cheaper to install than continuous freezers. Continuous scraped surface freezers work similarly to batch freezers, but there are some key differences. Heat transfer is less efficient in batch freezers, and it takes longer to freeze the same amount of ice cream mix. The mix residence time in continuous freezer is about 2 minutes to produce more than 40-50% of ice crystals and batch freezers could be up to 1 hour residence time. This means that the ice crystals in batch-frozen ice cream are much larger. In addition, batch freezers whip the ice cream mix at atmospheric pressure, while continuous freezers distribute air under pressure. Whipping is less important in continuous freezers because the air it is directly injected and controlled than in batch freezers.

Since it was first invented, many small changes have been made to the scraped surface heat exchanger, but two major modifications have been made in the form of low temperature extrusion freezing and product recirculation. These changes have been found to improve the quality of ice cream. Low temperature extrusion freezing is a new technology that combines a conventional scraped surface freezer with a low temperature extrusion freezer. In this process, the frozen product is both sheared and frozen to very cold temperatures of around -10°C to -20°C . The ice cream mix comes out of the conventional scraped surface freezer at a temperature of -5 to -6°C and is then sent to the low temperature extrusion freezer instead of the hardening tunnel. About 40-50% of the water in the mix

is already frozen at this temperature, depending on the composition. If the mix were to be frozen further in the hardening tunnel, the remaining water would crystallise on the surface of the existing ice crystals, making them larger. This would reduce the quality and shelf life of the ice cream. Therefore, the mix is subjected to shear stress in the low temperature extruder, which causes additional ice crystal nuclei to form. This results in 2-3 times smaller and more evenly dispersed ice crystals than the conventional process. Another way to improve commercial freezers is to recirculate some of the frozen ice cream mix back to the pre-aeration device. This cools the mixture entering the freezer, which helps to form smaller ice crystals and air cells. This system also helps to prevent unused or unfrozen product. The recirculated mixture mixes with the fresh mixture and provides a place for ice crystals to grow. This also increases the residence time of the mixture, which leads to larger ice crystals and more effective whipping⁵⁹.

3.2.5.10 Freeze drying

In freeze drying a product is first frozen and then the ice is sublimated under vacuum. To enable sublimation (as it is an endothermic process) some heat is required, provided via warm air or other sources such as microwave heating. However, while higher heating temperatures favour more complete sublimation and dehydration, they can also denature the product and reduce quality. Although freeze dried products have advantages such as low weight and volume than fresh products, and they can be stored at ambient temperatures rather than chilled or frozen, their quality tends not to be as high after rehydration as a fresh product.

There are many published studies on specific food types and processing parameters, but these are mostly concerned with quality rather than energy efficiency (see for example Liu et al. (2022⁶⁰) whose review included extensive lists of products which have been studied). There are however some general observations on costs and energy efficiency. Duan et al. (2016⁶¹) suggested that because of the significant use of energy in the process, it should only be considered for high value foodstuffs, and cited Ratti 2001⁶² who stated that costs for freeze-drying were typically 4 to 8 times those of air drying. Ratti 2001 also made the point that the basis of cost comparison is important and used the example of whether or not refrigerated storage costs are included. These costs come from energy use to refrigerate fresh/frozen products, which is not required for freeze-dried products. The transport of freeze-dried food can also reduce emissions, with a lot less weight (70 to 90% less) to carry than the equivalent ingredients. Despite this, for two example products (meat and peas) the balance of costs was still in favour of freezing compared to freeze-drying.

3.3 Types of refrigeration systems

Comprehensive details of industrial refrigeration systems are provided in the ENOUGH cold storage road map ([Cold storage road map](#)). This includes details of:

⁵⁹ Shrivastav A, TK Goswami. Conventional industrial ice cream freezers and its thermal design: a review. J Food Sci Nutr. 2018;1(1):21-28.

⁶⁰ Liu, Y., Zhang, Z. and Hu, L., 2022. High efficient freeze-drying technology in food industry. Critical Reviews in Food Science and Nutrition, 62(12), pp.3370-3388.

⁶¹ Duan, X., Yang, X., Ren, G., Pang, Y., Liu, L. and Liu, Y., (2016). Technical aspects in freeze-drying of foods. Drying Technology, 34(11), pp.1271-1285.

⁶² Ratti, C., (2001). Hot air and freeze-drying of high-value foods: a review. Journal of food engineering, 49(4), pp.311-319.

- Direct expansion (DX) plant.
- Pumped overfeed systems.
- Pumpless overfeed systems (low pressure receiver (LPR) systems).
- Gravity fed flooded systems.
- Cascade systems.
- Absorption refrigeration.
- Secondary refrigerants.

3.4 Thermal processes (including cooking/heating)

A range of thermal processes are applied in food cooking (Table 4).

Table 4. Typical current heating processes and where they are applied in food processing.

Process	Meat	Fish	Fruit	Vegetables	Milk
Baking	✓	✓	✓	✓	✓
	(usually part of baked food, e.g. in pie or pastry)				
Blanching				✓	
Boiling	✓	✓		✓	
Canning	✓	✓	✓	✓	✓
Cleaning-in-place (CIP)	✓	✓	✓	✓	✓
Conching					✓ (chocolate)
Crystallisation					✓
Drying	✓	✓	✓	✓	✓
Evaporation					✓
Extraction			✓	✓	
Fermentation				✓	✓
Frying	✓	✓		✓	
Grinding	✓	✓			
HTST (high-temperature-short -time) and UHT (ultra-high temperature)					✓
Homogenisation					✓
Microwave	✓	✓	✓	✓	
Milling				✓ (beans, pulses)	
Mixing	✓	✓	✓	✓	✓
Pasteurisation					✓
Refining				✓ (oils)	
Roasting	✓	✓		✓	
Ohmic heating	✓ (sec)	✓ (sec)	✓ (sec)	✓ (sec)	✓
Steaming	✓	✓	✓	✓	✓
Sterilisation					✓
Tempering/thawing	✓	✓	✓	✓	

3.4.1 Baking

Baking uses a process of cooking by dry heat usually in some kind of oven. Baked products include bread products, pies and cakes and are usually prepared from flour or meal derived from some form of grain.

Improving energy efficiency of ovens has been suggested by means of design improvements. In most studies, computer simulation approaches such as computational fluid dynamics (CFD) are used to assess the effects of design changes on energy efficiency (Al-Nasser et al., 2021⁶³; Chhanwal et al., 2012⁶⁴; Therdthai et al., 2003⁶⁵). CFD computes fluid flow, heat and mass transfer in ovens to render spatial and time maps of important process variables such as temperature and moisture of the fluid and product, and the different heat transfer rates composing the overall energy balance. In some cases, the CFD analysis is calibrated using experimentally determined inputs (Khatir et al., 2013⁶⁶; Paton et al., 2013⁶⁷). Simplified quality kinetics indices are used to benchmark effects of changes on baking quality. The major variables affecting the baking process are the baking time and temperature, moisture content, and distribution of heat flux in the oven.

The model based analysis of (Paton et al., 2013⁶⁷) predicted that 19% of the energy used in an industrial oven is baseload, i.e. the energy that escapes via the oven walls, roof and flue gas losses. Their analysis estimated that a 10% baking time reduction could mean an energy reduction of $19\% \times 10\% = 2\%$ per food item (in this case, bread). Building further on this model, (Khatir et al., 2013⁶⁶) found that increasing convective heat transfer coefficients (CHTC) from the hot air to the food in a bread baking oven from $10 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ in a conventional oven to $35 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ after improving the airflow rates and distribution, could save energy by a reduction of baking time and thereby reduced heat losses through the oven walls (44.7 kJ/kg , expressed per unit product mass in the oven), although additional energy is required for running the fans (2.9 kJ/kg , expressed per unit product mass in the oven). Increasing the CHTC beyond $35 \text{ W/m}^2 \cdot \text{K}$ was not found useful in terms of energy savings because of the limited gain in baking time and the 2nd power increase in fan energy per increase in fan speed. The energy required for baking the bread was assessed to be 800 kJ/kg product, thus an energy saving of 5.2% ($41.8/800$) could be achieved on a specific food unit (kg) base. No experimental verification was presented. The potential energy savings for the UK were estimated to be around 25 GWh/year in the UK based on the bread total production, leading to a reduction in carbon emissions of 4484 tonnes CO_{2e}. For France, this was estimated to be 11.22 GWh/year, or 2019 tonnes CO_{2e}; For Sweden it was

⁶³ Al-Nasser, M., Fayssal, I., and Moukalled, F. (2021). Numerical simulation of bread baking in a convection oven. *Applied Thermal Engineering*, 184, 116252. <https://doi.org/10.1016/J.APPLTHERMALENG.2020.116252>.

⁶⁴ Chhanwal, N., Tank, A., Raghavarao, K. S. M. S., and Anandharamakrishnan, C. (2012). Computational Fluid Dynamics (CFD) Modeling for Bread Baking Process-A Review. *Food and Bioprocess Technology*, 5(4), 1157–1172. <https://doi.org/10.1007/S11947-012-0804-Y/TABLES/2>.

⁶⁵ Therdthai, N., Zhou, W., and Adamczak, T. (2003). Two-dimensional CFD modelling and simulation of an industrial continuous bread baking oven. *Journal of Food Engineering*, 60(2), 211–217. [https://doi.org/10.1016/S0260-8774\(03\)00043-8](https://doi.org/10.1016/S0260-8774(03)00043-8).

⁶⁶ Khatir, Z., Paton, J., Thompson, H., Kapur, N., and Toropov, V. (2013). Optimisation of the energy efficiency of bread-baking ovens using a combined experimental and computational approach. *Applied Energy*, 112, 918–927. <https://doi.org/10.1016/J.APENERGY.2013.02.034>.

⁶⁷ Paton, J., Khatir, Z., Thompson, H., Kapur, N., and Toropov, V. (2013). Thermal energy management in the bread baking industry using a system modelling approach. *Applied Thermal Engineering*, 53(2), 340–347. <https://doi.org/10.1016/J.APPLTHERMALENG.2012.03.036>.

70 tonnes CO₂e. An estimate for Europe as whole was 43466 CO₂e (Khatir et al., 2013⁶⁶). Differences were attributed to differences in total industrial production volumes of bread.

Díaz-Ovalle et al. (2017⁶⁸) proposed geometric changes in an oven to reduce the preheating time and maintain temperature uniformity using CFD simulation. The authors showed that the baffle plate geometry exerted an important hydrodynamic influence in the reduction of pre-heating time, but it was less obvious from the study what the actual expected savings were. An air-forced convection rotary bread-baking oven with a 60 kW natural gas burner and 2 fans was modelled with CFD but implications of design on energy use were again not shared (Pinelli and Suman, 2017⁶⁹).

Shevade et al. (2019⁷⁰) performed a CFD study of plenum and nozzle design parameters of a pizza air impingement oven on the heat transfer rates to the surface of pizza type food product. They only considered the turbulent airflow and heat transfer expressed by the surface heat transfer rates and air leakage. They suggested that with an optimal selection of the nozzle and plenum design features 20% energy savings could be achieved, but a comprehensive energy balance analysis of the complete system was also here lacking.

Ramirez-Laboreo et al. (2016⁷¹) modelled (with validation) a small convection-radiation oven and explored the energy flows. Two different one-hour cooking processes were simulated to analyse the energy behaviour of the system: a convective cooking method such as bread baking and a mostly radiative process like meat roasting. To properly compare the results, the set point oven temperature in both simulations was 200°C with the same initial temperature. Heat has been more evenly distributed in the convective process and the load received a larger amount of energy, about 13% compared to 11% in the radiative one. However, in the convective operating mode also caused a high increase in water evaporation (20% of the energy compared to 8%). They also found that energy losses in the radiative simulation were much higher than in the convective one, mainly in stationary state (non-transitory). The results of a design study revealed that energy consumption would be reduced by 0.9% in the one-hour convective process and by 1.3% in the radiative one, mainly because design changes caused the mass to be heated be lower.

3.4.2 Canning

Canning is a heat treatment process where food is sealed in a container for heat treatment, which ensures the destruction of harmful micro-organisms, while proper sealing prevents further micro-organisms from colonising the food. Canning is a preservation process widely used in the food industry to increase the shelf life of products while maintaining the right nutritional and quality parameters. The result is a long shelf-life, high quality, healthy product. The food must arrive at the canning step in a properly prepared state, as no further technological operations are carried out afterwards.

⁶⁸ Díaz-Ovalle, C. O., Martínez-Zamora, R., González-Alatorre, G., Rosales-Marines, L., and Lesso-Arroyo, R. (2017). An approach to reduce the pre-heating time in a convection oven via CFD simulation. *Food and Bioproducts Processing*, 102, 98–106. <https://doi.org/10.1016/J.FBP.2016.12.009>.

⁶⁹ Pinelli, M., and Suman, A. (2017). Thermal and fluid dynamic analysis of an air-forced convection rotary bread-baking oven by means of an experimental and numerical approach. *Applied Thermal Engineering*, 117, 330–342. <https://doi.org/10.1016/j.applthermaleng.2017.02.037>.

⁷⁰ Shevade, S., Rahman, M., and Guldiken, R. (2019). Optimization of turbulent air jet impingement for energy efficient commercial cooking. *Energy Procedia*, 160, 691–698. <https://doi.org/10.1016/J.EGYPRO.2019.02.191>.

⁷¹ Ramirez-Laboreo, E., Sagues, C., and Llorente, S. (2016). Dynamic heat and mass transfer model of an electric oven for energy analysis. *Applied Thermal Engineering*, 93, 683–691. <https://doi.org/10.1016/J.APPLTHERMALENG.2015.10.040>.

The method is used to process vegetables, fruits, ready meals, meats, various fish and beverages, so overall it can be concluded that canning technology can be preceded by many different technological steps, depending on the product being processed. How long it takes to cook and sterilise products depends on a few things, like how the products are heated, how acidic the products are, what microbes and enzymes are to be killed and what kind of packaging is used. Various types of autoclaves are in use. The most common type for canning is the static autoclave, the rotating autoclave and the continuous autoclave

High temperatures need to be reached at several points, either by heating large quantities of water or by producing hot steam which require either large amounts of gas or electricity. Alternative solutions are the recovery of waste heat; in addition, cooling also requires energy. A more sustainable practice can be created by appropriate heat pump solutions, good insulation or alternative heat transfer methods to compensate.

3.4.3 Conching

The quality of chocolate is determined by the quality of the cocoa used. The conching process, which involves mixing, shearing, and aerating the chocolate mass while heating ($T > 40^{\circ}\text{C}$) it, is crucial for achieving the desired taste, aroma, texture, and viscosity of the final product. Different conching temperatures, times, and shearing methods used by different producers can impact these qualities. However, it is an expensive step due to its lengthy duration and the high temperatures involved. During this process, complex chemical reactions take place. The time it takes depends on the amount of chocolate and the type of equipment used. There are two main types of conching systems: traditional systems with various designs and universal systems that combine refining and conching functions.

Universal conching systems are often used for compound chocolate and coatings due to their lower cost and smaller size. However, traditional continuous or batch conching systems are preferred for producing quality chocolate, as they offer significant advantages in flavour development.

To create the desired aroma and flavour in chocolate, a conching process of 6 to 24 hours is recommended in modern conching machines. In older machines, this could take up to 72 hours. For milk chocolate with a partially caramelised taste, the process typically takes 16 to 24 hours at a temperature of 50 to 60 °C. Although the ideal conching time is 6 to 24 hours, many chocolate manufacturers shorten it to 4 to 6 hours. This can lead to poor quality chocolate and instability in the mixture.

According to some researchers, conching is a two-step process. In the first step, the moisture content is reduced, volatile acids are removed, and the solid particles are coated with fat. In the second step, a smooth, paste-like mixture is formed by adding more cocoa butter and emulsifiers. These steps are called the dry phase and the wet phase. Some researchers believe that conching has three phases: dry, paste, and fluid. In the dry phase, the chocolate mass is heated, mixed, and aerated to remove volatile acids and water. The acetic acid concentration remains constant due to the lack of free water. In the paste phase, the mass is further processed under heat and degassing conditions. In the fluid phase, cocoa butter, lecithin, and Polyglycerol polyricinoleate (PGPR) are added to improve flowability and rheological properties. Lecithin is added at the end of the fluid phase to avoid water removal issues and to ensure maximum effectiveness. Adding lecithin early in the conching process can reduce its impact as it may be absorbed by cocoa particles. The conching temperature can also affect lecithin performance.

3.4.4 Crystallisation

Crystallisation technology is a process that involves the transformation of solutes from a supersaturated solution to form crystals⁷². This method is extensively employed in the food industry to control the size, shape, and purity of crystals, thereby influencing the texture, taste, and shelf life of various products.

The quality, texture, and stability of food products are significantly influenced by their crystalline structure. In conjunction with various other elements, this structure plays a crucial role in shaping the product's appearance, mechanical properties during handling, mouthfeel during consumption, and shelf stability. The manipulation of product composition and processing/storage conditions governs the nature of this crystalline structure⁷³.

The significance of crystallisation technology in food processing lies in its ability to enhance product quality, reduce production costs, and streamline manufacturing processes. Manufacturers can achieve desired product characteristics by precisely manipulating crystal formation, such as smooth textures, consistent flavours, and prolonged shelf stability⁷³.

Crystallisation technology finds applications in diverse areas within the food industry. From the production of chocolate and confectionery to the crystallisation of fats in margarine and the formation of sugar crystals in candies, the versatility of this technology contributes to the creation of a wide array of high-quality food products⁷⁴.

3.4.5 Drying

Drying is the unit operation of removing water (moisture) from a material to reduce its water activity and extend shelf life. In food processing, drying is one of the oldest and most common preservation methods – it produces stable products that are lighter and store longer by preventing microbial growth and slow chemical changes. Drying can be applied to solids (e.g. fruits, vegetables, meat slices, grains) and to liquids or slurries (by first converting them to solids, as in spray drying of milk or juice into powder). The fundamental principle is applying heat to evaporate water from the product and carrying that water vapor away. State-of-the-art drying encompasses a variety of techniques: hot air drying (convective drying) is the most widely used for fruits, vegetables, cereals, and meats; spray drying is dominant for liquid foods like milk, coffee, or egg, producing powders; freeze drying (lyophilisation) is used for high-value products where quality retention is paramount (coffee, probiotics, specialty fruits); and there are other methods like drum drying (for viscous purees), vacuum drying (drying under reduced pressure at lower temperatures), microwave or infrared drying (where energy is delivered by radiation), etc. The role of drying in food processing is crucial for creating products like milk powder (for infant formula, etc.), dried fruits, powdered beverage mixes, dehydrated soups and sauces, jerky and dried fish, cereals and snacks, and many ingredients (spices, tea, coffee). Drying not only preserves food but also greatly reduces weight and volume, cutting transport and storage costs. It sometimes also creates desired textures (e.g. the crunchy texture of a cereal or snack is achieved by drying/extrusion). Currently dominant technologies include:

⁷² L. Yu, S. R.-E. (2003). Crystallization, Basic Principles. In B. Caballero, *Encyclopaedia of Food Sciences and Nutrition* (pp. 1697-1702). Academic Press.

⁷³ Hartel, R. W. (2002). Crystallization in foods. In R. W. Hartel, *Handbook of Industrial Crystallization* (pp. 287-304).

⁷⁴ Earle, D. (1983). Contact Equilibrium Processes - Applications (cont'd) Crystallization. NZIFST (Inc.).

- **Tunnel and belt dryers (hot air drying):** These are common for fruits, vegetables, and herbs. Products are laid on trays or a moving belt and conveyed through a long tunnel where hot air is blown across them. Early stages may use higher temperatures, and later stages lower, to efficiently remove moisture. Modern belt dryers can have multiple zones with controlled temperature and humidity. They are suited for pieces of food (fruits slices, vegetable dices, etc.) and can be quite large, running continuously. A schematic would show a conveyor belt passing through chambers where fans circulate heated air. Fluidised bed dryers (FBD) are a variant where small pieces (e.g. peas, grain, spice seeds) are suspended in a hot air stream, behaving like a boiling fluid; this ensures very uniform and quick drying. These are often used for final drying/cooling of products (for example, after spray drying milk powder, a fluid bed is used to gently dry the powder to final moisture and cool it).
- **Spray dryers:** Spray drying is the go-to method for turning liquid foods into powders (milk, whey, coffee, egg, flavourings, etc.). A spray dryer typically is a tall cylindrical chamber. The liquid feed is atomised into fine droplets (via a high-speed spinning disk atomiser or high-pressure nozzles) at the top, and hot air (150–220 °C inlet) is blown through the chamber. The droplets dry in seconds as they fall, turning into powder particles which are collected at the bottom and via cyclones. State-of-the-art spray dryers include features such as fines recirculation (recycling small particles to agglomerate for better instant properties), multiple stages (primary drying in the main chamber, then secondary drying in an external fluid bed), and sophisticated control of air flow to maximise drying and minimise heat damage. Large dairy spray dryers can evaporate many tons of water per hour. Modern designs emphasise energy recovery, such as using exhaust air heat to preheat incoming air, and use closed-loop air systems when needed (for instance, when
- **Freeze dryers:** Freeze drying involves freezing the product and then removing water by sublimation (ice turning directly to vapor under vacuum). Equipment for this includes vacuum chambers with heated shelves. Products (often fruit pieces or coffee concentrate) are frozen and placed on the shelves; a vacuum is drawn, and the shelves gently warm the product. Water sublimates and is captured on a condenser as ice. Freeze dryers preserve flavour, nutrients, and structure exceptionally well (no liquid water phase to damage).
- **Drum Dryers:** A less common but still used method for certain viscous foods (like mashed potatoes, baby food puree, or fruit leathers) is drum drying. A drum dryer has one or two large, heated drums that rotate. A thin layer of the product is applied to the drum surface (which is heated internally by steam), and as the drum rotates, the thin film dries rapidly, then is scraped off as a flaky solid. Drum drying is quite efficient (direct contact heating) but can cause more cooked flavour and sometimes uneven texture. used for things like potato flakes or some instant soup bases.
- **Others:** There are also rotary dryers (a rotating cylinder through which hot air passes, used for granular products like animal feed or fishmeal), vacuum belt or vacuum tray dryers for heat-sensitive materials (operating at lower boiling points under vacuum), and hybrid dryers (microwave-assisted dryers, radio-frequency dryers, etc., which can accelerate moisture removal from thick products). Each has niche applications, but the core idea remains apply heat, remove moisture-laden air.

In the meat industry, drying is used to produce products like beef jerky, biltong, and dried sausage (salami) – these are usually dried in chamber dryers or smokehouses with controlled humidity over many hours. Meat drying is also critical for pet foods and treats (often meat-based kibbles or chews are hot-air dried). Another meat example is dried meat floss or meat powders used in some cuisines. In the fish industry, drying is an ancient method for fish preservation (dried salted fish, stockfish). Industrially, fish drying may be done in large rack dryers or tunnel dryers for products like dried anchovies, cod, etc. The fishmeal industry uses drying to turn fish byproducts into stable meal for animal feed – typically, fishmeal plants use large rotary drum dryers or direct steam dryers to reduce moisture from ~70% down to <10% in the meal. Dairy industry is one of the largest users of drying. Milk powder production involves evaporating milk and then spray drying it; similarly, whey is spray dried. These large spray dryer installations are found in dairy plants worldwide to make products like skim milk powder, whole milk powder, infant formula (which may use two-stage drying with vacuum or freeze drying for certain sensitive components), etc. Lactose and other dairy byproducts are also dried. For fruits and vegetables, huge volumes of products are dried – from simple raisins (grape drying is often sun plus tunnel drying) to dehydrated vegetable flakes for soups. In bakery/cereals, many ready-to-eat cereals are dried after extrusion or soaking; for example, corn flakes are toasted (dried) to a crispy texture. Biscuit and cracker baking is essentially a drying process too (removing moisture to make them crisp). In beverages, though final products are liquid, intermediate ingredients like tea and coffee are dried. Instant coffee is either spray dried or freeze dried. Tea leaves are dried in hot air flow during processing. Herbs and spices are dried to powders. Thus, drying touches almost every corner of food processing. Drying is notoriously energy intensive. Evaporating water requires a large input of heat – roughly 2250 kJ/kg (about 630 Wh per litre) just for the phase change at 100 °C, and in practice 2–4 times that when accounting for inefficiencies and heating up the product. It's estimated that drying operations account for a significant portion of energy use in food manufacturing (on the order of 15–25% in many plants) and thus are prime targets for efficiency improvements.

Conventional drying technologies generally rely on drying processes driven by using hot air, where these processes have significantly high energy consumption and greenhouse gas emissions. With our knowledge based on the limited nature of fossil fuels and the impact of climate change, every technology has to be cleaner, cheaper, and more efficient to limit our carbon footprint while maintaining sustainable development⁷⁵. In terms of energy efficiency, over 85% of all industrial thermal dryers used in the food industry are conventional using 12–20% from the overall energy consumption, which corresponds to 30% of energy efficiency and 90% of the overall processing costs. Around 35–45% of the energy input is wasted as the hot exhaust gases, incurs high energy losses and emits high GHG emissions (Menon et al, 2020⁷⁶).

Novel drying techniques: There is ongoing research into more energy-efficient methods.

- **Microwave- and radio frequency (RF) drying:** These use electromagnetic energy to directly heat the moisture inside the product. They can speed up drying of thick or dense products (because conventional hot air drying gets limited by slow internal diffusion of heat). By shortening drying time, they can reduce overall energy or at least make the process more electrical (which can be greener if electricity is green). Industrial microwave dryers are already

⁷⁵ Acar, C., Dincer, I., Mujumdar, A., 2022, A comprehensive review of recent advances in renewable-based drying technologies for a sustainable future, *Drying Technology*, Vol 40, Issue 6.

⁷⁶ Menon, A., Stojceska, V., Tassou, S.A., 2020, A systematic review on the recent advances of the energy efficiency improvements in non-conventional food drying technologies, *Trends in Food Science and Technology*, Volume 100, p. 67-76.

used for pasta and some snacks, often in combination with hot air (the term “hybrid dryer” applies).

- **Ultrasound-assisted drying:** high-frequency vibrations can disrupt the moisture boundary layer and help water escape faster, potentially saving energy – this is still more in pilot research.
- **Vacuum-microwave drying:** pulling a vacuum to lower boiling point and using microwaves to rapidly remove water – known for producing high-quality dried fruits/veggies with less energy than freeze drying.
- **Refractance window drying:** a newer method for purees, where a hot water bath and plastic film are used to gently dry pumpable products with good energy efficiency. Many of these novel methods aim to either increase the effective heat transfer/mass transfer rates or use alternative energy forms to cut drying time, thus saving energy.

3.4.6 Evaporation

Evaporation in food processing refers to the removal of water from a liquid food by boiling it off, usually to *concentrate* the product. It differs from drying in that evaporation yields a concentrated liquid (or slurry) rather than a dry solid. The process involves heating the liquid to induce vaporisation of water and collecting the water vapor (usually condensing it for reuse or disposal). Evaporation is widely used in industries such as dairy (to concentrate milk or whey prior to drying), juice and beverage (to make fruit juice concentrates, or concentrate coffee/tea extracts), sweeteners (concentrating sugar syrups, corn syrups), tomato paste (evaporating tomato juice to a thick paste), and in some meat/fish applications (e.g. concentrating fish solubles or meat extracts). The role of evaporation is often to reduce volume and weight – for example, orange juice is evaporated into a concentrate (~65°Brix) for economical shipping, then re-diluted later. It also can increase the solids content to a level that is stable (high sugar concentrates are shelf-stable because of low water activity). In dairy, evaporating milk (from ~12% solids to ~50% solids) before spray drying massively reduces the energy needed in dryers.

Evaporation technology is crucial in the food processing industry, offering an efficient and sustainable method for concentrating liquids, preserving flavours, and reducing waste. The food processing industry, a major consumer of energy and water resources within manufacturing, is intricately connected to the human living environment. Evaporation is commonly the primary objective of the heating process, and in food processing, it is categorised into continuous and batch evaporation. The typical production processes involve salt crystallisation and lactose evaporation, respectively.

Evaporation technology has applications across a wide range of food processing sectors, including but not limited to ^{78,77}:

- Fruit and vegetable processing for the production of concentrated juices, e tomato and garlic pastes, sugar confectionery
- Dairy industry for the concentration of milk and the production of condensed milk.
- Soups, sauces, and condiments are manufactured for flavour enhancement and waste reduction.
- Pharmaceutical industry for the concentration of active ingredients in liquid formulations.

⁷⁷ Giner Santonja, G, P Karlis, K Stubdrup, T Brinkmann, and S. Roudier. 2019. Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control), EUR 29978 EN. Luxembourg: Publications Office of the European Union.

- Concentrated products that are used by manufacturers as ingredients in other processed foods include liquid pectin, fruit concentrates for use in ice cream or bakery products, liquid malt extract for breweries, fruit juices, milk and coffee extracts.
- The operation also concentrates brines and syrups to produce crystallised salt and sugar.

Through evaporation, water is partially extracted from liquid foods by boiling off water vapour. Concurrently, more volatile components, including those contributing to the product's flavour, are also expelled with water vapour. If desired, these volatile components can be recovered and reintroduced to the concentrated food⁷⁸. This process is particularly valuable in the food industry for producing various products such as fruit juices, dairy products, soups, and sauces. The technology employs natural or forced circulation systems, utilising evaporators ranging from simple single-effect units to more complex multiple-effect configurations.

The standard apparatus is an evaporator unit which includes a heat exchanger to heat the product, and a separator to remove and condense the vapor. Over the years, designs have evolved for efficiency and product quality:

- **Multiple-Effect Evaporators:** Instead of a single boiling stage, modern systems have multiple effects (stages) connected in series. The principle is: the vapor boiled off from one effect is used as the heating medium for the next effect (which is kept at a lower pressure so that vapor is hot enough to boil the next stage). For example, in a triple-effect evaporator, live steam boils the product in the first effect; the vapor from effect 1 goes to heat effect 2 (operating at lower pressure, thus lower boiling point); effect 1's vapor condenses (releasing heat to boil effect 2's product), and effect 2's vapor in turn heats effect 3. In this way, one unit of steam does the work of three, cutting energy use. It's common to have 3–7 effects in large food evaporators. The equipment for each effect can be a falling-film evaporator (most popular for heat-sensitive liquids), where product flows as a thin film down the inside of heated tubes and evaporates rapidly – this has very short residence time and high heat transfer. Other types include rising-film (climbing) evaporators and forced circulation evaporators (where a pump forces product through a heat exchanger and then to a separator). Falling-film multiple-effect evaporators are the workhorses in milk, juice, and similar industries because they can handle large volumes gently. A schematic would show multiple cylindrical bodies/vessels interconnected: each with a bundle of heating tubes, a separator above to collect vapor, and pipes conveying product from one to the next. The final effect operates at the highest vacuum (lowest boiling temp) to eke out the last bit of vapor with minimal heat.
- **Thermal Vapor Recompression (TVR):** This is a technique to improve efficiency often integrated into multiple-effect systems. A steam-jet ejector (motivated by high-pressure steam) draws some of the vapor from an effect and compresses it slightly to reuse as heating steam for an earlier effect. It's like adding an extra "half effect" of energy recycling. Many evaporators use TVR on the last effect vapours to boost overall steam economy.
- **Mechanical Vapor Recompression (MVR) Evaporators:** This is considered state-of-the-art for energy efficiency. In MVR, instead of using multiple steam effects, the evaporator may effectively have one or two effects, but *all* the vapor produced is mechanically compressed (via a compressor or high-speed fan) to a higher pressure/temperature and sent back to the evaporator as the heat source. Essentially, the latent heat of the vapor is recycled

⁷⁸ Fellows, P.J. 2017. Food Processing Technology: Principles and Practice, Fourth Edition. Online: Woodhead Publishing.

continuously. MVR evaporators act as an open-cycle heat pump – using electrical energy to elevate vapor heat. MVR systems drastically reduce steam requirements; they might need steam only for start-up, with the compressor handling the continuous operation. In dairy, MVR became the technology of choice for new plants because of its efficiency. MVR can be used alone or combined with multiple effects (e.g. a 2-effect evaporator with MVR on one effect). The machinery includes a large centrifugal compressor (or blower) on the vapor line and a robust electrical drive for it. MVR evaporators usually operate at quite low pressures (e.g. they boil at 50–70 °C under vacuum, compress vapor to maybe 70–90 °C for the heating side) – ideal for heat-sensitive products like milk, where lower temperatures preserve quality.

Common configurations in food include plate evaporators (using plate heat exchanger concepts for small capacities), centrifugal evaporators, and open-pan vacuum evaporators for certain traditional products. But the dominant tech for large-scale is falling-film (or forced-circulation) multi-effect for high throughput, and MVR for cutting-edge efficiency.

Evaporation has seen substantial improvements over the last century mainly to reduce the huge energy demand of boiling off water. A single-effect evaporator would typically require about 1 kg of steam to evaporate 1 kg of water (neglecting losses). Each “effect” added ideally multiplies the efficiency (e.g. 2-effect uses ~0.5 kg steam per kg water, 3-effect ~0.33, etc.). Thermal vapor recompression can trim it further, and mechanical vapor recompression can almost eliminate external steam. If an evaporator needs upgrading, adding an effect or two can be a way to save steam (provided the additional capital and complexity are justified). The steam economy (kg water evaporated per kg steam) increases roughly linearly with number of effects. Therefore, the fuel consumption and CO₂ emissions tied to steam generation drop accordingly. Thus, a first step in decarbonising evaporation is ensuring as many effects as is practical for the duty. This is generally cost-effective unless production scale is too small. If steam is needed (for effects or start-up or as backup), using a renewable fuel boiler (biomass, biogas) or electric boilers can decarbonise that portion. But since evaporators lend themselves to electrification via MVR, the long-term trend is likely toward MVR use. Another emerging idea is using high-temperature heat pumps that output steam or very hot water to drive evaporators.

3.4.7 Extraction

Extraction is the selective leaching of specific components, which can be both valuable and harmful. The extraction may be from a solid or liquid mixture using a liquid solvent. The solvent from which the leaching takes place is the delivery phase and the solvent with which the process is carried out is the receiving phase. This operation does not lead to 100% pure components and therefore solvent regeneration is required. A distinction is made between solid-liquid, liquid-liquid and supercritical extraction.

Liquid-liquid extraction is used for e.g.: purification of food wastewater, ethanol and acetic acid extraction, purification of vegetable oils. Equipment examples include Graesser extractors, gravity towers and mixing towers.

Solid-liquid extraction: diffusion plays one of the most important roles in the process, as the extracting solvent diffuses in the material and the solution leaves the solid by diffusion. This process can take place at higher temperatures, which helps diffusion and the solubility of the components. Food applications: extraction of active ingredients from medicinal plants, extraction of vegetable oils from seeds, sugar producer industry. Equipment examples include batch extractors such as Soxhlet extractor or continuous systems such as Kennedy or Bollman extractors.

Supercritical extraction: in this type of extraction a component is extracted from a matrix using a solvent that is a supercritical fluid. Supercritical fluid extraction (SCF) is usually performed for extraction from solids, but this process is also valid for extraction from liquids. Extraction of this type is used for preparation of samples in analytical laboratories. On larger scale it is being used for removal of unpalatable material (decaffeination) from the product stream.

Extraction can be defined in 3 main steps:

- mixing and proper blending of the supply and receiving phases
- the time required for the process to be completed in order to ensure successful leaching and transport of the material between the phases
- separation of the resulting 2 phases: raffinate and extract

Relative volatility is a measure of how easy it is to separate two components in a mixture. If the relative volatility is 1, distillation is ineffective because the components have similar boiling points. However, when the relative volatility is greater than 1, extraction becomes a viable option. Extraction can also be a preferred method over distillation when the cost of distillation is prohibitive.

Prepress solvent extraction, is the process method utilised today for the majority of sunflower seed as it provides the highest oil recovery yield. In the process sunflower is crushed for oil recovery via one of two process methods, hard pressing or prepress solvent extraction. Prepress solvent extraction relies on exerting medium pressure on the prepared seed to separate the majority of the oil, followed by solvent extraction to separate additional oil from the solids fraction, recovering over 40% of the oil from the seed in modern crushing plants. Prepressing extracts approximately 65% of the oil in the seed. After this process the extracted sunflower cake is conveyed to the desolventiser toaster for solvent removal. The desolventiser toaster is the largest energy consumer in the solvent extraction process area. In addition to the considerable electrical energy necessary to convey and stir the meal inside the desolventiser toaster, there is significant thermal energy input. Currently, the desolventiser toaster uses the thermal energy of steam to warm the extracted cake from 60°C up to 109°C, and to evaporate approximately 25–30% (by weight) of solvent from the extracted cake. The energy efficiency of the desolventiser toaster can be measured by the temperature of the exiting vapours. The purpose of the miscella distillation process is to remove the residual solvent in the oil to a negligible quantity, with the least amount of energy input.

3.4.8 Fermentation

Fermentation was originally developed for food preservation but also enhances flavour, texture, and nutritional value of foods. Scientific research has linked the consumption of fermented foods to various health benefits. The fermentation process breaks down complex compounds, making them easier to digest. It also reduces the presence of harmful toxins and pathogens. Moreover, fermented foods are rich in probiotics, beneficial bacteria that support gut health and nutrient absorption. Fermentation is a promising approach for producing innovative food components and products. Fermented foods have been associated with numerous health benefits. These benefits include lower cholesterol levels, a stronger immune system, protection against infections, cancer, osteoporosis, obesity, diabetes, allergies, atherosclerosis, and reduced lactose sensitivity. The beneficial effects of fermented foods are primarily attributed to bioactive peptide fractions. These peptides are produced during the fermentation process through the microbial breakdown of proteins⁷⁹.

⁷⁹ Siddiqui, S.A., Erol, Z., Rugji, J., Taşçı, F., Kahraman, H.A., Toppi, V., Musa, L., Di Giacinto, G., Bahmid, N.A., Mehdizadeh, M. and Castro-Muñoz, R., 2023. An overview of fermentation in the food industry-looking back from a new perspective. *Bioresources and Bioprocessing*, 10(1), p.85.

Fermentation is a process that involves the use of microorganisms such as bacteria, yeast, and moulds. These organisms produce enzymes and catalysts that break down complex organic compounds in food into simpler, beneficial substances. Fermented foods and beverages can be classified based on the type of substrate used. Common categories include fermented milk, cereals, legumes, vegetables, fruits, meat, fish, and herbs. Fermentation can also be categorised, according to the main biochemical pathway, into four basic categories: alcoholic, lactic, acetic, and alkali fermentation⁸⁰.

Traditional fermentation processes rely on aerobic bacteria that require significant amounts of oxygen for growth and product formation, particularly in large-scale bioreactors. Air compressors supply oxygen to these bioreactors, but oxygen solubility in water is limited, leading to a significant portion of oxygen escaping into the air. Overexpressing bacterial haemoglobin has been one approach to improve oxygen uptake but utilizing anaerobic or microaerophilic bacteria could offer a more effective solution. These microorganisms would reduce energy consumption, especially during product formation. Additionally, using microorganisms that can grow in a wide range of temperatures would further optimise energy efficiency⁷⁹.

Solid-state fermentation (SSF) is a fermentation method used in industries such as food, pharmaceuticals, and textiles. In SSF, microorganisms grow on solid supports rather than in liquid media. This method offers several advantages, including minimal waste generation, reduced environmental impact, the use of natural solids as a low-cost medium, reduced energy and capital requirements, no need for sterilisation, simplified downstream processing, and fewer microbial contaminants⁷⁹.

3.4.9 Frying

Deep-frying is a centuries-old and widely used cooking method that remains prevalent for preparing various foods. Traditional deep frying involves immersing food in hot oil at temperatures typically ranging from 160 to 180°C or higher (Devi et al., 2021⁸¹). This technique is widely used for its ability to quickly cook foods and develop unique textures and flavours – a crispy, browned exterior and a moist interior. In industrial processing, frying is used not only for traditional snacks (potato chips, French fries) but also in preparing partially fried products that will be finished by consumers (e.g. par-fried chicken nuggets or fish sticks). Frying combines heat transfer and mass transfer: hot oil transfers heat into the food (much faster than hot air would), causing water inside the food to evaporate. The escaping water vapor leaves pores that get filled with oil, creating the crispy fried texture. The rapid cooking also contributes to desirable Maillard browning (colour and flavour development on the surface).

Industrial fryers come in batch and continuous configurations:

- **Batch fryers:** Large open kettles or pans of oil where a batch of product (e.g. nuts, or small-scale chip production) is fried and then removed. These are simple but used for smaller throughputs or specialty items.
- **Continuous fryers:** These dominate large-scale production. They consist of a long, heated frying pan or trough filled with oil, with a conveyor system (often a mesh belt) that carries products through the oil at a controlled speed. For example, potato chips are fed in on one

⁸⁰ Manna, M., Han, G., Seo, Y.S. and Park, I., 2021. Evolution of food fermentation processes and the use of multi-omics in deciphering the roles of the microbiota. *Foods*, 10(11), p.2861.

⁸¹ Devi, Shoma, Min Zhang, Ronghua Ju, and Bhesh Bhandari. 2021. "Recent Development of Innovative Methods for Efficient Frying Technology." *Critical Reviews in Food Science and Nutrition* 61 (22): 3709–24. <https://doi.org/10.1080/10408398.2020.1804319>.

end and travel under an oil “bath”, coming out fried. Continuous fryers have various design features: infeed gates, submerger belts to keep product submerged, and take-out belts or drums.

Other relevant components of the fryer are:

- **Filtration and oil management:** Because maintaining oil quality is crucial (degraded oil affects product and can pose safety issues), industrial fryers include filter systems to remove crumbs and particulates, and often an oil turnover (fresh oil addition) system. Some advanced systems have vacuum steam removal to quickly take out moisture and improve heat transfer.
- **Exhaust system:** Fryers produce steam and volatiles; a hood captures the oil vapours and steam above the oil. Many have chimneys with exhaust fans, and some incorporate *exhaust heat exchangers* or even condensers to recover energy.

Frying is heavily used in the meat industry for breaded products: e.g. chicken nuggets, patties, and schnitzels are usually par fried (partially cooked) in oil to set the coating and initiate browning, then frozen; consumers finish the cooking by baking or re-frying. Similarly, many prepared fish products like fish fingers or breaded shrimp are par fried. Potato-based foods (fries, chips, hash browns) are massive product categories reliant on continuous fryers – while not meat/fish, they often share production lines in frozen food companies that also handle meat items. In the dairy realm, direct frying isn’t common (since most dairy is liquid or powder), but there are niche examples: e.g. Indian *paneer* cheese or cheese curds can be fried as snacks, and donuts (with dairy in dough) are fried in bakery operations. Mozzarella sticks (cheese sticks breaded and fried) combine dairy and frying technology. Even some dairy desserts like fried ice cream involve a frying step (a batter-coated ice cream ball briefly fried). Thus, frying technology spans many categories – from meat proteins to starchy sides – valued for the taste and texture it imparts.

Fryer oil is typically heated by gas burners (directly firing tubes or plates in contact with the oil) or by electric immersion heaters. Some systems circulate the oil through an external heat exchanger (heated by gas or thermal oil) to more evenly distribute heat. This process is highly energy-intensive, especially in industrial settings, where frying can account for over 90% of the total energy consumption (Wu et al., 2012). In the case of potato chips, Wu et al. (2012⁸²) found that most of the energy used in frying is spent on evaporating the water from both the surface and interior of the potato slices, while the rest is used for evaporating frying oil, ventilating air, and compensating for heat lost through fryer walls by convection and radiation. The frying oil was heated by an industrial gas furnace, with an efficiency calculated at 84%. However, the overall frying process, which has an efficiency of around 70%, could be enhanced by using exhaust heat recovery and optimizing operational parameters like exhaust gas recirculation. Wu et al. (2013⁸³) further estimated that optimizing the combustion fuel flow rate, based on parameters such as moisture and oil content of the final product, could lead to energy savings of 5–10% in a continuous fryer.

⁸² Wu, H., H. Jouhara, S. A. Tassou, and T. G. Karayiannis. 2012. “Modelling of Energy Flows in Potato Crisp Frying Processes.” *Applied Energy* 89 (1): 81–88. <https://doi.org/10.1016/J.APENERGY.2011.01.008>.

⁸³ Wu, H., S. A. Tassou, T. G. Karayiannis, and H. Jouhara. 2013. “Analysis and Simulation of Continuous Food Frying Processes.” *Applied Thermal Engineering* 53 (2): 332–39. <https://doi.org/10.1016/J.APPLTHERMALENG.2012.04.023>.

To improve efficiency and cut emissions, modern frying systems implement several measures: waste heat recovery, insulation and energy management, process innovations (such as vacuum frying, Pulsed electric field [PEF] pretreatments) and electrification.

3.4.10 Grinding and milling

Grinding is a unit operation widely used in the food industry and designed to reduce the size of materials to give a usable form or to separate their components. In general, grinding is part of a larger set of operations involved in the process of size reduction. These operations can be implemented separately, in combination (dehydration, crystallisation followed by grinding) or associated with sorting, mixing, agglomeration or coating.

Today grinding spans from very crude and rough applications in cutting of materials at high material-removal rates (MRR) to finishing and ultraprecision processes. The energy consumed during a grinding process depends upon the hardness of the material to be ground, moisture content, reduction ratio, bulk density, type of pre-treatment, feed rate of the product and the variables of the grinder, namely, size of the screen required for the final size of the particles, speed and type of grinder^{84,85}.

Different materials require various superfine grinding methods. These include high-speed airflow pulverisation (jet milling), ball milling, high-pressure homogenisation (HPH), microfluidisation, high-speed homogenisation, colloid milling, ultrasonic disintegration, roll or roller grinding, and high-speed rotary strike crushing.

In the powder industry, dry milling is commonly used to reduce the particle size of dried materials and enhance their texture, whether elastic, plastic, or rigid. The three most renowned dry superfine grinding techniques are jet milling, ball milling, and vibration milling.

- Jet milling, also known as high-speed airflow pulverisation, utilises compressed gas to produce micro-powders with a narrow size distribution. In this process, raw material is sprayed into the milling chamber at high speed through nozzles, aided by compressed air. This results in size reduction through high-speed interparticle collisions and sharp impacts against the chamber's solid surface. Due to the Joule-Thomson effect, there is minimal temperature rise within the chamber, making jet milling particularly useful for materials rich in thermosensitive ingredients, such as essential oils (spices and herbs), easily oxidizable components (vegetables and tea), and other biologically active substances. Jet mills are typically powered by pressurised gases like superheated steam, compressed air, and inert gases (nitrogen), with compressed air being the most commonly used, delivering up to about 10 bars^{86,84}.
- Ball milling is a technique that uses mechanical as well as thermal effects to change the physical and chemical properties of raw materials.
- Vibration milling reduces the particle size of raw materials through continuous impaction. The grinding container, typically a tube supported by springs, undergoes frequent, small vibrations during milling, causing size reduction through repeated violent impacts. This vibration can be either two-dimensional or three-dimensional, with the latter being more common. Similar to

⁸⁴ Wegener, K., Bleicher, F., Krajnik, P., Hoffmeister, H.W. and Brecher, C., 2017. Recent developments in grinding machines. *CIRP Annals*, 66(2), pp.779-802.

⁸⁵ Gao, W., Chen, F., Wang, X. and Meng, Q., 2020. Recent advances in processing food powders by using superfine grinding techniques: A review. *Comprehensive Reviews in Food Science and Food Safety*, 19(4), pp.2222-2255.

⁸⁶ Karam, M.C., Petit, J., Zimmer, D., Djantou, E.B. and Scher, J., 2016. Effects of drying and grinding in production of fruit and vegetable powders: A review. *Journal of Food Engineering*, 188, pp.32-49.

ball milling, particles in a vibration mill are crushed between abrasive media (such as porcelain or metal balls/bars) and the container. However, vibration milling is more efficient than conventional ball milling due to its high medium filling rate and impacting frequency. These grinding methods primarily rely on compression, impact, attrition, or cutting to achieve fine particles. Despite its efficiency, vibration milling has disadvantages, including excessive energy consumption and significant loss of heat-sensitive components (volatile oils, aroma components, and phenolics). These issues can be mitigated to some extent by precooling or chilling the feed material during grinding using cooling devices (air cooling or jacket cooling). However, these solutions are often insufficient to significantly reduce the temperature rise.

Wet milling is a process in which a solid is suspended in a liquid. During the wet milling, materials in the suspension are downsized to a nanometre scale by the shear forces provided by collisions between the media beads, wall of the milling chamber, and the materials themselves⁸⁷. Five main wet milling technologies include planetary ball milling, HPH, microfluidisation, ultrasonic homogenisation, and colloid milling.

- A planetary ball mill is a highly efficient and versatile grinding device suitable for both dry and wet milling. It is a high-energy ball mill where the speed ratio between the rotating disk (jar holder) and the grinding jar is 1:2. This means that for every rotation of the disk, the grinding jar rotates in the opposite direction twice. Most planetary ball mills lack an integrated cooling system, so most of the energy introduced into the grinding chamber converts into heat, which dissipates into the suspension. The temperature increase during milling is another mechanism for reducing granularity.
- During HPH, the sample is pumped through one or more homogenizing valves. As the sample passes through the narrow channels of the valves, it accelerates due to the enormous pressure gradient, generating high shear, turbulence, cavitation, and velocity gradients. This process leads to the breakage of suspended particles or globules.
- A microfluidiser consists of a high-pressure interaction chamber, which is the core component determining the homogenisation effect. The chamber often has different internal structures to facilitate various applications. It typically features two main interaction chambers: Y-type and Z-type, which can be used independently or in combination based on practical needs. Like HPH, microfluidisation relies on high pressure to create uniform superfine particle sizes. However, during microfluidisation, the high pressure generated by the hydraulic pump disperses the sample into two or more thin streams in the impingement chamber, causing a strong high-speed impact in a very small space. This impact transforms most of the energy instantly, resulting in a significant pressure drop and highly fragmented liquid particles.
- An ultrasonic homogeniser (UH) usually consists of two main parts: a transducer and a sonotrode. The sonotrode is equipped with a booster and a horn. The booster is a mechanical amplifier that increases amplitude, while the horn is a specially designed tool that provides ultrasonic energy to the target mixture. During the ultrasonic process, the energy generated by the UH dissipates through the liquid matrix, creating pressure differential cycles that produce a cavitation effect in the liquid. This leads to the formation of numerous microbubbles, which collapse in split seconds during the high-pressure cycle, causing highly localised turbulence, shear forces, pressures, and increased temperature. This results in the release of tremendous amounts of energy. In milk processing, UH treatment is a very effective method for reducing the size of fat globules compared to traditional homogenisation.

⁸⁷ Jung, H., Lee, Y.J. and Yoon, W.B., 2018. Effect of moisture content on the grinding process and powder properties in food: A review. *Processes*, 6(6), p.69.

3.4.11 Homogenisation

Homogenisation is a mechanical process used in dairy processing to create a stable and uniform mixture of fat and liquid. This step is essential for ensuring consistent texture, flavour, and appearance in beverages.

The purpose of homogenisation is to prevent cream separation. In untreated milk-drinks, fat globules tend to rise to the top, forming a cream layer. Homogenisation breaks down these larger fat globules into smaller ones, preventing separation and ensuring a uniform distribution of fat throughout the milk. The process also improves texture and enhances the creaminess and mouthfeel of milk drinks by creating a smoother, more homogenous product. This is particularly important for consumer acceptance and overall quality. It also increases the shelf life of milk and plant based ready-to-drink products. Homogenised products have improved physical stability, reducing the likelihood of spoilage and extending shelf life. Smaller fat globules are less prone to clumping, which helps maintain freshness. In addition, homogenisation can also make milk more suitable for subsequent processing steps, such as cheese production, by ensuring a consistent composition.

Types of homogenisation

- Single-stage homogenisation: In this method, milk passes through a single homogenisation unit. It is efficient for many products and commonly used in the dairy industry.
- Two-stage homogenisation: This method involves two passes through the homogeniser, which provides even finer fat globule size and increased stability. It is often used for premium products such as cream or high-fat milk-drinks.
- Downstream or upstream homogenisation: upstream homogenisation occurs before major processing steps, while downstream homogenisation occurs afterward. Upstream focuses on creating a uniform mixture for efficient processing, while downstream emphasises stabilizing and refining the final product. Upstream homogenisation influences how the product behaves during processing, whereas downstream homogenisation affects the product's final quality and shelf stability.

3.4.12 Hot water processes

3.4.12.1 *Blanching*

Blanching is typically applied as a process prior to freezing of fruits and vegetables. Blanching is a short-time heating process, usually applying hot water (typically ~70–100 °C) or steam to the food. The quality of frozen fruits and vegetables depends on several factors, including the quality of the raw materials, the preparation methods before freezing, the freezing process itself, and the handling after freezing. Blanching is a crucial step before freezing, but traditional water blanching can damage the texture, vitamins, colour, and flavour of the produce. Therefore, different freezing methods are used to preserve the quality of frozen fruits and vegetables.

If fruits and vegetables aren't frozen correctly, large ice crystals can form and damage their cellular structure. Improper blanching or freezing methods can cause permanent and unwanted changes to the quality of the frozen product. Hence, new freezing and blanching methods are important for preserving the quality of frozen food.

In meat and fish processing, true “blanching” is less common, but analogous hot water scalding steps are used (e.g. scalding carcasses to remove hair/feathers, or blanching shellfish in brine). For example, shrimp and crab are often briefly boiled in salt brine, which imparts the characteristic pink colour to the meat and reduces bacterial load

Blanching pretreatment is used to (I) inactivate the enzymes responsible for producing off-flavour and unpleasant odour, (II) maintain the freshness colour, stabilisation of texture and nutritional quality; (III) expel air between the cells; (IV) destroy microorganisms to some extent.

Blanching, though necessary, can cause negative changes in food. Heat can lead to the loss of nutrients like sugars, minerals, and vitamins. Blanching can also extract valuable nutrients and alter the food's aroma, texture, and colour, which are important factors for consumers.

Modern blanching is performed either by **steam blanchers** or **hot-water blanchers**, with several designs prevalent in industry. In steam blanching, foods are conveyed through an environment of saturated steam for a controlled time. Common configurations include:

- *Tunnel steam blanchers*: a mesh conveyor carries product through a steam-filled tunnel.
- *Screw conveyor blanchers*: product is moved through a steam chamber by a helical screw.
- *Fluidised bed blanchers*: a mixture of steam and air both heats and transports the product, suspending it in a heated airflow.

In hot-water blanching, the product is submerged in or sprayed with hot water. Two dominant machines are:

- *Reel (rotary drum) blanchers*: a perforated rotating drum (with internal flights) tumbles the product in a hot water bath.
- *Pipe blanchers*: product and hot water flow together through a pipe; after a set residence time the product is separated out.

In all cases, blanchers are equipped with temperature controls and timing to ensure the center of pieces reach the target temperature for enzyme inactivation. After heating, products are rapidly cooled (often in a cold water or air cooler) to stop the cooking action and avoid quality loss. (*Schematic*: In industry diagrams, a blancher often includes a feed hopper, a heated tunnel or tank (with steam injection or a heat exchanger to maintain water temperature), a conveyor mechanism, and a discharge where product exits to a cooling step.). Blanching times are typically short (for example, 1–5 minutes for vegetables), to balance enzyme kill with minimal nutrient loss. Newer blanching methods under study are aimed to achieve enzyme inactivation with potentially less nutrient damage or water usage. New technologies like Ohmic, radio frequency, microwave, high pressure, ultrasound, and infrared are being used to blanch fruits and vegetables before freezing. These methods could replace traditional water blanching. New thermal blanching technologies can be divided into indirect heating (like radio frequency and microwave) and direct heating (like Ohmic). Indirect heating uses electromagnetic energy to create heat inside the food, while direct heating applies an electrical current directly to the food. Blanching relies on thermal energy (often steam or heated water), so improving its efficiency is important for sustainability. New blanchers are engineered to retain heat and minimise steam losses. Features like insulated chambers, and steam seals (e.g. water spray curtains or hydrostatic seals at conveyor openings) prevent heat escape. Internal circulation fans or steam injection ensure even heating, which shortens required blanch time and avoids wasted energy. Process controls (Programmable Logic Controllers [PLC] systems) adjust steam flow based on product load and temperature, preventing over-heating. Instead of continuously steaming for the entire blanch duration, heat-and-hold blanchers briefly heat the product surface then hold it in an insulated section, so the heat penetrates to the core without additional steam. The hot water or condensate from blanching can be reused to save energy. Advanced blanchers recirculate unused steam. To align with net-zero goals, processors are exploring low-carbon heat sources. Options include using biomass or

biogas boilers for steam or electrifying the heat supply via electric boilers or high-temperature heat pumps.

3.4.12.2 Boiling

Boiling is a fundamental cooking method employed in food processing for centuries. The technique involves the application of heat to a liquid, typically water, resulting in the formation of bubbles and the conversion of the liquid to vapour⁸⁸. In the realm of food processing, boiling plays a crucial role in various applications, including blanching, pasteurisation, and cooking.

Boiling is a versatile and efficient method for heat transfer, making it indispensable in the food processing industry. Boiling has extensive applications in the food processing industry, contributing to food products' safety, preservation⁸⁹, and enhancement^{90,91}. These are: (1) Cooking: Boiling is a prevalent cooking method for a variety of foods, including vegetables, pasta, rice, and proteins. It effectively reduces microbial contamination, making the final product safe for consumption. (2) Blanching: see section 3.4.12.1 (3) Sterilisation and pasteurisation: see section 3.4.13. (4) Reduction of Anti-nutritional factors: boiling is employed to reduce anti-nutritional factors in certain raw materials, such as legumes and grains, making them more nutritionally accessible.

In an industrial context, this includes not only open kettle boiling but also other forms of water or steam cooking of food. Boiling accomplishes full cooking of products – it gelatinises starches, tenderises proteins, and destroys harmful bacteria (though boiling at 100 °C is pasteurisation-level, not sterilisation). It is a fundamental step in many recipes (soups, sauces, broths) and is used to **develop product characteristics** (texture, flavour) as well as to **ensure safety**. For example, in meat processing, some sausages and hams are simmered or poached in hot water to cook them evenly without drying out. In fish/seafood processing, boiling is used for products like crab and shrimp (often termed blanching in brine) to cook and sanitise the meat for either direct consumption (e.g. cooked shrimp) or before freezing. In fruit and vegetable processing, boiling is used in the production of jams, jellies, and sauces – fruit is boiled with sugar to concentrate it and achieve proper gel texture. In beverage and brewing industries, boiling plays a critical role: during beer brewing, the wort (sweet liquid from malt) is boiled vigorously with hops. This wort boiling is essential for sterilisation, enzyme deactivation, flavour compound formation, and is actually one of the most energy-intensive steps in beer-making. Overall, boiling processes are central to cooking and product formulation across a broad range of food sectors, from ready-meals and canned foods to beverages.

Industrial boiling is carried out in various types of cooking vessels or continuous systems, chosen based on the product and scale:

- **Steam-jacketed kettles:** These are common in food processing for batch boiling or simmering. A steam jacketed kettle is a large vessel (50–1000+ litres) with double walls;

⁸⁸ Silva, E., Oliveira, F.A.R., and Boillereaux, L. (2017). Comparison of traditional boiling and vacuum cooking (sous-vide) in bovine liver: Mineral bioaccessibility and cooking water losses. *Food Research International*, 99, pp. 234-242. DOI: 10.1016/j.foodres.2017.07.054.

⁸⁹ Wu, J., Li, Y., and Zhang, H. (2023). Food spoilage mechanisms, foodborne diseases, and commercial food preservation methods: A review. *Food Control*, 152, 110248. DOI: 10.1016/j.foodres.2023.112685.

⁹⁰ Fang, X., Zhao, W., and Chen, L. (2023). Impact of cooking techniques on food quality, digestibility, and safety. *Food Chemistry*, 406, 134012. DOI: 10.1016/j.foodres.2023.112685.

⁹¹ Zhang, R., Wang, J., and Liu, Q. (2023). Effects of traditional and novel cooking processes on the nutritional and bioactive properties of kale (*Brassica oleracea*). *Journal of Food Science and Technology*, 60(8), pp. 4123-4135. DOI: 10.1155/2023/2827547.

steam circulates in the jacket to heat the contents. They often have agitators to prevent sticking and ensure uniform heating. Kettles may be stationary or tilting (for easy unloading of soups, sauces, cooked meats, etc.). Large-scale soup or sauce manufacturing, for example, uses multiple steam kettles. Modern kettles may use self-contained electric or gas heaters to generate steam internally. (Compared to kettles hooked to a central boiler, self-contained kettles can save water and energy by avoiding steam distribution losses and blowdown waste. Proper insulation and lids on kettles are employed to reduce heat loss and energy consumption.

- **Continuous cooking systems:** For high throughput, continuous cookers are used. These can be similar in design to continuous blanchers. For instance, a blancher can double as a continuous cooker for products like pasta, rice, or vegetables in prepared foods – the product travels through a hot water bath on a conveyor or auger. Other continuous systems include scraped-surface heat exchangers (used for viscous foods like custards or sauces, where the product is pumped through a heated barrel while scrapers prevent burn-on) and tubular cookers for liquids. In seafood canneries, continuous belt cookers steam or boil tuna and other fish before canning. In vegetable canning factories, products might be cooked in brine or syrup as they are filled into cans (e.g. some beans or pumpkin pieces are hot filled with brine).
- **Brewhouse kettles:** In breweries, the brew kettle (or copper) is a specialised boiling vessel. It's designed to achieve a “rolling boil” of the wort. Many have an internal heat exchanger called a calandria (or an external wort boiler loop) where steam heats the wort rapidly. These kettles are usually stainless steel with chimneys to vent water vapor and volatiles. A vigorous boil (usually ~60–90 minutes) sterilises the wort, inactivates enzymes, allows hops to isomerise (for bitterness), coagulates proteins, and evaporates unwanted volatile compounds. Typically, ~4–10% of the wort volume is evaporated during boiling. Brewing kettles thus function as both cooking and moderate evaporation units.
- **Vacuum boiling pans:** In some applications (particularly in confections and fruit processing), boiling under partial vacuum is used. By reducing pressure, water boils at a lower temperature – this is used to concentrate products like fruit purees or syrups at ~60–80 °C instead of 100 °C, to prevent flavour or colour degradation. For example, industrial jam makers might use vacuum kettles to gently boil down fruit preserves. (This overlaps with evaporation technology – see Evaporation section – but is mentioned here as a form of “boiling” in a controlled-pressure environment to achieve a cooking/concentrating effect with less thermal damage.)

Recent advancements in boiling technology focus on enhancing efficiency, reducing energy consumption, and improving overall process control. For instance, introducing vacuum evaporation/cooling loops for lower boiling temperatures reduces damage to sensitive food components⁹². Furthermore, the integration of automated control systems and precise temperature monitoring ensures optimal processing conditions, enhancing product quality and safety. A more advanced solution is vapor recompression, akin to what is used in evaporators. Thermal vapor recompression (TVR) uses a steam-jet ejector to entrain and compress part of the vapor back to a usable pressure. Mechanical vapor recompression (MVR) uses an electrically driven compressor or fan to compress the vapours. In effect, these turn the boiling step into a cycle that reuses its own vapor as

⁹² Sharanabasava, and MR, R. (2018). Vacuum processing of food—a Mini Review. MOJ Food Process Technol., 283-290.

a heat source. Energy can be also saved by avoiding over-boiling. In brewing, for example, research into “low-pressure boiling” (boiling wort at a slight vacuum to lower the boiling point) can achieve the same objectives (iso-alpha acid extraction from hops, protein coagulation) with less heat input. Modern kettles and cookers incorporate features to enhance heat transfer and reduce losses. Examples include better agitator designs to improve heat distribution (reducing localised overcooking and allowing lower steam settings), and thicker insulation or even double lids to trap heat. Ensuring the kettle or cooker is well-sealed (except for necessary vents) minimises steam escape. Regular maintenance of steam traps and condensate return lines is also crucial. To decarbonise boiling, switching from fossil-fuel steam to electric heating is an option. Electric resistance-heated kettles or induction-heated vessels can be as effective as steam, especially for small-to-medium batch sizes, and if the electricity is renewable, the process becomes low-carbon.

Boiling technology, while indispensable, is not without environmental implications. The energy-intensive nature of boiling processes, due to the utilisation of boilers⁹³, contributes to GHG. However, innovations such as energy recovery systems and renewable energy sources are being explored to mitigate these environmental concerns.

One of the critical challenges associated with boiling technology in food processing is its environmental impact. Direct emissions savings can be achieved by implementing energy-efficient boilers, optimising process parameters, and utilising alternative energy sources. Studies have shown that integrating energy recovery systems in boiling processes can significantly reduce greenhouse gas emissions, contributing to a more sustainable food industry.

Maintaining boiling equipment is crucial for ensuring continuous and efficient food processing. Common challenges include scaling, corrosion, and wear of components due to the high temperatures and chemical interactions involved in boiling processes. Regular maintenance and corrosion-resistant materials are essential to address these issues and extend the lifespan of boiling equipment.

3.4.12.3 Steaming

Steam is an efficient and convenient method for transferring energy in food processing operations, as it is generated from water, a cheap and plentiful resource. Using pressure control valves allows for precise regulation of steam temperature. Given that steam contains significant energy in a relatively small mass, heat-transfer equipment can be designed to be compact. Steam can also be easily and inexpensively transported over long distances, including to remote areas of a process. In this review, the focus is on clean steam, commonly referred to as “culinary” steam, which is directly injected into the product. Any additives in culinary steam must comply with hygiene regulations for human consumption⁹⁴.

3.4.13 Microwave and Radio Frequency (RF) heating

The heating of food by microwaves is the result of the transfer of energy from the electromagnetic field in the chamber of the appliance, with the mechanism taking place at the molecular level. In a variable electric field, polar particles rotate and collide with each other. The second mechanism is ionic conductivity, which is based on the acceleration of ions. They move in the direction of the electric field

⁹³ BurnerCombustionSystems. (2024, January 9). Food Processing. Retrieved from Burner Combustion Systems: <https://burnercombustion.com/food-processing/>.

⁹⁴ Bowser, Timothy J. 2017. “Steam Basics for Food Processors.” Robert M. Kerr Food and Agricultural Products Center. Food Technology Fact Sheet FAPC-142: 1–8. www.fapc.biz.

and collide with the water molecules, transferring kinetic energy. Many millions of such collisions occur every second. The result is friction, which causes the release of thermal energy⁹⁵.

Microwaves are part of the electromagnetic radiation spectrum with a wavelength in between infrared and radio waves. Their range is from 0.001 to 1 m, which corresponds to frequency between from 300 MHz and 300 GHz. The Federal Communications Commission (FCC)⁹⁶ is in charge of managing and reserving microwave frequencies at the national and international levels (**Error! Reference source not found.**). This is done to prevent interference with the waves used in industrial or research equipment, medical equipment, and even in environments like our own homes.

The frequency of domestic microwave ovens is 2.45 GHz. Industrial microwaves used for heating operate at frequencies of 915 MHz or 2.45 GHz⁹⁷. RF heating uses lower frequency radio waves (typically 13, 27 or 40 MHz) which penetrate deeper due to longer wavelength and heat the material in a similar way.

Table 5. Bands designated for industrial, scientific and medical applications by the FCC (Federal Communications Commission)⁹⁸

Frequency	Tolerance
6.78 MHz	± 15.0 kHz
13.56 MHz	± 7.0 kHz
27.12 MHz	± 163.0 kHz
40.68 MHz	± 20.0 kHz
915 MHz	± 13.0 MHz
2450 MHz	± 50.0 MHz
5800 MHz	± 75.0 MHz
24.125 GHz	± 125.0 MHz
61.25 GHz	± 250.0 MHz
122.50 GHz	± 500.0 MHz
245.00 GHz	± 1.0 GHz

An industrial microwave heating system often takes the form of a tunnel oven or continuous conveyor belt passing through a shielded microwave chamber. Multiple magnetrons (microwave generators) are positioned along the tunnel to emit microwaves into the cavity, ensuring even coverage. The chamber is a reflective metal enclosure that contains the microwaves (to prevent leakage) and focuses energy into the product. RF heating systems typically consist of a pair of electrodes (plates or coils) creating an alternating electric field that the product passes through (e.g. a conveyor between two plates). The product's dielectric properties cause it to heat as it passes the RF field. Both microwave and RF systems

⁹⁵ Guzik, P., Kulawik, P., Zajac, M. and Migdał, W., 2022. Microwave applications in the food industry: An overview of recent developments. *Critical Reviews in Food Science and Nutrition*, 62(29), pp.7989-8008.

⁹⁶ Federal Communications Commission, "Title 47 —Telecommunication Chapter I —Federal Communications Commission Subchapter A —General Part 18 Industrial, Scientific, and Medical Equipment," 1985.

⁹⁷ Thostenson, E.T. and Chou, T.W., 1999. Microwave processing: fundamentals and applications. *Composites Part A: Applied Science and Manufacturing*, 30(9), pp.1055-1071.

⁹⁸ Federal Communications Commission. 1985. Telecommunication Chapter I —Federal Communications Commission Subchapter A —General Part 18 Industrial, Scientific, and Medical Equipment.

often incorporate turntables, agitators, or field stirrers to even out the heating and avoid cold spots. Ancillary components include cooling systems for the magnetrons, sensors for temperature (often infra-red sensors or fiber optic probes since microwaves can interfere with electronics), and sometimes vacuum systems (in the case of microwave-vacuum dryers).

Microwaves are used industrially for rapid tempering of frozen meat blocks. For instance, large 27 MHz microwave tempering systems can take meat from -20 C to -4 C in a few minutes, allowing continuous sausage production. This is far faster than air thawing and reduces drip loss. In terms of cooking, there have been trials of microwave pasteurisation of packaged ready meals containing meat. A notable example is the microwave-assisted thermal sterilisation (MATS) process developed for shelf-stable meals: trays containing, for example, beef stew is conveyed through a pressurised microwave cavity with water to help distribute heat – the microwaves heat the product much faster than a conventional retort, achieving sterilisation with less damage to texture and nutrients. These systems can sterilise packaged foods because microwaves penetrate packaging materials like plastic easily. After heating, the packages are cooled, all in a continuous tunnel. Some cured meat products (bacon, jerky) have used microwaves for finish-cooking or post-packaging pasteurisation to eliminate surface pathogens in a sealed bag.

Similar to meat, fish processors use microwaves primarily for thawing/tempering. Blocks of frozen fish (for fish fillet portions or surimi production) are tempered with microwaves to soften them for cutting, greatly speeding up production. There is also research into microwave cooking of seafood-based ready meals and microwave pasteurisation of smoked fish to extend refrigerated shelf life. RF heating has found application in pasteurizing vacuum-packed fish products, as RF can penetrate salt-containing fish well.

Microwaves have been studied for milk pasteurisation – continuous microwave units can heat milk to pasteurisation temperature almost instantaneously, then it is cooled in a heat exchanger. This avoids contact with hot surfaces, reducing fouling and possibly better preserving heat-sensitive nutrients. Commercial adoption is still limited, but some systems exist for microwave pasteurizing juice and milk in flow. Another dairy use is drying where microwave-vacuum dryers gently dry heat-sensitive dairy powders (like probiotics or enzymes) at lower temperatures than conventional spray dryers. Microwaves have also been used to temper butter or cheese to a workable temperature for further processing.

State of the art

According to Guzik et al. (2022)⁹⁵ microwave technology is superior to conventional methods in terms of food quality and nutritional value. It is more economical and environmentally friendly, reducing processing time and energy consumption. The following overview summarises the areas of application in the food industry considered by Guzik et al. (2022)⁹⁵.

Applications in food processing

- Defrosting, baking, drying, pasteurisation, and blanching:

Microwaves enhance production efficiency by reducing processing time and energy consumption. Microwave-assisted sterilisation and pasteurisation offer shorter processing times and better product quality.

- Microwave drying:

Methods like vacuum-microwave drying and microwave-freeze drying heat food evenly, resulting in a porous structure and crispier texture. This significantly reduces drying time and improves product quality.

- **Microwave thawing:**
Primarily used to reduce defrosting time, it preserves the nutritional quality of some products better than other methods but can cause severe damage to the microstructure of some foods.
- **Microwave blanching:**
Effective in enzyme inactivation while preserving thermolabile nutrients, it can also reduce undesirable compounds like arsenic in shiitake mushrooms.
- **Nutrients and nutraceuticals production:**
Microwaves are used for drying granules and powders, enhancing bioavailability and solubility of sensitive compounds. They are also used in pharmaceutical powder drying and synthesis processes, offering reduced solvent use and improved efficiency.
- **Waste management:**
Microwave technology is effective in recovering valuable compounds from food processing waste, such as extracting pectin from fruit peels and pyrolyzing lignocellulosic biomass. Microwave pyrolysis offers economic advantages by reducing the need for further removal of water and acidic compounds.

3.4.14 Mixing

Mixing is a fundamental step in cooking and food production. It ensures that ingredients are evenly combined, affecting the taste, texture, and appearance of the final product. The right mixing equipment depends on what is being mixed (liquids, solids, or a combination) and the desired texture of the final product. Many mixers can be used for similar tasks, but cost and efficiency are important factors to consider. Choosing the best mixer is crucial for optimizing the food production process.

Several types of mixers are available:

- The ribbon blender is a popular machine used for mixing dry ingredients in the food industry. It has a U-shaped container with rotating blades that move the ingredients around efficiently. This blender is often used for things like cake mixes, flour, cereal, and powdered drinks and is efficient and affordable.
- High shear mixers (HSMs) are used to blend and break down ingredients into smooth mixtures such as sauces and pastes. They have a rotating part that cuts and mixes ingredients very quickly. These mixers can be used in batches or continuously. A new feature called SLIM technology allows HSMs to suck in powdered ingredients directly into the mixing chamber, making the process more efficient.
- Ultra-high shear mixers can create very small droplets and particles, which is useful for products like sauces, condiments, and juice concentrates. Ultra-high shear mixers can sometimes do the same job as high-pressure homogenisers and colloid mills, but they require less maintenance.
- Dual-shaft and triple shaft mixers are used to mix thick substances like candy syrups, sauces, and peanut butter. They are good for mixing large batches of these products.

When mixing thick substances, traditional mixers with fixed blades can sometimes struggle to move the ingredients around evenly. This can cause problems like uneven heating and mixing. In these cases, a planetary mixer is a better choice. Planetary mixers have blades that rotate and move around the mixing bowl, ensuring that all ingredients are mixed thoroughly.

- Single planetary mixers are often used for mixing thick foods like dough, but they can struggle with materials that are too sticky, heavy, or prone to climbing up the mixing blades. In these situations, a double planetary mixer is a better option.
- Double planetary mixers have two mixing blades that rotate and move around the mixing bowl. These blades can be different shapes, including rectangular, finger-like, or high viscosity (HV) blades. HV blades are a special type of blade with a curved design that pushes the mixture downward, preventing it from sticking to the blades. This is especially helpful for mixing very thick materials. HV blades also have a simpler design that makes them easier to clean and use. Double planetary mixers are also used to mix syrups, gels, pet food, candies, and other thick substances.

Hybrid planetary mixers are a combination of a traditional planetary mixer and a high-speed disperser. This type of mixer is ideal for mixing very thick materials that are also sensitive to heat. The planetary blade moves around the mixing bowl, sweeping the ingredients towards the disperser, which breaks them down. The variable speed settings allow for precise control, minimizing damage to sensitive ingredients. Some examples of applications include sausage casing gels, gum solutions, and starchy mixes⁹⁹.

3.4.15 Pasteurisation

Pasteurisation, a key process in dairy and beverage industries, relies on boiling to eliminate harmful microorganisms while maintaining the product's sensory attributes. Boiling is a key component of sterilisation and pasteurisation processes, vital for preserving perishable goods. Canning and bottling industries extensively use boiling to eliminate harmful microorganisms and enzymes, ensuring extended shelf life.

Pasteurisation is a heat treatment process designed to kill pathogenic microorganisms in food and beverages, particularly liquid products like milk. Named after French scientist Louis Pasteur, this method significantly enhances food safety and extends shelf life while preserving the nutritional quality and flavour.

The pasteurisation process

Milk is typically pasteurised using two main methods:

1. High-temperature short time (HTST): Milk is heated to about 72°C for at least 15 seconds. This method is widely used for commercial milk processing.
2. Low-temperature long time (LTLT): Milk is heated to approximately 63°C for at least 30 minutes. This traditional method is less common for large-scale production.

After heating, the milk is rapidly cooled to about 4°C (39°F) to prevent any surviving microorganisms from multiplying. This quick cooling helps maintain the quality of the milk.

Benefits of pasteurisation

Safety: Pasteurisation effectively kills harmful bacteria such as Salmonella, E. coli, and Listeria, reducing the risk of foodborne illnesses.

Quality: The process maintains the nutritional content of milk while enhancing its flavour and aroma, making it more appealing to consumers.

⁹⁹ Mixing Equipment and Applications in the Food Industry; A White Paper Prepared by Charles Ross and Son Company.

Extended Shelf Life: Pasteurised milk can be stored for several weeks under refrigeration, providing convenience for consumers and retailers.

3.4.16 Ohmic heating

Ohmic heating (also known as Joule heating or direct electrical resistance heating) involves passing an electrical current directly through food to heat it internally. The food, if sufficiently liquid or moist, acts as a resistor; as the electric current flows, the electrical resistance of the food converts electrical energy to heat uniformly throughout the volume. In essence, the food heats itself from the inside out due to its own electrical conductivity. This method can heat very rapidly and evenly, making it valuable for pasteurisation or sterilisation of liquid and semi-liquid foods (especially those with particles) and for fast cooking where conventional heat transfer is too slow. Ohmic heating is gentle on food quality because it avoids very high surface temperatures – there is no hot surface causing localised burning, and heating stops as soon as the current stops, giving fine control. An ohmic heating system typically consists of a product feed system, an ohmic heater unit, and a holding section. In a continuous ohmic heater, the food (e.g. a soup with particulates, or a fruit puree) is pumped through a tube or chamber where electrodes are in contact with the product. Often, multiple electrode pairs are arranged along a pipe. A power supply (generally low-frequency AC at 50 or 60 Hz is used, to avoid electrochemical reactions) applies voltage across the electrodes, causing current to flow through the conductive food between them. The design ensures that the electric field covers the entire cross-section of the flow, so heating is uniform. The equipment must be made of food-grade, non-corrosive materials (electrodes are often titanium or coated to resist corrosion). A holding tube after the heater keeps the product at target temperature for the required time to achieve microbial kill, similar to a conventional system but typically shorter due to the rapid heating. For batch ohmic heating, a vessel with electrodes is filled with product and energised until it reaches the set temperature.

Ohmic heating has shown great potential in cooking processed meats. Research demonstrated that meat emulsions (like sausage batter) cook very rapidly with ohmic heating, significantly faster than in a smokehouse or water bath. Ohmic heating has also been tested for beef patties, meatballs, and chicken pieces in sauce, where uniform heating is otherwise hard to achieve. The ability of ohmic heating to handle foods with particulates means things like stews or curries with meat chunks can be pasteurised quickly in bulk. There is commercial interest in ohmic heating for ready meal sauces (often containing meat or poultry pieces) to sterilise them aseptically before packaging.

Conductive fish products (like soups, chowders or surimi mixtures) are suitable for ohmic heating. Ohmic processes could cook fish mince or gels evenly without hot spots that could overcook the protein. Studies have included applications like fish soups and even enhancement of processes like brine infusion. Because ohmic can handle solids, a fish stew with chunks of fish and vegetables can be brought to sterilisation temperature with all particles heating at the same rate as the liquid – a challenge for conventional inert or microwave systems (where different components heat differently). This preserves texture of delicate fish pieces. Also, similar to meat, ohmic heating could be used to pasteurise fish pâtés or spreads that are rich in protein (ensuring safety without ruining quality).

Ohmic heating has been explored for milk pasteurisation and sterilisation. Milk is a good conductor and can be ohmically heated very fast. Ohmic pasteurised milk, for the same microbial reductions as conventional pasteurisation, may have possibly less cooked flavour and be using less energy. The latter because of shorter heating times and no heat wasted in metal walls. Another important dairy use is in viscous products: for example, processed cheese or dairy sauces that can foul hot surfaces. Ohmic heating eliminates hot surface fouling, which is a big advantage in maintaining quality (no burned-on protein) and reducing cleaning frequency. Ohmic heating is also suitable for particulate dairy products like yogurt with fruit – it could heat the fruit preparation, or the yogurt mix quickly in-line. In summary,

dairy processes benefit from ohmic's gentle uniform heat, avoiding localised overprocessing (useful for heat-sensitive nutrients like whey proteins or vitamins).

Fruit preparations (pie fillings, purees) and multi-component foods (like rice puddings, which are dairy + starch particulates) have been successfully ohmically heated. The technology's ability to uniformly heat solids up to about 1-inch in size in a liquid matrix is a unique strength. Conventional heating struggles with slow heat conduction into particles; microwaves can create hot spots especially in larger particles, whereas ohmic heats them uniformly if conductivity is similar.

Electrodes and power units capable of high throughputs can be expensive. Also, not all foods are suitable – the food must conduct electricity (though most water-containing foods do to some degree). Processors have to ensure the product formulation or the system design accounts for such differences (sometimes mixing or modest movement is applied during ohmic heating to even out temperature). Electrode fouling or corrosion is another concern, especially with salty or acidic foods that can cause metal ions to leach. However, using alternating current and proper electrode materials practically eliminates electrolysis and metal contamination.

From a decarbonisation angle, ohmic heating's use of electricity aligns with the push to electrify food processing. If the electricity comes from renewable sources, the process heat is virtually carbon-free. The main barriers for ohmic heating have been capital cost and complexity.

3.4.17 Refining and extraction

Refining and extraction are different but often interconnected processes used in the production of food materials. Extraction is the initial process of removing a desired substance from its source. Refining is the subsequent purification process to remove impurities and achieve a higher level of purity.

Refining is used to remove unwanted components from edible oils and fats to improve their quality, stability, and nutritional value. For example, vegetable oil is rich in triglycerides and contains fatty acids and micronutrients (tocopherols, phospholipids, sterols, carotenoids, etc.) some of which need to be removed to improve the palatability or cooking performance of the oil.

Vegetable oil extraction methods traditionally include organic solvent extraction, cold pressing, and hot pressing. However, with technological advancements, new extraction techniques have emerged. These include supercritical CO₂ fluid extraction, ultrasound-assisted solvent extraction, enzyme-assisted aqueous extraction, pulsed electric field extraction, and microwave-assisted extraction. Compared to traditional methods, these innovative techniques offer benefits such as higher oil extraction rates, reduced extraction times, and lower solvent usage. (Wen et al, 2023¹⁰⁰).

Refining vegetable oils can be done through chemical or physical methods. Chemical refining involves more steps, starting with degumming to remove phospholipids and gums. Membrane degumming is more efficient, using less energy and fewer chemicals. The next step is neutralisation, where free fatty acids are removed with caustic soda. Hydrodynamic Nano Reactors® are used for nanoneutralisation, mixing oil and caustic solution under high pressure to improve oil quality. The oil is then washed, dried, and further processed. Vacuum bleaching prevents oxidation and colour changes, while dewaxing removes waxes. Deodorisation uses high-temperature steam to eliminate odours and contaminants.

¹⁰⁰ Wen, C., Shen, M., Liu, G., Liu, X., Liang, L., Li, Y., Zhang, J. and Xu, X., 2023. Edible vegetable oils from oil crops: Preparation, refining, authenticity identification and application. *Process Biochemistry*, 124, pp.168-179.

Generally chemical refining methods require more energy due to multiple processing steps and the need for high temperatures and vacuum conditions, especially during deodorisation (Gharby, 2022¹⁰¹)

Physical refining also starts with degumming, followed by bleaching and deodorisation. Although chemical refining consumes more energy and can be costlier, it effectively removes impurities and is suitable for high-quality crude oils. Generally, chemical refining requires more energy due to multiple steps and high-temperature processes¹⁰¹.

Significant progress has been made to reduce GHG emissions. In downstream processing, measures such as the mandatory capture of biogas to generate power for mills and the utilisation of palm oil mill effluent (POME) as a biofuel feedstock have been introduced¹⁰².

3.4.18 Roasting

Roasting is an intense thermal process in which food is heated, surface-dried, and chemically altered at temperatures ranging from 150 to 300°C or higher. During the initial stage, a dry crust forms on the food's surface. As roasting progresses, various chemical reactions such as hydrolysis, oxidation, reduction, and pyrolysis occur, contributing to the development of flavour, aroma, and colour. This process also enhances the food's eating qualities by preserving interior moisture, as the crust resists water loss.

Roasting techniques vary in heat application methods and heat transfer types, and the quality of the final product depends on the type of roaster used and the time–temperature profiles employed¹⁰³. Industrial roasting methods include forced convection roasting, microwave roasting, superheated steam roasting, vibration roasting, and infrared roasting.

In hot air forced convection roasting, a continuous process suspends food in heated air within a rotating cylinder, ensuring even exposure to heat and producing a uniformly roasted product. The process could be made more energy-efficient due to thermal insulation and continuous recirculation of heated air, minimizing heat loss¹⁰⁴. Still, it is generally considered as the least energy efficient of the options further described below, mostly because the process is slower than the given alternatives.

Infrared (IR) heating uses electromagnetic radiation, typically in the infrared spectrum (wavelength ~0.7 to 10 µm), to directly heat the surfaces of foods. IR heating is a contactless method – IR emitters radiate energy that is absorbed by the product's surface and converts to heat. It's effectively the same principle as a toaster or broiler, but industrial IR systems are more controlled and can cover large areas. IR heating excels at rapidly delivering heat for surface treatments: browning, roasting, grilling, and thin layer drying. It can raise surface temperatures very quickly, which is useful for processes that need

¹⁰¹ Gharby, S., 2022. Refining vegetable oils: Chemical and physical refining. *The Scientific World Journal*, 2022(1), p.6627013.

¹⁰² Ramanath, T., Foo, D.C., Tan, R.R. and Tan, J., 2023. Integrated enterprise input-output and carbon emission pinch analysis for carbon intensity reduction in edible oil refinery. *Chemical Engineering Research and Design*, 193, pp.826-842.

¹⁰³ Sruthi, N. U., Yashaswini Premjit, R. Pandiselvam, Anjineyulu Kothakota, and S. V. Ramesh. 2021. "An Overview of Conventional and Emerging Techniques of Roasting: Effect on Food Bioactive Signatures." *Food Chemistry* 348 (June): 129088. <https://doi.org/10.1016/J.FOODCHEM.2021.129088>.

¹⁰⁴ Schoeman, Letitia, Anton Du Plessis, and Marena Manley. 2016. "Non-Destructive Characterisation and Quantification of the Effect of Conventional Oven and Forced Convection Continuous Tumble (FCCT) Roasting on the Three-Dimensional Microstructure of Whole Wheat Kernels Using X-Ray Micro- Computed Tomography (MCT)." *Journal of Food Engineering* 187 (October): 1–13. <https://doi.org/10.1016/J.JFOODENG.2016.04.015>.

high heat flux for short times (for example, giving a roasted appearance to a product or quickly evaporating surface moisture).

Typical Machinery: There are two main categories: batch ovens and continuous ovens. Batch ovens (e.g. rack ovens) are insulated rooms or chambers where a batch of product is loaded, roasted, then unloaded. Continuous ovens (common in large bakeries and some meat processing) are long tunnel-like machines through which product moves on belts or trays, continuously entering raw and exiting cooked. These ovens often have multiple zones where heat input and airflow can be independently controlled. The heating mechanisms can include:

- **Convection heating:** circulating hot air via fans (forced convection ovens). Most industrial ovens use convection as a primary mode for even heating.
- **Radiant heating:** either from hot surfaces or dedicated burners/emitters (e.g. ceiling “radiant panels” or gas-fired radiant tubes). This helps with crust formation and browning.
- **Steam injection:** in some ovens, steam is injected to control humidity (useful for bread crust quality or to avoid product weight loss in meats).
- **Hybrid designs:** Modern “hybrid ovens” combine multiple heat transfer modes (e.g. a zone of infrared radiant heaters followed by a convection zone) to optimise energy use and product quality

Thermal oil or direct gas burners are often used to heat the air. Newer designs include fully electric ovens with resistive heating elements or infrared elements. Electric ovens also don’t need a chimney for combustion exhaust, which reduces heat loss points. The oven structure is heavily insulated to retain heat. Controls manage conveyor speed, temperature setpoints in each zone, airflow rates, and exhaust dampers. Industrial ovens are historically energy-hungry, often running continuously and operating at high temperatures. They also lose efficiency with age – a bakery oven can lose ~30–40% of its energy efficiency over decades due to insulation degradation, air leaks, and fouling.

IR heating equipment includes:

- **IR lamps or emitters:** These can be electric (e.g. quartz tube emitters, ceramic plates with heating elements) or gas-fired (like catalytic IR panels that emit IR without an open flame). Electric IR lamps often glow red/orange (for near IR) or can even operate at lower temperature for far IR. Gas catalytic panels burn gas in the presence of a catalyst, emitting a broad IR spectrum without visible flames. A typical emitter surface might run at 300–700 °C, corresponding to IR wavelengths that food absorbs well.
- **Arrays and modules:** In an industrial oven or tunnel, multiple IR emitters are arranged above and/or below the product conveyor. They may be combined with reflectors to focus the radiation and ensure even coverage. IR tunnels might have a reflecting cavity design to maximise the fraction of IR hitting the food.
- **Control systems:** The intensity of IR can be controlled by adjusting power to electric emitters or gas flow to catalytic panels. IR heaters respond quickly, which allows for fine control. Often IR is one zone of a multi-zone cooker.

The IR machinery is generally simpler and more compact than hot-air ovens, since IR doesn’t require large circulation fans or heat exchangers – emitters directly produce the radiation that heats the

product. Electric IR systems can be powered by renewable electricity, thus zero-carbon at point of use. They also avoid the standby losses of keeping an oven hot when not needed – IR can be turned on and off rapidly, so energy is used on demand. Efficiency of IR heat transfer to the product can be quite high. The literature reports radiation efficiency of catalytic (gas) IR emitters ranging from 30% up to 75%, depending on design and operating temperature. By reducing processing time, IR can indirectly save energy in downstream cooling or in facility air conditioning (less waste heat). For decarbonisation, replacing or supplementing a gas oven with IR (especially electric IR) can cut natural gas usage. IR heating finds many uses:

- **Meat:** Infrared broilers are used to roast and brown meats. For example, precooked meats like grill-marked chicken breasts or steaks can be passed under IR panels to sear the surface, creating an appealing colour and flavour without overcooking internally. Bacon processing can use IR heat to crisp the strips quickly with less oil than pan frying.
- **Fish:** IR can be applied to fish fillets for broiling/glazing. In smoked fish production, after the smoking step, an IR grill might be used to firm or lightly char the surface. IR drying is also used for fish jerky or drying fish skin. Because IR doesn't heat the surrounding air much, it can dry the surface of fish rapidly and then a short air drying or cooling can remove remaining moisture.
- **Fruits/Nuts:** IR is employed in nuts roasting and drying of fruits/vegetables (like IR dry-blanching of potatoes before frying, or raisins drying) because it can be more energy-efficient and faster than hot air alone.
- **Secondary products:** IR is not commonly used to heat liquid dairy (not suitable for volumetric heating), but it appears in some niche areas like drying dairy-based foods or toasting/baking cheese toppings. For example, in pizza production lines, IR radiant burners melt and brown cheese on the pizza very quickly before the pizza is frozen.

3.4.19 Smoking

Smoking, one of the oldest techniques for preserving food, involves eliminating water from food to inhibit microbial growth as well as reducing oxidation, which could spoil stored foods (Plaza-Bolaños, et al, 2010¹⁰⁵). The applications of smoking technology span a wide range of food products, including meats, cheeses, fish, and even vegetables¹⁰⁶. Smoked products are highly sought after for their unique taste, making them popular choices in the culinary world. The exposure of the food product to smoke from sources such as wood chips, sawdust, or liquid smoke is controlled. The process imparts distinct flavours and aromas, enhancing the sensory profile of the final product.

Several types of smoking methods are available: cold temperature, hot temperature, partial roasting and chemical¹⁰⁶:

1. In the process of cold-smoking, foods undergo curing at an air temperature below 33°C for a duration ranging from 6 to 24 hours up to several weeks, resulting in the desired smoked flavour and colour. The texture of the products remains largely unchanged, and they exhibit a milder taste compared to hot-smoked foods. Cold smoking does not destroy microorganisms, so it is preceded by salt curing.

¹⁰⁵ Plaza-Bolaños, P., Frenich, A.G. and Vidal, J.L.M., 2010. Polycyclic aromatic hydrocarbons in food and beverages. Analytical methods and trends. *Journal of Chromatography A*, 1217(41), pp.6303-6326.

¹⁰⁶ Nizio, E., Czwartkowski, K. and Niedbała, G., 2023. Impact of Smoking Technology on the Quality of Food Products: Absorption of Polycyclic Aromatic Hydrocarbons (PAHs) by Food Products during Smoking. *Sustainability*, 15(24), p.16890.

2. Warm smoking, which shares similar effects, also involves curing foods. Hot-smoking, conducted at temperatures between 60–80°C, achieves preservation through various mechanisms and hurdle technology. These mechanisms include reducing moisture content to lower water activity, the antioxidant action of smoke chemicals, destruction of microorganisms and enzymes by heat, antimicrobial action of smoke constituents, and the antimicrobial effects of salt pretreatments when used¹⁰⁷.
3. Fish, especially, is commonly hot smoked. In hot-smoking, crucial factors for controlling bacteria include the number of contaminating bacteria, the D-values of the bacteria of interest, temperature variations in different parts of the kiln, core temperatures reached by the product during processing, and the duration of smoking. While smoke and salt possess antimicrobial effects, microbial destruction during hot smoking primarily relies on the heat treatment applied¹⁰⁷.
4. Partial roasting and smoking is a cooking technique where a product (usually meat) is partially cooked in the oven (roasting) before being transferred to a smoker to finish the cooking with smoke.
5. Chemical smoking is the process of using chemicals to add smoke flavour to food. This can be done through liquid smoke, smoke essences, or zeolite-filtered smoke.

3.4.20 Sterilisation

Steam cooking and retort sterilisation involve heating food (often in sealed containers) with steam or hot water under pressure. Retort processing is a classic method to achieve commercial sterility in canned or packaged foods, effectively destroying *Clostridium botulinum* spores and other pathogens. In retort sterilisation, products (e.g. canned meat or fish, dairy-based infant formula cans) are placed in a pressure vessel and heated, typically to ~121°C for low-acid foods, for a specified time. This ensures shelf-stability and safety for ambient storage. Steam cooking is also used for large-scale preparation of foods (e.g. cooking hams or sausages in steam cabinets) to a pasteurisation level, preserving quality while reducing microbial loads.

The dominant equipment for in-package sterilisation is the batch retort (autoclave). In a batch retort, baskets of cans or pouches are loaded into a robust vessel that is sealed and injected with steam (or a mix of steam and air or water spray) to raise the internal pressure and temperature. Modern batch retorts often recirculate water or use cascading sprays to improve heat distribution uniformity. Continuous retort systems also exist for high-throughput operations: hydrostatic retorts (tall towers where containers ride a conveyor through zones of hot water/steam) and rotary retorts (where containers rotate for faster heat penetration) are state-of-the-art for products like canned beverages or sauces. These continuous systems are designed to reuse heat and have steady-state operation, improving energy efficiency. In all cases, retort machines have precise controls to monitor temperature and pressure, ensuring each product batch gets the required thermal treatment. Auxiliary equipment includes steam boilers, and cooling systems to bring product temperature down after processing.

Examples in meat, fish, and dairy: Many shelf-stable meat and fish products rely on retort sterilisation. For example, canned tuna, salmon, or sardines are packed in brine/oil and retorted to achieve sterility. Meat stews, canned poultry, and pet foods (often meat-based) are processed similarly. In the dairy sector, canned evaporated milk and sweetened condensed milk are sterilised in retorts to extend shelf life. Dairy-based baby foods and clinical nutrition formulas in pouches or cartons also undergo retort processing. Additionally, steam cooking without full sterilisation is used for pasteurizing some prepared foods – e.g., vacuum-packed roast beef or ham can be steam-cooked to ~80 °C internal

¹⁰⁷ Fellows, P.J. 2017. Food Processing Technology, Principles and Practice, Fourth Edition. Online: Woodhead Publishing.

temperature for foodservice, killing *Listeria* and other pathogens. These processes illustrate the breadth of steam-based heating's role, from gentle cooking to full sterilisation.

Batch retort processes are energy intensive – each cycle involves heating a large vessel and product load, then cooling it, often wasting unused heat. Energy savings can be obtained through heat recovery, water recirculation, cycle design optimisation and electrification.

3.4.21 HTST and UHT

HTST pasteurisation and UHT processing are continuous flow heating methods critical in the dairy, beverage, and liquid food industries. In HTST pasteurisation, a liquid food (commonly raw milk) is quickly heated to about 72–75 °C for 15–30 seconds, then rapidly cooled. This thermal process kills pathogenic microbes and spoilers to make products safe (e.g. milk, juice) while causing minimal taste changes. UHT treatment is a food processing technique that involves heating liquids to temperatures of 135°C or higher for a short time (typically 3 to 10 seconds), achieving commercial sterility for aseptic packaging (as used for shelf-stable milk or cream).

The dominant machinery for HTST is the plate heat exchanger pasteuriser. This system consists of a series of thin stainless-steel plates clamped together, forming alternating channels for the product and heating/cooling fluids. The raw cold product is first pre-warmed by heat exchange with the hot pasteurised product leaving the system (regeneration section), then brought to pasteurisation temperature by a hot water or steam-heated section, held for the required time in a holding tube, and finally cooled (often by exchanging heat with incoming product, and then with chilled water). Efficient designs achieve regeneration efficiencies up to ~95%, meaning most of the heat energy is recovered internally. Tubular heat exchangers (pipes within pipes) are used for thicker liquids or those containing particles, as they can handle higher pressures and viscous flow. For UHT, two main systems are used: Indirect UHT (usually tubular or plate heat exchangers with multiple regeneration stages, plus a high-temp heating section) and Direct UHT systems, which either inject steam directly into the product or infuse the product into high-temperature steam. Indirect heating via tubular heat exchangers may utilise product-to-product and product to water heat recovery to save energy. In direct UHT, the product is heated almost instantaneously by steam and then a flash evaporation step removes the added moisture, rapidly cooling the product. Both systems include aseptic chambers and packaging machines downstream to fill the product into sterile containers. Continuous pasteurisation/UHT systems are generally more energy-efficient than batch heating processes because of regenerative heat exchange. Dominant technologies like plate and tubular exchangers are already optimised for efficiency; current state-of-the-art improvements include better plate designs for turbulent flow (improving heat transfer coefficients) and automation to maintain optimal flow rates and temperatures, preventing energy waste.

HTST and UHT are most crucial in dairy processing. Nearly all milk sold in cold chain is HTST pasteurised; a standard dairy HTST line pasteurises milk at 72°C for 15 s with about 90–94% heat regeneration. Similar systems pasteurise cream, ice cream mix, liquid egg (to ~65 °C), and beer (flash pasteurisation of beer or cider at ~72 °C for 30 s is done in-line before packaging). UHT is heavily used for shelf-stable dairy: e.g. boxed milk, single-serve creamers, and nutritionally fortified dairy drinks. It's also used in plant-based milk alternatives for shelf stability. In other sectors, HTST principles apply to fruit juices (though some juices use slightly lower temps to preserve vitamin C), and to liquid egg and broth products. Meat/fish applications of continuous pasteurisation are less common (since those foods aren't typically pumpable liquids), but there are cases like brine or liquid smoke pasteurisation, or gravy/sauce with meat pieces processed in continuous systems. Also, some processed egg products in meat processing (e.g. liquid whole egg for sausage mixes) are pasteurised by HTST to reduce contamination. Overall, HTST/UHT are cornerstone technologies in dairy and beverage, ensuring safety with high throughput.

Benefits of UHT treatment

- Extended shelf life: UHT treatment significantly extends the shelf life of foods by effectively destroying spoilage microorganisms. This allows for longer storage without refrigeration, making it ideal for distribution in various markets.
- Retention of flavours and nutrients: Unlike traditional pasteurisation methods, UHT processing minimises flavour changes.
- Convenience for consumers: UHT-treated products are often packaged in convenient, ready-to-use formats with long shelf life that can reduce food-waste and allows easy transport and storage at ambient conditions.
- Safety: the UHT process ensures that the product is free from pathogenic bacteria and spoilage organisms, providing a safe beverage option for consumers.
- Versatile flavouring options: manufacturers can incorporate various flavourings, sweeteners, and dairy alternatives without compromising safety or quality, catering to diverse consumer preferences.

3.5 Cleaning systems

Disinfection is the process of reducing the number of harmful microorganisms on food processing equipment. For disinfection to work well, the equipment must be thoroughly cleaned first. Disinfectants need to be applied correctly, following the instructions and using the right amount. There are oxidizing disinfectants, non-oxidizing disinfectants, buffering agents and non-ionic or anionic surfactants. Most cleaning systems incorporate water or steam (see section 3.4.10) to physically wash away dirt or debris in food processing plants.

Cleaning place systems may also be applied. These can clean without taking things apart. They are highly automated, reliable and consistent, where the whole process can be tracked. CIP systems use chemicals and water to clean all surfaces that touch food. The chemicals are circulated through the equipment, and jets or sprays help remove residue. This process is designed to be fast, efficient, and consistent. CIP has been used in food processing for over 50 years. Food companies have found that CIP is generally better than other cleaning methods.

CIP systems combine three types of energy to clean efficiently: chemical energy from the detergents, thermal energy from the hot water, and mechanical energy from the sprays and jets. Other important factors include water quality, complete coverage of all surfaces, the CIP program, equipment design, and the work of the cleaning staff.

There are four main types of CIP systems: fill-boil-and-dump, single-path, single-use, and reuse. The best type for a plant depends on cost, local water regulations, the size and number of things to clean, how often cleaning is needed, and the risk of contamination.

Reuse systems are more complicated than single-use systems, so they cost more to set up. However, they can save money on water, detergent chemicals, and energy, so they pay for themselves quickly.

Cleaning agent manufacturers are working to develop new cleaning formulas that can combine multiple steps of the cleaning process. They want to create products that can remove both organic and inorganic dirt in one step or that can clean and disinfect at the same time.

CIP cleaning involves three steps: (1) removing dirt using chemicals and physical forces, (2) mixing the dirt with the cleaning solution, and (3) preventing the dirt from sticking back to the equipment. The first step needs a cleaning agent that can penetrate into the dirt and surface pores. The second step needs a cleaning agent that can keep oils and fats mixed in the solution. The third step requires the cleaning agents to continue working to prevent the dirt from returning. There is no single perfect

cleaning agent, so there is a need to choose one that works best for the specific type of dirt. Selecting the right cleaning agent is important because it needs to meet several requirements:

- Be effective on many different types of dirt.
- Be able to penetrate into dirt and mix with oils and fats.
- Work well even when used in small amounts.
- Dissolve quickly in water.
- Work well in hard water.
- Produce minimal foam to make rinsing easy.
- Be safe for food and free of harmful substances.
- Be safe to use and approved by regulations.
- No damage the equipment.
- Be environmentally friendly.
- Be easy to measure electronically.
- Be affordable.

There are different types of cleaning agents available, depending on how clean the equipment needs to be. These agents can be alkaline, neutral, or acidic. Alkaline detergents are used to remove organic dirt (e.g. NaOH, KOH, EDTA etc.). Neutral detergents are used when alkaline detergents would damage certain metals. They have a neutral pH (e.g. phosphates, citrates etc.). Mineral deposits on equipment are challenging to remove with alkaline cleaners, and in some cases, alkaline cleaners can even exacerbate mineral deposit formation. Therefore, an acid cleaning cycle is essential for dissolving mineral salts or removing scale that forms after using alkaline cleaners. In the fermentation and brewery industries, acid cleaning is commonly employed during CIP (clean-in-place) processes. This is because CO₂ produced during fermentation can rapidly convert NaOH and KOH into Na₂CO₃ and K₂CO₃, which can then precipitate as scale. Acid detergents must achieve a pH of 2.5 or lower in the final solution, be effective in both hard and soft water, and minimise metal corrosion. Acid detergent formulations are usually blends of inorganic acids, organic acids, or acid salts, often combined with other ingredients.

New cleaning technologies are being explored, such as ultrasonic cleaning, to improve the cleaning process. To reduce water and wastewater costs, companies are trying to recover as much water and cleaning solution as possible. Membrane modules are being used in modern CIP systems, but more durable and heat-resistant membranes are needed. Improved sensors and instrumentation can help separate CIP solutions more efficiently, reducing water and chemical consumption and waste.

3.6 Tempering/thawing

Thawing is a crucial step for all frozen foods, and there are several methods to accomplish it. It affects emissions not only due to the energy required for the process (and applied method), but also because improper thawing can impact food quality, shelf life, and waste, all of which have environmental implications. Freezing food has been widely studied, while thawing has received far less attention in scientific research. Yet, it is often more difficult to control and predict. As thawing progresses, heat flow becomes less efficient, slowing the process, and if the temperature difference is too high there is

an increasing risk of quality deterioration or microbial growth (Haugland, 2002¹⁰⁸). A common way to thaw frozen products is to leave them in ambient or chilled environments (0-4°C), which doesn't directly add to energy costs. However, this method is slow, carries a high risk of dehydration, and is unsuitable for industrial use. In recent years, several reviews have examined industrial techniques for thawing (Backi, 2018¹⁰⁹; Cai et al., 2019¹¹⁰; Svendsen et al., 2022¹¹¹).

Industrial thawing methods include air thawing, which can be carried out either naturally or using forced convection. The energy required for this process largely depends on the use of fans. In systems with no fans, like still air rooms, energy use is minimal, while blast thawers rely on high-powered fans. It's crucial to optimise the thawing speed because the energy consumption of fans rises sharply with higher speeds, increasing in proportion to the cube of the fan's speed. Thawing fish blocks and seafood products is commonly done using water or seawater. The amount of energy required depends on the complexity of the thawing process, such as temperature regulation, filtration systems, water recirculation, and agitation methods. Dielectric thawing methods, such as microwaves (MW) and radiofrequency (RF), differs fundamentally from air and water by heating products from the inside, promoting uniform thawing. However, issues like overheating or hot spot development makes these methods better suited for tempering rather than complete thawing¹¹¹. In industrial settings, RF equipment can use 20-100 kWh/ton to thaw products from -20 to -6/0°C, depending on penetration depth (wavelength) and whether the product is lean or fatty. Additional thawing methods include plate thawing^{112,113} which can be energy efficient due to conduction heat transfer, ultrasound-assisted thawing which can reduce thawing times and high-pressure assisted thawing (see separate review).

When thawing fish, important quality considerations include drip loss, bacterial growth on the surface, protein denaturation, lipid oxidation, water-holding capacity, and dehydration. Moreover, changes in colour, texture and pH may occur during thawing. These lead to microstructural changes of the fillet, ultimately affecting the quality and consumer's acceptance¹¹⁴. These effects depend not only on the thawing method and procedure but also on the type of food being thawed, its thermophysical properties, and its packaging¹¹¹. Poor thawing practices can lead to product waste, reduced shelf life, and decreased weight, all of which indirectly contribute to emissions, though quantifying these effects is challenging. In their 2017 study, Ragnarsson and Viðarsson¹¹⁵ assessed various seafood thawing

¹⁰⁸ Haugland, A., 2002. Industrial Thawing of Fish - to improve quality, yield and capacity. PhD Thesis Nor. Univ. Sci. Technol.

¹⁰⁹ Backi, C.J., 2018. Methods for (industrial) thawing of fish blocks: A review. *J. Food Process Eng.* 41. <https://doi.org/10.1111/jfpe.12598>.

¹¹⁰ Cai, L., Cao, M., Regenstein, J., Cao, A., 2019. Recent Advances in Food Thawing Technologies. *Compr. Rev. Food Sci. Food Saf.* <https://doi.org/10.1111/1541-4337.12458>.

¹¹¹ Svendsen, E.S., Widell, K.N., Tveit, G.M., Nordtvedt, T.S., Uglem, S., Standal, I., Greiff, K., 2022. Industrial methods of freezing, thawing and subsequent chilled storage of whitefish. *J. Food Eng.* 315. <https://doi.org/10.1016/j.jfoodeng.2021.110803>.

¹¹² Backi, C.J., Leth, J., Gravdahl, J.T., 2016. Optimal boundary control of a contact thawing process for foodstuff. *IFAC-Pap.* 49, 183–188. <https://doi.org/10.1016/j.ifacol.2016.07.243>.

¹¹³ Roiha, I.S., Jónsson, Á., Backi, C.J., Lunestad, B.T., Karlsdóttir, M.G., 2017. A comparative study of quality and safety of Atlantic cod (*Gadus morhua*) fillets during cold storage, as affected by different thawing methods of pre-rigor frozen headed and gutted fish. *J. Sci. Food Agric.* 98, 400–409. <https://doi.org/10.1002/jsfa.8649>.

¹¹⁴ Cai, L., Wan, J., Li, X., Li, J., 2020. Effects of different thawing methods on physicochemical properties and structure of largemouth bass (*Micropterus salmoides*). *J. Food Sci.* 85, 582–591. <https://doi.org/10.1111/1750-3841.15029>.

¹¹⁵ Ragnarsson, S.Ö., Viðarsson, J.R., 2017. Overview of available methods for thawing seafood.

methods, comparing their impact on quality factors, cost efficiency, and the pros and cons of each approach. Table 6 is a tabular summary for some of the methods.

Table 6. Summary of industrial thawing methods.

Method	Drip loss	Cost	Pros	Cons
Still air thawing	High	Low	Low cost, easy to implement, no maintenance required	Slow process, high risk of bacterial growth, surface overheating, dehydration
Blast thawing	High	Mid-high	Faster than still air, better control over temperature, suitable for large batches	Risk of surface drying, requires maintenance and cleaning
Water immersion	Minimal	Low-high	Faster than air-based methods, reduced drip loss	Potential contamination, hygienic design necessary
Microwave (MW)	Low	Very high	Rapid thawing, low drip loss, hygienic	Uneven thawing, specialised maintenance, requires additional thawing step
RF	Low	Very high	Uniform thawing, low drip loss, hygienic	Requires specialised maintenance, risk of uneven thawing, requires additional thawing step

3.7 Packaging

3.7.1 Function of food packaging

The primary function of food packaging is to maintain the quality and safety of foods (Wani et al., 2014¹¹⁶). Packaging serves as a barrier against environmental factors and limit undesirable physical, chemical and biological changes during transport, distribution and storage. In doing so, packaging plays a critical role in extending the shelf life and significantly contributes to reducing food loss and waste along the value chain (Otto et al., 2021¹¹⁷).

Containment is another essential function, as packaging facilitates efficient transportation (Wani et al., 2014¹¹⁶), storage (Versino et al., 2023¹¹⁸) and distribution (Wani et al., 2014¹¹⁶). Moreover, the convenience offered by packaging provides consumers with practical solutions, such as boil-in-bags, which simplify food preparation and consumption (Versino et al., 2023¹¹⁸). Lastly, communication is another critical function of packaging, as it provides labels with information, such as nutritional content, shelf life and storage conditions (Gustavo et al., 2018¹¹⁹, Versino et al., 2023¹¹⁸).

¹¹⁶ Wani, A. A., Singh, P., and Langowski, H. C. (2014). Food technologies: packaging.

¹¹⁷ Otto, S., Strenger, M., Maier-Nöth, A., and Schmid, M. (2021). Food packaging and sustainability—Consumer perception vs. correlated scientific facts: A review. *Journal of Cleaner Production*, 298, 126733.

¹¹⁸ Versino, F., Ortega, F., Monroy, Y., Rivero, S., López, O. V., and García, M. A. (2023). Sustainable and bio-based food packaging: A review on past and current design innovations. *Foods*, 12(5), 1057.

¹¹⁹ Gustavo Jr, J. U., Pereira, G. M., Bond, A. J., Viegas, C. V., and Borchardt, M. (2018). Drivers, opportunities and barriers for a retailer in the pursuit of more sustainable packaging redesign. *Journal of Cleaner Production*, 187, 18-28.

Despite the critical role food packaging plays in preserving quality and reducing food waste, its production, use and disposal also have significant environmental impacts that must be considered (Lacourt et al., 2024¹²⁰). These impacts arise from various factors, including the resource-intensive production of certain materials, their short usage and the large volumes of waste generated. To mitigate these challenges, there has been a growing focus on developing sustainable alternatives, improving recycling systems (Versino et al., 2023¹¹⁸) and adopting circular economy principles (D’Almeida and Albuquerque 2024¹²¹).

3.7.2 Packaging materials

Due to the wide variations in the composition, structure and properties of different food and beverage products, the choice of packaging material varies greatly (Lacourt et al., 2024). Additionally, storage conditions, including duration and temperature, influence the suitability of specific materials and packaging methods.

The most widely used materials in food packaging include plastics, paper and cardboard, glass and metal (Marsh et al., 2007¹²², Petkoska et al., 2021¹²³, Otto et al., 2021¹¹⁷). Over recent decades, the use of plastic, paper/cardboard and other materials have increased, while the use of glass and metal has declined marginally (European Commission: Directorate-General for Environment, 2020¹²⁴). It is estimated the future will focus more on biodegradable materials, edible packaging and natural polymers (Verma et al., 2021¹²⁵), derived from plants, animals, and microbes, replacing fossil-based resources. Additionally, more emphasis will be given to developing smart packaging materials compatible with food products while also being ecofriendly (Wrona and Nerín, 2020¹²⁶).

3.7.3 Environmental aspect

The environmental impact of the packaging depends on several different aspects like the packed food product, distribution logistic and distances, clean energy resources, available waste management systems, re-use frequency, recyclability and/or biodegradability, end-of-life scenario selected for the

¹²⁰ Lacourt, C., Mukherjee, K., Garthoff, J., O’Sullivan, A., Meunier, L., and Fattori, V. (2024). Recent and emerging food packaging alternatives: Chemical safety risks, current regulations, and analytical challenges. *Comprehensive Reviews in Food Science and Food Safety*, 23(6), e70059.

¹²¹ D’Almeida, A. P., and de Albuquerque, T. L. (2024). Innovations in food packaging: from bio-based materials to smart packaging systems. *Processes*, 12(10), 2085. Dehghani, S., Hosseini, S. V., and Regenstein, J. M. (2018). Edible films and coatings in seafood preservation: A review. *Food chemistry*, 240, 505-513.

¹²² Marsh, K., and Bugusu, B. (2007). Food packaging—roles, materials, and environmental issues. *Journal of food science*, 72(3), R39-R55.

¹²³ Petkoska, A. T., Daniloski, D., D’Cunha, N. M., Naumovski, N., and Broach, A. T. (2021). Edible packaging: Sustainable solutions and novel trends in food packaging. *Food Research International*, 140, 109981.

¹²⁴ European Commission: Directorate-General for Environment. (2020). Effectiveness of the Essential Requirements for Packaging and Packaging Waste and Proposals for Reinforcement. European Commission. <https://data.europa.eu/doi/10.2779/228699>.

¹²⁵ Verma, M.K., Shakya, S., Kumar, P., Madhavi, J., Murugaiyan, J. and Rao, M.V.R., 2021. Trends in packaging material for food products: historical background, current scenario, and future prospects. *Journal of food science and technology*, 58(11), pp.4069-4082.

¹²⁶ Wrona, M., and Nerín, C. (2020). Analytical approaches for analysis of safety of modern food packaging: A review. *Molecules*, 25(3), 752.

packaging material, and overall cost of production, use, and disposal all affect the environmental impact (Gioia et al., 2021¹²⁷, Accorsi et al., 2022¹²⁸, Briassoulis et al., 2021¹²⁹, Briassoulis et al., 2019¹³⁰).

Plastics, which have the lowest recycling rates, are the most used material for food packaging (around 37%) (PlasticsEurope, 2024¹³¹). In Europe, while nine member states, plus Norway and Switzerland, landfill less than 10% of their plastics waste, eight other member states landfill more than 50% (PlasticsEurope, 2024¹³¹). This highlights the need for appropriate regulatory frameworks (e.g. landfill restrictions and collection systems), continued investment in innovation and required infrastructure for sorting and recycling. The most common materials in food packaging and their associated climate impacts, recycling rates, recycling impacts, and degradation times in accordance with European Commission, 2018¹³² is shown in Table 7.

Table 7: The most common material groups used in food packaging, their associated climate impacts, recycling rates within the EU, recycling impacts, and degradation times.

Material groups	Climate impact	Recycling rate in EU	Recycling, impact	Degradation time/composting
Plastics	Petroleum-based: high CO ₂ emissions, low recycling rate, slow rate of decomposition. Bio-based: poor recycling, lack of recycling systems (Otto et al., 2021 ¹¹⁷)	27% in EU in 2022 (Malta: 5%, Belgium: 39%). (PlasticsEurope, 2024 ¹³¹).	PET-bottles can be refilled up to 25 times (Otto et al, 2021 ¹¹⁷)	Petroleum-based: 450 years in soil (Orset et al, 2017 ¹³³ , Otto et al., 2021 ¹¹⁷). Bio-based: biodegradable with degradation times ranging from hours to days (Khalid and Arif 2022 ¹³⁴).

¹²⁷ Gioia, C.; Giacobazzi, G.; Vannini, M.; Totaro, G.; Sisti, L.; Colonna, M.; Marchese, P.; Celli, A. End of Life of Biodegradable Plastics: Composting versus Re/Upcycling. *ChemSusChem* 2021, 14, 4167–4175.

¹²⁸ Accorsi, R.; Battarra, I.; Guidani, B.; Manzini, R.; Ronzoni, M.; Volpe, L. Augmented Spatial LCA for Comparing Reusable and Recyclable Food Packaging Containers Networks. *J. Clean. Prod.* 2022, 375, 134027.

¹²⁹ Briassoulis, D.; Pikasi, A.; Hiskakis, M. Recirculation Potential of Post-Consumer /Industrial Bio-Based Plastics through Mechanical Recycling—Techno-Economic Sustainability Criteria and Indicators. *Polym. Degrad. Stab.* 2021, 183, 109217.

¹³⁰ Briassoulis, D.; Pikasi, A.; Hiskakis, M. End-of-Waste Life: Inventory of Alternative End-of-Use Recirculation Routes of Bio-Based Plastics in the European Union Context. *Crit. Rev. Environ. Sci. Technol.* 2019, 49, 1835–1892.

¹³¹ PlasticEurope (2024). The Circular Economy for Plastics. A European Analysis. <https://plasticseurope.org/knowledge-hub/the-circular-economy-for-plastics-a-european-analysis-2024/>.

¹³² European Commission, 2018. PEFCR Guidance Document: Guidance for the Development of Product Environmental Footprint Category Rules (PEFCRs).

¹³³ Orset, C., Barret, N., and Lemaire, A. (2017). How consumers of plastic water bottles are responding to environmental policies?. *Waste management*, 61, 13-27.

¹³⁴ Khalid, M. Y., and Arif, Z. U. (2022). Novel biopolymer-based sustainable composites for food packaging applications: A narrative review. *Food Packaging and Shelf Life*, 33, 100892.

Material groups	Climate impact	Recycling rate in EU	Recycling, impact	Degradation time/composting
Glass	High energy impact and CO ₂ release during heating, climate impact highly correlated to material weight (Otto et al., 2021).	76% in 2022 (Belgium: 98%, Hungary: 30%) (Eurostat, 2024 ¹³⁵).	Recycled glass bottles can be used up to 50 times (Otto et al., 2021 ¹¹⁷).	Not degradable, decomposes into sand in nature (Otto et al., 2021 ¹¹⁷).
Metal	Energy-intensive processing (canned products) (Otto et al., 2021 ¹¹⁷).	77% in 2022 (Belgium: 96%, Croatia: 19%) (Eurostat, 2024 ¹³⁵).	0.245 kg CO ₂ eq./0.093 kg (Navarro et al., 2018 ¹³⁶).	Biodegradation of one aluminium can take 200 years (Otto et al., 2021 ¹¹⁷).
Paper and cardboard	Land occupation, high energy demand (Dalla Riva et al., 2017 ¹³⁷). Dependent on energy source (Merrild et al., 2009 ¹³⁸). Addition of plastic/aluminium to keep functionality	83% in 2021 (same range for most EU countries) (Eurostat, 2024 ¹³⁵).	Highly dependent on energy source (Merrild et al., 2009 ¹³⁸).	2-3 months (Otto et al., 2021 ¹¹⁷).

3.8 Air compressors

Air compressors are used extensively throughout the food processing industry for a wide variety of applications, powering various equipment. The following are some examples of where air compressors are used in food and beverage processing:

- Conveying materials either by running conveyors or directly from the air stream.
- Cleaning containers before filling and to blow off particles while cleaning food and equipment.
- Packaging, to generate the vacuum used in the packaging process.
- Fermentation and aeration used in distilleries.
- Disinfecting by creating ozone gas for water sterilisation.
- Sorting, e.g. by blowing jets, at key times.
- Filling machines, e.g. for pies, cakes, cookies and other baked goods.
- Fluid pumps to move liquid products in the production and filling process.

¹³⁵ Eurostat (2024). Packaging waste by waste management operations. https://ec.europa.eu/eurostat/databrowser/view/env_waspac__custom_14339610/default/table?lang=en.

¹³⁶ Navarro, A., Puig, R., Martí, E., Bala, A., and Fullana-i-Palmer, P. (2018). Tackling the relevance of packaging in life cycle assessment of virgin olive oil and the environmental consequences of regulation. *Environmental management*, 62(2), 277-294.

¹³⁷ Dalla Riva, A., Burek, J., Kim, D., Thoma, G., Cassandro, M., and De Marchi, M. (2017). Environmental life cycle assessment of Italian mozzarella cheese: Hotspots and improvement opportunities. *Journal of dairy science*, 100(10), 7933-7952.

¹³⁸ Merrild, H., Damgaard, A., and Christensen, T. H. (2009). Recycling of paper: accounting of greenhouse gases and global warming contributions. *Waste Management and Research*, 27(8), 746-753.

- Nitrogen generation, where compressed air is filtered to produce nitrogen, used in the packaging process.
- Air knives for the cutting and peeling of products such as fruit and vegetables.

For some of these processes it is important that the air is pure to avoid contaminating the food or beverage. The International Standards Organisation (ISO) has defined purity standards for compressed air (ISO 8572-1:2010). This standard rates compressed air in three classes: dry particulates, water (both liquid and vapour), and oil concentration.

Moisture in the compressed air is a particular issue to the food industry as moisture can lead to microbial or fungal growth. For this reason, compressed air must be dried to a specified dew point is required, when purity of the air is important.

Oil is another issue. Air compressors, like most machinery, use oil for lubrication. It is important that that oil does not contaminate the food. Oil-free compressors are particularly important when used directly in the process, e.g. for fermentation.

There are generally two types of air compressor used. These are reciprocating (piston) and rotary screw compressors. Both of these are positive displacement compressors which squeeze air into a smaller volume. Screw compressors use rotating screws to compressor the air. Reciprocating compressors, compress air in cylinders using pistons.

Rotary screw compressors are the most common type and provide consistently clean air and are easy to use. However, they are more complex and thus have a higher initial cost. They are more reliable, running continuously, but due to their complexity may be more expensive to repair. Single-stage lubricated rotary-screw compressors produce between 35 psig and 210 psig (Ambrosino, 2008¹³⁹). Typical 100-psig specific power at full load is approximately 18 kW/100 cfm to 19 kW/100 cfm (Ambrosino, 2008¹³⁹).

Reciprocating compressors are common in large settings and for heavier duty applications. Large scale canning or packing operations may benefit significantly from these compressors. They are more simple and thus easier to maintain. They may need to be shut down periodically to prevent overheating and thus are well-suited for applications requiring short, intense bursts of air. Most single-stage compressors are designed for a maximum discharge pressure of 100 psig (Ambrosino, 2008¹³⁹). For a single-stage, single-acting compressor, the specific power is approximately 24 kW/100 cfm at 100 psig (Ambrosino, 2008¹³⁹).

Compressed air is provided at a variety of pressure depending on use. From as high as 750 psi for shaping plastic containers (blow moulding) (this would require multi-stage compression) to as low as 15 psi for removing excess material or debris from food products or machinery (blow off).

¹³⁹ Ambrosino, N. 2008. Comparing air compressors: Which one is best for your plant? <https://www.plantservices.com/equipment/compressed-air-systems/article/11339806/compressed-air-systems-comparing-air-compressors-which-one-is-best-for-your-plant>.

4 CURRENT TRENDS

4.1 Energy costs

Food processing facilities consume considerable amounts of energy. Figure 20 presents the final energy consumption in 2022 per industrial sector at EU level¹⁴⁰. The sectors with the highest final energy consumption were the petrochemical industry (1 892 PJ, 20.0% of the total final energy consumption), the non-metallic minerals industry (1 367 PJ, 14.5 %) and the paper, pulp and printing industry (1 279 PJ, 13.5 %). The food beverages and tobacco industry was the fourth most energy consuming industry (1 156 PJ, 12.2 %). This means that there are incentives for operators to reduce energy usage.

Total final energy consumption by industrial sector, EU, 2022 (PJ)

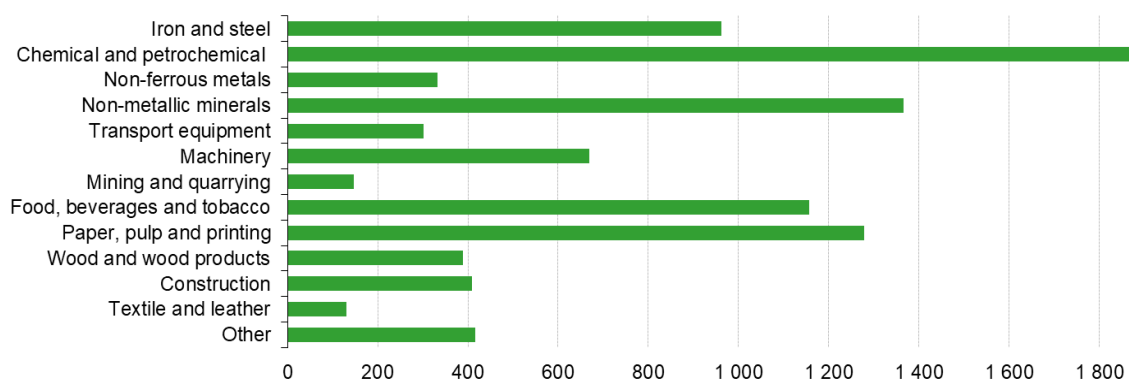


Figure 20. Total final energy consumption by industrial sector, EU, 2022.

Since 2021, energy prices have been rising steadily due to the rapid economic recovery, pandemic-related postponed maintenance, and earlier decisions by oil and gas companies and exporting countries to scale back investments. Russia began withholding gas supplies to Europe as early as 2021, months before the invasion of Ukraine. All this led to an already tense supply scenario.¹⁴¹

In the light of these developments, measures to decrease energy demand are gaining importance. The drastically increased prices potentially decrease the payback time of investments related to energy savings, however the future development of energy prices on the long term are questionable.

4.1.1 Electricity

The development of the electricity prices for non-household consumers within the European Union is shown in Figure 21 on a half-yearly basis. From 2008 until 2012, the price excluding all taxes increased slightly, followed by a slight decrease until 2020. Afterwards a steep increase leading to the highest ever recorded prices followed at the end of 2022. Since then, prices have dropped, but only to the level they were at the beginning of 2022. Governmental measures were introduced to reduce prices, which is reflected in the reduced difference between prices excluding recoverable taxes and levies and

¹⁴⁰ EUROSTAT. 2022. Final energy consumption in industry - detailed statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics.

¹⁴¹ <https://www.iea.org/topics/global-energy-crisis?language=en>.

prices excluding all taxes. In 2022, the share of taxes had reached a minimum since the data collection started, however, the share of taxes has recovered since then.¹⁴²

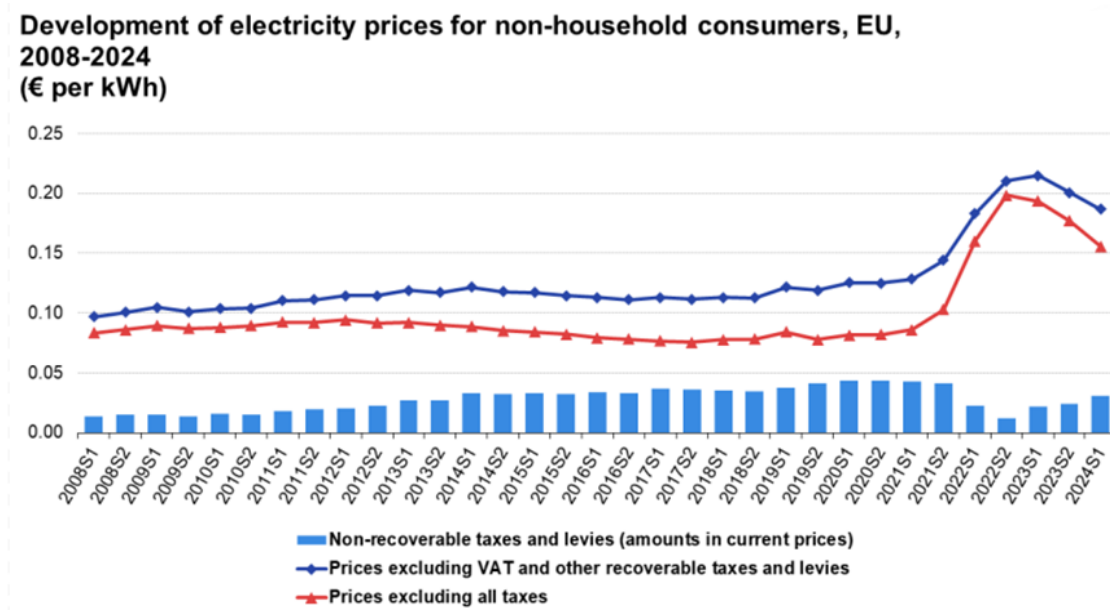


Figure 21. Development of electricity prices for non-household consumers, EU, 2008-2022¹⁴².

4.1.2 Natural gas

Natural gas is an important fuel in the food industry. Its combustion is used to create heat in many food processors, e.g. heating water, raising steam, cooking and burning.

According to EC (2018¹⁴³) decarbonisation analyses show a large uncertainty on the role of gas in the long term with unabated emissions from natural gas become increasingly incompatible with climate targets. The consumption of natural gas (excluding non-energy use) is expected to be severely reduced by 2050 in all prediction scenarios, from 345 Mtoe in 2015 to 273 Mtoe in 2030 and then in 2050, in scenarios achieving 80% GHG reductions, to between 87 Mtoe and 109 Mtoe and to less than 54 Mtoe in the scenarios achieving higher GHG reductions. Regardless of the overall gas demand evolution, the role of renewable and low-carbon gases is expected to increase in the coming decades.

In this context, a number of studies have been conducted on the potential development of low-carbon and carbon-neutral gases in Europe and its impact on the energy infrastructure (Trinomics, et al., 2018¹⁴⁴; Frontier Economics 2019¹⁴⁵; Navigant 2019¹⁴⁶; European Climate Foundation 2019¹⁴⁷; ICCT

¹⁴²https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_non-household_consumers.

¹⁴³ EC, 2018. IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM (2018) 773. A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. European Commission, Brussels.

¹⁴⁴ Trinomics, LBST and E3M, 2018. The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets.

¹⁴⁵ Frontier Economics, 2019. The Value of Gas Infrastructure in a climate-neutral Europe.

¹⁴⁶ Navigant, 2019. Gas for Climate - The optimal role gas in a net-zero emissions energy system.

¹⁴⁷ European Climate Foundation, 2019. Towards fossil-free energy in 2050.

2018¹⁴⁸). Despite methodological differences and diverging study outcomes, a consensus is emerging that low-carbon gases will play a major role in decarbonising the EU economy, with the support of the European gas infrastructure. Potential natural gas replacements, such as bio and synthetic methane and green hydrogen are discussed further in Section 5.2.

4.2 Economic pressures

The financial crisis has impacted both operators and customers. The Coronavirus Disease (COVID)-19 pandemic had a huge impact with food processors being a vital part of the COVID-19 response. Inflation and the economic crisis have had impacts on maintenance and equipment costs as well as restricting investment due to higher interest rates. At the same time labour costs have increased and the costs for transportation have increased due to increased fuel prices, changes in transportation regulations, and disruptions in supply chains.

4.3 Energy management

Energy management systems can aid reduction in energy. Increasingly there is a drive for certified energy management systems, often from regulatory bodies. A number of systems are available and include:

- Environmental performance such as resource use, waste management and pollution are covered in ISO 14001 which is an internationally agreed standard that sets out the requirements for an environmental management system. It has become the international standard for designing and implementing an environmental management system.
- Energy performance indicators and an energy baseline for a business is covered by ISO 50001 which is an energy management system standard that is used by large and small organisations to manage and reduce energy use. ISO 50001 provides a framework to help implement an energy management system.
 - *Potentially there is overlap between these 2 standards. Both provide ways to protect the environment through policies, objectives and processes. However, ISO 50001 focuses on energy usage whereas ISO 14001 concentrates on environmental protection in general.*
- The EU, Energy Savings Opportunity Scheme (ESOS) – certification to ISO 50001:2018 is a route to compliance. This is a mandatory (for organisations that meet the qualification criteria) energy assessment scheme to ensure that enterprises are energy efficient. An assessment every 4 years is required and applied to organisations that have over 250 members of staff or have a turnover of more than £44m and an annual balance sheet of over £38m (or the company is part of a larger organisation, which falls within the above clauses).
- The UK Streamlined Energy Carbon Reporting (SECR) – larger organisations must report annually on energy use, energy efficiency actions taken, and energy efficiency opportunities. The reporting methodology used must be stated and must be robust, transparent and widely accepted. Companies are encouraged to provide information on scope 3 emissions.
- The climate change agreement is a voluntary scheme applied in the UK since the early 2000s. It provides a discount on the climate change levy (a tax on energy bills) in return for meeting energy efficiency targets. It is claimed that a 19.3% improvement against a 11.7% target has been achieved (using a 2008 baseline).

¹⁴⁸ ICCT, 2018. The potential for low-carbon renewable methane in heating, power, and transport in the European Union.

4.4 The labour market

The food industry is reported to have significant challenges in recruitment, retention and upskilling of employees. Part of this is an image issue where there has been a lack of information on the range of jobs that are available within the industry. Improved pay and conditions as well as career and development opportunities are being used to encourage new entrants into the labour market.

The UK food manufacturing industry has been impacted by Brexit, which has led to labour shortages and made it harder to hire and retain EU workers. There is also an imbalance in the ratio of men to women in the industry, particularly in meat manufacturing.

4.5 The environment

The rise in global temperature is an important indicator of climate change which is largely caused by anthropogenic activities emitting greenhouse gases. Between 2013 and 2022, the global mean near-surface temperature was 1.13 to 1.17°C warmer than in the pre-industrial era. Europe heats up even faster with increases of the land temperature between 2.04 to 2.10°C. 2020 was the warmest year in Europe since instrumental records began.¹⁴⁹

Due to higher temperatures, the number and intensity of heat waves is also increasing. Compared to the 1960s, they occur three times more often and the average heat wave season is 49 days longer.¹⁵⁰

Increasing temperatures also bear a challenge to food processors. As a general rule large plants are built to cope better in warmer conditions as they are designed to a higher specification than smaller systems. Smaller stores are often designed to a less rigorous specification and so are more likely to be affected by warmer ambient. It is clear that extreme temperature events are becoming more common, and this is having an impact on refrigeration systems. A recent report from Imperial College has indicated that a 2°C increase in average UK summer temperature increased refrigeration energy demand by 6%¹⁵¹. The same report also found greater levels of break down in hotter weather increasing maintenance bills. All of this is bad news for food cold stores when food may be wasted if refrigeration systems can no longer cope with the warmer conditions.

In order to tackle climate change, member countries of the United Nations Framework Convention on Climate Change (UNFCCC) have committed to the Paris Agreement which aims to limit the global temperature increase to below 2°C (above pre-industrial levels) and ideally to less than 1.5°C by 2050⁵. In December 2020, the EU updated its NDC (nationally determined contribution) to the Paris Agreement to a reduction in greenhouse emissions of at least 55% by 2030 compared to 1990 emissions levels¹⁵². Transitioning to renewable energy and implementing energy efficiency measures are important contributions to the reduction of GHG emissions.

In order to protect the environment in the event of refrigerant leakage, the trend is increasingly towards natural refrigerants. These substances are known for their low global warming potential (GWP) and ozone depletion potential (ODP) and offer a more sustainable and environmentally friendly alternative. The motivation for this can be found in their sustainability and through legislative pressure from the European Union. Hydrofluoroolefins (HFOs) also offer zero ODP and low GWP, however, have

¹⁴⁹ <https://www.eea.europa.eu/ims/global-and-european-temperatures>.

¹⁵⁰ <https://www.epa.gov/climate-indicators/weather-climate>.

¹⁵¹ <https://www.imperial.ac.uk/news/198934/warmer-summer-risk-chilling-energy-bill/>.

¹⁵² https://climate.ec.europa.eu/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en.

other environmental impacts. The topic of natural and HFO refrigerants will be discussed in detail in the following section.

4.6 The move to low GWP refrigerants

The move to low GWP refrigerants has been driven primarily by legislative pressures from the European F-gas regulations (Regulation on the Use of F-Gases (EU 517/2014, 2014))¹⁵³ to reduce the GWP of refrigerants. The F-gas Regulation has a step-by-step reduction plan that calls for a 79% reduction in GWP-related emissions from the use of hydro fluorocarbons (HFCs) by 2030, using 2010 as the reference year.

This legislation was updated (EU F-Gas regulation 573/2024) in February 2024 and introduced stricter requirements on F-gases, their use and phase out dates. This updated legislation:

- Completely eliminates (100% reduction) f-gases by 2050.
- References per- and polyfluorinated substances (pfas). It states that 'pfas are chemicals which resist degradation and potentially have negative effects on health and the environment'. It states that 'undertakings should consider using alternatives, where available, which are less harmful for health, the environment and the climate'. HFOs are pfas substances and pfas regulation is currently being considered by the European chemicals agency (eca).
- Lists certification and training requirements. To be able to carry out maintenance, servicing, recovery or repair of equipment, personnel shall be trained. This covers fluorinated greenhouse gases, relevant alternatives to fluorinated GHGs and natural refrigerants. Member countries shall establish or adapt certification programmes within 1 year of the regulation entering into force. Therefore, there is now a requirement for all service engineers to be trained regardless of the refrigerant being used.

The most significant prohibited product and equipment in the legislation to effect food processors will be a prohibition on 1st January 2030 on refrigeration equipment, except chillers, that contains, or whose functioning relies upon using fluorinated greenhouse gases with a GWP of 150 or more, except if required to meet safety requirements at the site of operation. This will prohibit also all non-flammable HFC refrigerants.

For chillers, the prohibitions occur:

- 1st January 2027 for f-gases with a GWP of 150 or more up to a rated capacity of 12 kW.
- 1st January 2032 for f-gases up to a rated capacity of 12 kW.

1st January 2027 for f-gases with a GWP of 750 or more above a rated capacity of 12 kW. Split air-conditioning equipment and heat pumps also have prohibitions, with the first in 2025 for single systems, containing less than 3 kg of fluorinated greenhouse gases with GWP of 750 or more, and the last in 2033 for systems with rated capacity of more than 12 kW containing with GWP of 150.

Many of the above prohibitions are except if required to meet safety requirements at the site of operation.

¹⁵³ https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/eu-legislation-control-f-gases_en.

5 FUTURE ISSUES AND TRENDS

5.1 Increased use of renewables

Using renewable energy in food processing facilities is feasible if sufficient roof area or land adjacent to the facility are available. Recent increases in energy costs have made the benefits of solar panels greater. If the energy generated from renewables can also be stored (electrically or thermally) there is the potential to benefit from demand side response (DSR) and use the stored energy at periods when energy costs are higher. The proportion of the energy produced by the PV plant that can be used by two different size food retail stores can be increased dramatically (20 to 70%) by applying some form of energy storage¹⁵⁴.

Cost of energy

Energy costs are a significant driver in decarbonisation decisions. The electricity grid is decarbonising rapidly as more renewable energy is used for generation. However, a large proportion of cooking and heating in the food processing industry is still provided from fossil fuels (primarily gas). The cost of gas is substantially less than electricity in most European countries. The ratio of cost (in kWh) varies from almost parity in Sweden and Finland to above 4.5 in the UK. This means that to have parity in operational costs electrical systems have to be very efficient. For example, in the UK in 2023 an electrically driven heat pump would have to have a Coefficient of Potential (COP) of greater than 4.6 to even begin to compete with a gas system (Figure 22). Part of the reason for high electricity costs is that decarbonisation taxes are often added to the cost charged. For example, in the UK environmental and social obligation costs are 23% higher for electricity than gas (Figure 23).

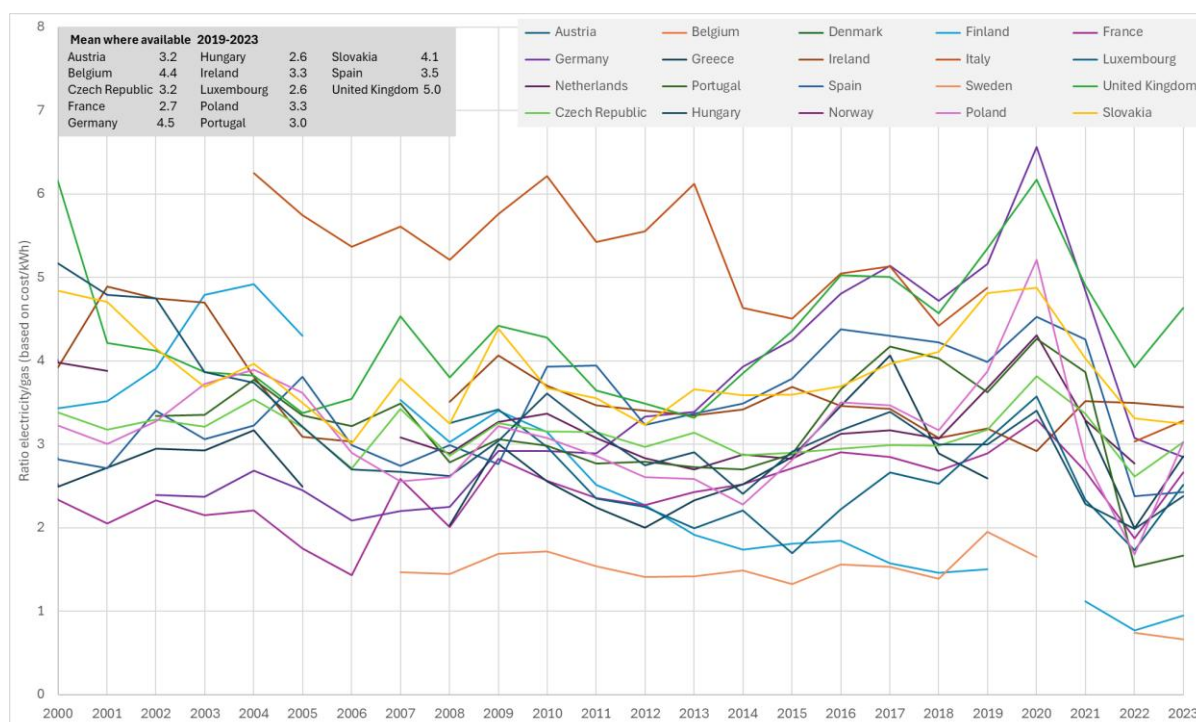


Figure 22. Ratio of electricity to gas costs across Europe.

¹⁵⁴ Franco, A.; Cillari, G. Energy Sustainability of Food Stores and Supermarkets through the Installation of PV Integrated Plants. *Energies* 2021, 14, 5678. <https://doi.org/10.3390/en14185678>.

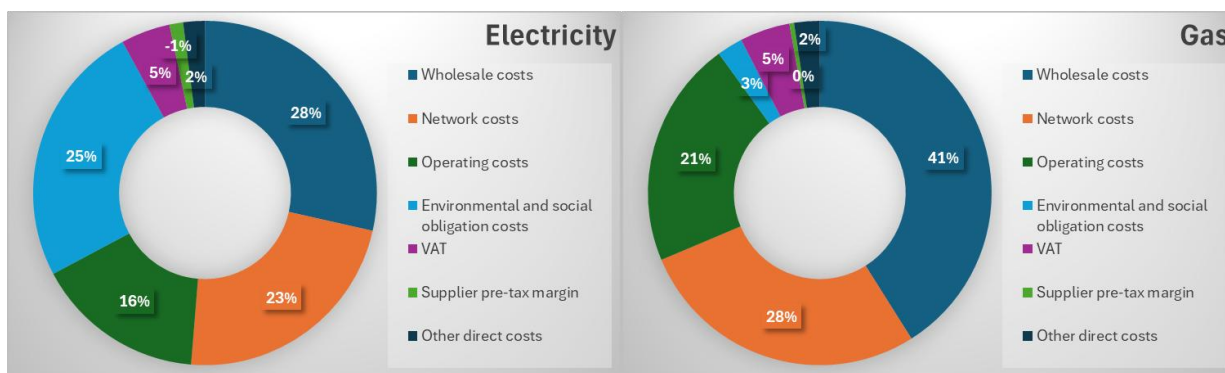


Figure 23. Breakdown of electricity and gas bills in the UK¹⁵⁵.

5.2 Availability of new technologies to replace fossil fuels

To decarbonise the food industry needs to move away from fossil fuels. Most fossil fuels in the food industry are used for heating and electrically driven heat pumps are a promising technology for increasing system efficiencies and decreasing GHG emissions¹⁵⁶. Currently commercial heat pumps are limited to supply temperatures below 100°C. However, there is a need for systems to provide heat at higher temperatures (Annex 58 states that 67 % of the overall EU heat demand currently provided by fossil fuels is between 100°C and 200°C). There is therefore considerable potential for the development of high temperature heat pumps (HTHPs). Annex 58 predicts that high-temperature heat pumps could cover 37% of the EU industrial process heat demand if they could extend the application supply temperature up to 200°C. Annex 58 have assessed timescales for availability of HTHPs and their capacity (Figure 24). This predicts that heat pumps of up to 10 MW will be available that can provide temperatures of >160°C by 2027/2028 and that these will be established technology by 2029.

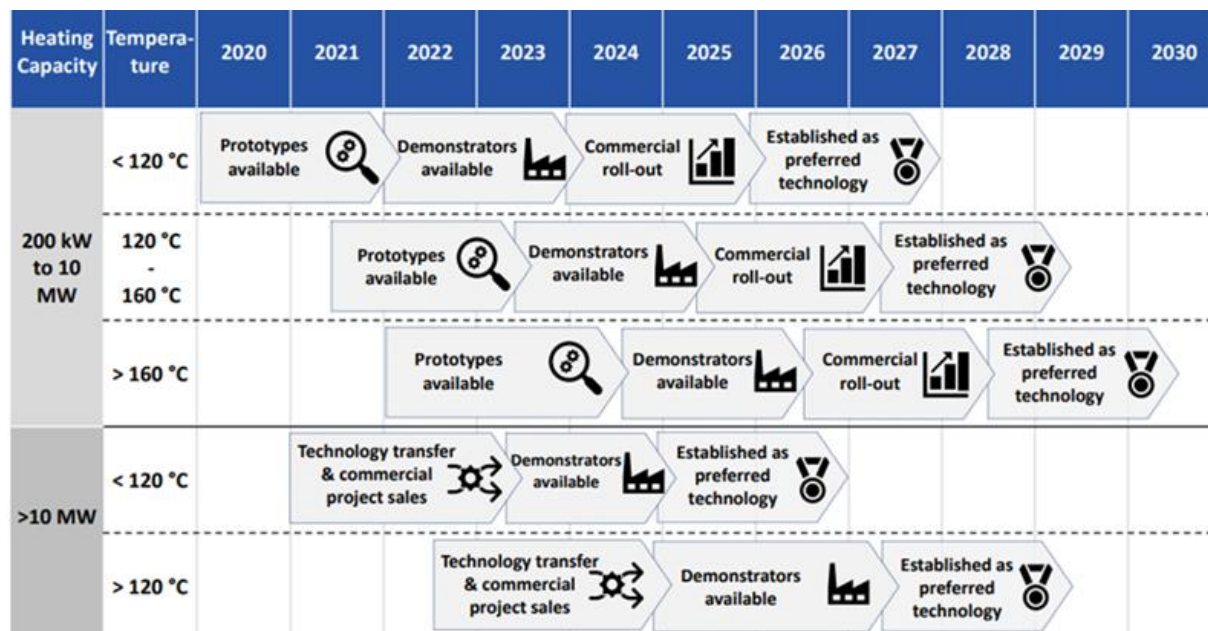


Figure 24. Timescale for development of HTHPs¹⁵⁶.

¹⁵⁵ <https://www.ofgem.gov.uk/all-available-charts>.

¹⁵⁶ Annex 58. High-Temperature Heat Pumps <https://heatpumpingtechnologies.org/annex58/>.

For certain processes where HTHPs are not applicable, sustainable combustible fuels could be used. Bio and synthetic methane and hydrogen are expected to play an important role in the transition to a decarbonised energy system.

Biogas is produced through anaerobic digestion of organic waste. Biogas is a mixture of CH₄ (45-75% by volume) and CO₂ and can be used for heating and cooking. This gas can be further refined into biomethane (CH₄ >96%) which can then be stored and/or injected into the gas grid or used as a transportation fuel. Using biomethane/biogas in the food industry is a good example of a circular economy as the feedstock required is a waste source from the food industry. A constraint to the expanded use of biomethane/biogas are the relatively limited quantities of waste feedstocks, especially if transport fuels compete for this limited resource.

Synthetic methane, also known as e-methane is created by reacting carbon dioxide with hydrogen, often using renewable electricity to produce the hydrogen. Grey and hybrid blue hydrogen can also be used, but without eliminating fossil fuel use. Blue hydrogen, while cleaner than grey, still relies on carbon capture and storage (CCS).

Rivera, et al. (2018¹⁵⁷) studied the environmental sustainability of renewable hydrogen in comparison with conventional cooking fuels. They found that renewable hydrogen produced in a proton-exchange membrane electrolyser using solar energy would reduce climate change up to 14 times compared to conventional fuels, e.g. liquified petroleum gas (LPG) and reduce summer smog and health effects from emissions of particulates. However, there would be negative impacts due to depletion of metals and freshwater and marine ecotoxicity due to the solar photovoltaic panels used to generate power for the electrolyser.

These non-fossil fuel gases can potentially be injected into existing natural gas infrastructure. According to Zhao et al. (2019¹⁵⁸) up to 15% hydrogen added to natural gas has little impact on cooking performance and operability and flashback during ignition is the limiting factor for the amount of hydrogen added. ACER (2020¹⁵⁹) carried out a survey on the European gas network. The readiness of the gas transmission networks to accept hydrogen or biomethane, as well as the foreseen developments to enable such acceptance, are quite diverse across the EU. 65% of member states do not allow hydrogen into their networks. Even the most hydrogen friendly (Germany) only allowed a maximum concentration of 10% in some sections of its transmission network and under certain conditions. The UK government sees potential strategic and economic value in supporting the blending of up to 20% hydrogen (by volume) into the Great Britain (GB) gas distribution networks in certain scenarios and circumstances (DESNZ, 2023¹⁶⁰). There is no consistent policy nor regulatory framework in place in Europe to allow small or large-scale injection of hydrogen to the gas network and this will

¹⁵⁷ Rivera, X.C.S., Topriska, E., Kolokotroni, M. and Azapagic, A., 2018. Environmental sustainability of renewable hydrogen in comparison with conventional cooking fuels. *Journal of cleaner production*, 196, pp.863-879.

¹⁵⁸ Zhao, Y., McDonell, V. and Samuelsen, S., 2019. Influence of hydrogen addition to pipeline natural gas on the combustion performance of a cooktop burner. *International Journal of Hydrogen Energy*, 44(23), pp.12239-12253.

¹⁵⁹ ACER, 2020. ACER Report on NRAs Survey - Hydrogen, Biomethane, and Related Network Adaptations. European Union Agency for the Cooperation of Energy Regulators, Slovenia.

¹⁶⁰ DESNZ, 2023. Hydrogen Blending into GB Gas Distribution Networks - A Strategic Policy Decision. Department for Energy Security and Net Zero, UK. <https://assets.publishing.service.gov.uk/media/657a0a82254aaa0010050cde/hydrogen-blending-strategic-policy-decision.pdf>.

need to be addressed if hydrogen is to replace natural gas. Currently there are many pilot scale facilities, which may drive this forward.

It is possible that blending/mixing hydrogen into the current network is only a temporary solution as it does not eliminate natural gas. Marconi, and Rosa, (2023¹⁶¹) investigated the biomethane potential to replace fossil natural gas use in countries throughout the world. They found In Europe, Czechia, the Netherlands, Belgium, and the United Kingdom can offset at least 8%–11% of their natural gas use. Germany, Italy, Ireland, and Slovakia can offset 14%–17%. Croatia, Lithuania, Hungary, Latvia, Portugal, Spain, and Austria can offset at least 19%–28%. Poland, Romania, Finland, and Estonia can offset from 30% to 38%, while Greece, Bulgaria, and Slovenia can offset nearly 47%. Sweden can completely offset its natural gas use. Lastly, Norway, can offset 8%. The authors then calculated the GWP reduction from biomethane. They found that In Europe, Italy, the United Kingdom, Belgium, the Netherlands, Germany, Portugal, Czechia, Austria, Slovenia, Hungary, Croatia, Slovakia, Belarus, and Norway can reduce their emissions by 4%–12%. Additionally, Spain, France, Poland, Greece, Bulgaria, Romania, Ukraine, Finland, Moldova, Lithuania, Latvia, Estonia, and Switzerland can reduce their emissions by 13%–20%, while Bosnia and Herzegovina and Denmark by nearly 60%.

The other solution is to develop a new pure hydrogen infrastructure. According to International Renewable Energy Agency (IRENA) (2021¹⁶²), thanks to the decline in renewable power costs, hydrogen could become a cost-competitive clean energy carrier worldwide by 2030. The cost of green hydrogen is driven by the cost of the renewable energy to produce it, which is dropping. In 2021 the cost was US\$4-6/kg, which is 2-3 times more than grey hydrogen (IRENA, 2021¹⁶²). The cost will also depend on the electrolyzers which split water into hydrogen and oxygen. These must also be scaled up and improved to make green hydrogen cost competitive. According to IRENA (2021¹⁶²), this could bring green hydrogen costs below the US\$2/kg mark – a crucial milestone for cost competitiveness – before 2030.

5.3 Integration (of heating and cooling)

Currently there is limited consideration of thermal integration within food processing facilities. However, this is an area that installers and operators are beginning to investigate (e.g., within the ENOUGH demonstration activities). It is feasible to reclaim heat and use this heat for generating hot water, cooking or to heat office areas within an establishment. Similar systems have been applied in other sectors of the food chain and generally have reclaimed heat from CO₂ refrigeration systems where the opportunities for heat reclaim are greater. Integration is not simple in existing outlets as they have not been designed for thermal integration. However, thermal integration could be designed into new facilities.

Some companies are beginning to consider the benefits of thermal storage. An example recently publicised is Dearnside Fruit in the UK¹⁶³. They installed a heat recovery system 2 years ago that is saving the business £20k (€24k) per year. Waste heat is recovered from the cold store refrigeration system which is used for heating water. The system is capable of generating up to 1,800 litres of hot water per hour which is mainly used in the pack house and for staff showers.

¹⁶¹ Marconi, P. and Rosa, L., 2023. Role of biomethane to offset natural gas. *Renewable and Sustainable Energy Reviews*, 187, p.113697.

¹⁶² IRENA (2021), *Making the breakthrough: Green hydrogen policies and technology costs*, International Renewable Energy Agency, Abu Dhabi.

¹⁶³ <https://www.coldchainnews.com/heat-recovery-system-saves-fruit-business-20000/>.

5.4 Automation and robotics

Automation works best when there are repetitive tasks and where products are consistent. Automation and robotics technologies offer several advantages in terms of efficiency, accuracy, and safety in food processing operations. Automated systems can efficiently move product, pack it and track and manage inventories. This reduces manual errors and ensures accurate stock control and streamlined supply chain management. Automation can significantly contribute to the reduction of GHG emissions in the food industry. This includes:

1. Increased efficiency and reduced waste:

Optimised processes: automation technologies, such as sensors, data analytics, and process control systems, can optimise production processes, leading to more efficient use of resources like energy, water, and raw materials. This reduces waste and minimises the environmental footprint.

Waste reduction: automated sorting and packaging systems can minimise food waste during processing and packaging. Additionally, automation can help in better inventory management, reducing the amount of food that spoils before reaching consumers.

2. Energy efficiency:

Optimised energy use: automated systems can monitor and control energy consumption in food processing facilities, optimising energy use and reducing waste. For example, automated lighting and temperature control systems can ensure that energy is used only when and where needed.

Renewable energy integration: automation can facilitate the integration of renewable energy sources, such as solar or wind power, into food production processes. Automated systems can manage energy storage and distribution to maximise the use of renewables and reduce reliance on fossil fuels.

3. Reduced labour and associated emissions:

Reduced labour needs: automation can reduce the need for manual labour in some food industry operations. This can lead to lower emissions associated with transportation of workers, heating and lighting of workspaces, and other labour-related activities.

4. Life cycle assessment (LCA) perspective:

Comprehensive impact assessment: LCA studies can assess the environmental impacts of food products and processes, including the role of automation. By considering the entire life cycle of a product, from raw material extraction to consumption and disposal, LCA can identify areas where automation can have the most significant impact on GHG emissions reduction.

Although there are many positives related to automation there are also issues that should be considered:

- The manufacturing and operation of automated systems themselves require energy, which can contribute to GHG emissions. It is therefore crucial to ensure that the energy used for automation is from renewable sources and that the systems are designed for energy efficiency.
- Implementing automation technologies can involve significant upfront investment costs, which may be a barrier for some food businesses. However, the long-term benefits of reduced emissions and increased efficiency can outweigh these costs.
- Automation can lead to job displacement in some sectors of the food industry. It is important to consider the social and economic impacts of automation and implement strategies to mitigate any negative effects.

5.5 Advanced controls

An increasing focus has been on measurement and analysis to assess efficiency and identify where maintenance issue may be beginning to develop. This requires energy sub metering and often creating 'digital twins' of the food processing facility to identify when performance moves away from the optimum. The benefits are claimed to be significant, as even small adjustments can have impact on energy bills. In addition, such systems can identify where maintenance problems are beginning to occur, and this means that service engineers are able to spot faults early and to be able to carry out remedial actions quickly and in a planned manner.

5.6 Training and skills

Businesses are placing a greater emphasis on sustainable operational practices. This is an area where workers will need new and enhanced skills to adopt eco-friendly practices. As part of sustainability and also due to the impact of energy price increases there is likely to be greater emphasis on energy management. Better training on design, operation of equipment and operational practices which minimise energy use are likely to be valued more in the future.

5.7 Integration into electricity grid

As the electrical grid decarbonises it will rely on more renewable energy. Much renewable energy is intermittent (e.g. wind and solar) and therefore, the need to flexible demand to match the more flexible supply is required. Demand side response (DSR) is when electricity users switch off appliances to help balance the grid. Most DSR periods are requested by grid operations at peak energy usage times (typically early evening). Although DSR does not save energy, it enables the more carbon intensive power generation facilities to be turned off/down during DSR periods and so carbon is saved. Operators are paid to remove load from the grid, or penalised for not removing it, making DSR an economic proposition. This has been common in large food cold stores (mainly frozen stores) for many years. DSR periods are generally made up of 30-minute durations. Other sectors of the food chain have recently embraced how they can benefit from integrating into national electrical grids. Retailers as whole estates of hundreds of supermarkets can provide significant aggregation and reductions to grid demand if switched off.

5.8 Waste processing

5.8.1 The issues

Food waste presents significant societal, economic, nutritional, and environmental challenges. The food processing industry generates substantial waste continuously, leading to serious problems that require urgent solutions. To address these issues, it is essential to convert food waste into value-added products or use it as a source for extracting bioactive compounds (Saini et al, 2019¹⁶⁴).

Poorly managed food waste poses health risks, contributes to greenhouse gas emissions, and contaminates water bodies through mineral and leachate runoff, creating vectors for diseases. Beyond environmental damage, food waste exacerbates nutritional, social, and economic challenges.

Food waste affects the environment negatively through its contributions to greenhouse gas emissions, exhaustion of natural resources, use of energy to produce food, and interruption of natural biological

¹⁶⁴ Saini, A., Panesar, P.S., Bera, M.B., 2019. Valorization of fruits and vegetables waste through green extraction of bioactive compounds and their nanoemulsions-based delivery system. *Bioresour. Bioprocess.* 6, 26. <https://doi.org/10.1186/s40643-019-0261-9>.

cycles (Bartek et al., 2021¹⁶⁵). The intensive production of animal proteins has a direct impact on climate change, as it results in 12% of total GHG emissions and 30% of all human-induced terrestrial biodiversity loss (Henchion et al, 2017¹⁶⁶).

Food waste primarily consists of lipids, cellulose, hemicellulose, starch, lignin, and protein, collectively making up 82%–96% of its volatile content from total solids. It shares similarities with other organic or carbonaceous solid waste used in bioenergy applications, such as woody biomass, agricultural waste, and municipal solid waste. However, food waste stands out for its significantly higher lipid (saturated fat) and protein content, making it especially appealing for conversion into biofuel and valuable chemicals. Studies have shown that food waste is very rich in nutrients such as nitrogen (N), potassium (K) and phosphorus (P). These elements, which are collectively referred to as NPK soil nutrients (Ouadi et al., 2019¹⁶⁷), are very vital for the growth and reproduction of plants.

5.8.2 The trends

Future valorisation techniques should be moulded in such a way that they should be economically feasible with less environmental impact. Some of the protocols used for food waste such as anaerobic digestion; well-crafted chemical techniques for separation; unified bio-conversion of base compounds to essential molecules and significant prototypes of biofuel; and advanced extraction techniques for recovering bioactive molecules have a less environmental impact with better economic benefits (Arun et al. 2024¹⁶⁸).

The valorisation from food waste streams is a sustainable approach concerning the circular economy, green environment, and recovery of valuable neglected food nutrients through conversion into precious bioproducts. A hypothetical hierarchy pyramid of food waste management and the valorisation approach deciphering the least priority to top priority approaches (Figure 25). This figure depicts the vital points concerning policy implications toward advanced food waste recycling (Sarker et al, 2024¹⁶⁹).

¹⁶⁵ Bartek, L., Strid, I., Henryson, K., Junne, S., Rasi, S., and Eriksson, M. (2021). Life cycle assessment of fish oil substitute produced by microalgae using food waste. *Sustainable Production and Consumption*, 27, 2002–2021. <https://doi.org/10.1016/j.spc.2021.04.033>.

¹⁶⁶ Henchion M.; Hayes M.; Mullen A. M.; Fenelon M.; Tiwari B. Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium. *Foods* 2017, 6, 53. <https://doi.org/10.3390/foods6070053>.

¹⁶⁷ Ouadi, M., Bashir, M. A., Speranza, L. G., Jahangiri, H., and Hornung, A. (2019). Food and market waste—A pathway to sustainable fuels and waste valorization. *Energy and Fuels: An American Chemical Society Journal*, 33(10), 9843–9850. doi:10.1021/acs.energyfuels.9b01650.

¹⁶⁸ Arun, K. B. Madhavan, A., Sindhu, R., Binod, P., Pandey, A., Ranjna Sirohi, R. Remodelling agro-industrial and food wastes into value-added bioactives and biopolymers, *Industrial Crops and Products*, Volume 154, 2020, 112621, <https://doi.org/10.1016/j.indcrop.2020.112621>.

¹⁶⁹ Sarker, A., Ahmmed, R., Ahsan, S. M., Rana, J., Ghosh, M. K., and Nandi, R. (2024). A comprehensive review of food waste valorization for the sustainable management of global food waste. *Sustainable Food Technology*, 2(1), 48–69. doi:10.1039/d3fb00156c.

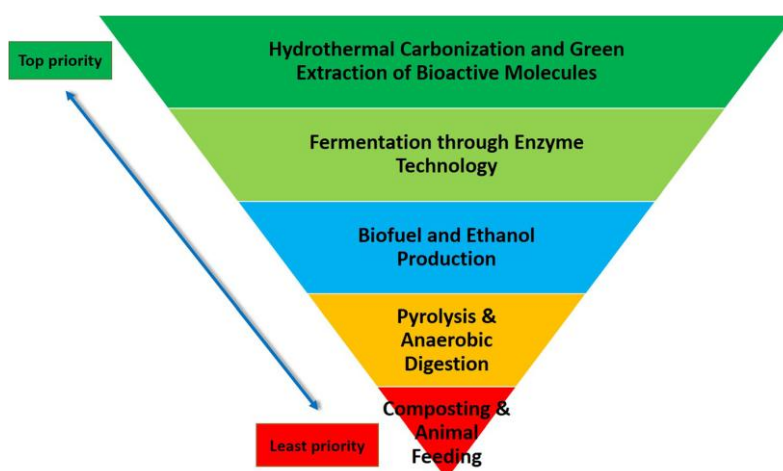


Figure 25. A hypothetical hierarchy pyramid of food waste management and valorisation.

Integrated valorisation methods combine multiple waste treatment and conversion processes to maximise the value extracted from waste streams, such as food waste. These approaches aim to boost resource efficiency, minimise waste, and promote sustainability. They often involve a mix of biological, chemical, and thermal processes, alongside the recovery and use of valuable byproducts.

5.9 Circular economy and food loss/waste

Food loss/waste is a major environmental and economic problem, as it contributes to greenhouse gas emissions and resource depletion. By applying circular economy principles and practices, multiple benefits can be achieved, such as reducing environmental impacts, saving costs, enhancing quality and safety, and creating new value-added products from food waste.

The future of the food processing sector lies at the intersection of circular economy principles and effective food waste management. As global concerns surrounding climate change and sustainability intensify, food processors face an array of future issues and trends that necessitate a paradigm shift towards circularity and waste reduction. Sustainable and resource-efficient designs will prioritise energy optimisation, waste reduction, and the integration of renewable energy sources. Building upon the comprehensive roadmap, several critical themes emerge that will shape the trajectory of the sector in the coming years.

Food processors will focus on waste valorisation initiatives, harnessing organic waste to generate biogas through anaerobic digestion, converting food waste into biogas and fertiliser, which can be used for renewable energy generation and soil improvement. The development of circular waste management infrastructure will facilitate the efficient collection, sorting, and processing of food waste generated by food manufacturers. Recycling and composting facilities will play a crucial role in diverting organic waste from landfills. Some of the future issues and trends for circular economy and food waste include exploring bio-based circular economy approaches, such as using food waste as a feedstock for biorefineries, biofuels, bioplastics, and other value-added products; and optimising food supply chains and operations to reduce food waste, improve efficiency, and enhance quality and safety.

5.10 Food eating habits

Rising energy costs have had an impact on consumer cooking habits. Since the pandemic (where consumers cooked more) many consumers are reporting using the hob less and microwave more to

save energy¹⁷⁰. Consumers are also reporting that they cook meals that require less cooking and cook less energy intensive meals. In extreme cases some consumers are reporting that they no longer use their oven. Consumer trends are to plan meals better and batch cook to better utilise energy. There is also an increase in the purchasing of frozen food. This is likely to have been partially driven by changes in shopping habits in the pandemic (fewer shopping trips and the wish to store foods in case of lock downs). This also drove an increase in purchase of non-perishable foods. Increased energy costs and the financial crisis are also reported to be having an impact on food waste in the home with 3 in 5 consumers in the UK stating that they are reducing the amount of food they waste and consequently are buying less food¹⁷¹.

There is a general trend for consumers to consume perceived 'healthier' plant based and more sustainable options. Before the financial crisis (which has changed food choices to those more based on cost) a survey conducted by research company Toluna showed there was a reduction in the consumption of meat-based products with 50% of people saying they have started or were continuing to reduce their meat intake. Since 2019 meat eaters have reduced from 83% to 78%¹⁷². There is also a growing trend for veganism and vegetarianism (7% saying they planned to consume a vegan diet and 12% a vegetarian diet). There is a growing need for alternative plant-based products which are generally perceived by consumers as being healthy¹⁷³.

There is a growing trend for health-based foods. Consumers are also becoming more aware of how their food choices affect the environment and so are more aware of sustainability and interested in provenance and sourcing of foods they buy. In particular, packaging has a high profile with consumers who are much more concerned about single use packaging than in the past. One developing trend is for personalisation of food where consumers use technology to select foods that suit their health, welfare and lifestyle choices¹⁷⁴.

All these trends have an impact on food processors who will provide choices to consumers according to what is demanded at the retail outlet by consumers. Currently the major trend is to provide customers with cheaper alternatives and deals to reduce the cost of eating. Although this has been exacerbated by the financial crisis it is a trend that has been ongoing for several years. In the past consumers still bought treats and would trade up to more expensive options for special occasions. This has reduced due to lack of disposable income. Although current supermarket trends are very much driven by food costs, there is still a strong trend for consumers to be very aware of sustainability issues and want brands and supermarkets to be honest in their claims and avoid greenwashing.

6 PERFORMANCE OF FOOD PROCESSING SECTORS

6.1 Current performance metrics

Detailed performance metrics are often difficult to obtain. Broad metrics covering a production site are available, but these data do not always clearly identify what is included or excluded from the metrics.

¹⁷⁰ <https://www.bbc.co.uk/news/business-65954252>.

¹⁷¹ <https://www.foodmanufacture.co.uk/Article/2022/09/23/How-are-consumers-changing-their-eating-habits>.

¹⁷² <https://tolunacorporate.com/dietary-trends-and-plant-based-perceptions-in-the-uk/>.

¹⁷³ <https://www.foodmanufacture.co.uk/Article/2022/05/30/how-are-consumers-diets-changing>.

¹⁷⁴ <https://sialamerica.com/white-papers/the-4-biggest-consumer-food-trends-shaping-2022/>.

General performance metrics are available for a range of food processes. These cover the whole of the production site and do not divide the process into categories (as is done for the focus products below). FoodDrinkEurope provide KPIs for a range of food types as MWh/tonne of energy¹³. Together with information collated by the ENOUGH team this provides a broad range of KPIs across a range of products (Figure 35). Even within one food category the range in KPIs collected across often a large number of facilities ranges widely. This indicates that there is a large degree of difference between processes applied even for similar foods.

One explanation for the large variability in performance metrics for different processing operations is related to the throughput of the processing plant. Larger processors use less energy per tonne of food processed, probably due to economies of scale. Figure 27 clearly shows that small processors who process less than 250,000 tonnes or product a year have far more variability in their performance metrics. This was found across all food sectors examined. Larger processors will tend to focus on one product and be able to apply the economies associated with automation and mass production.

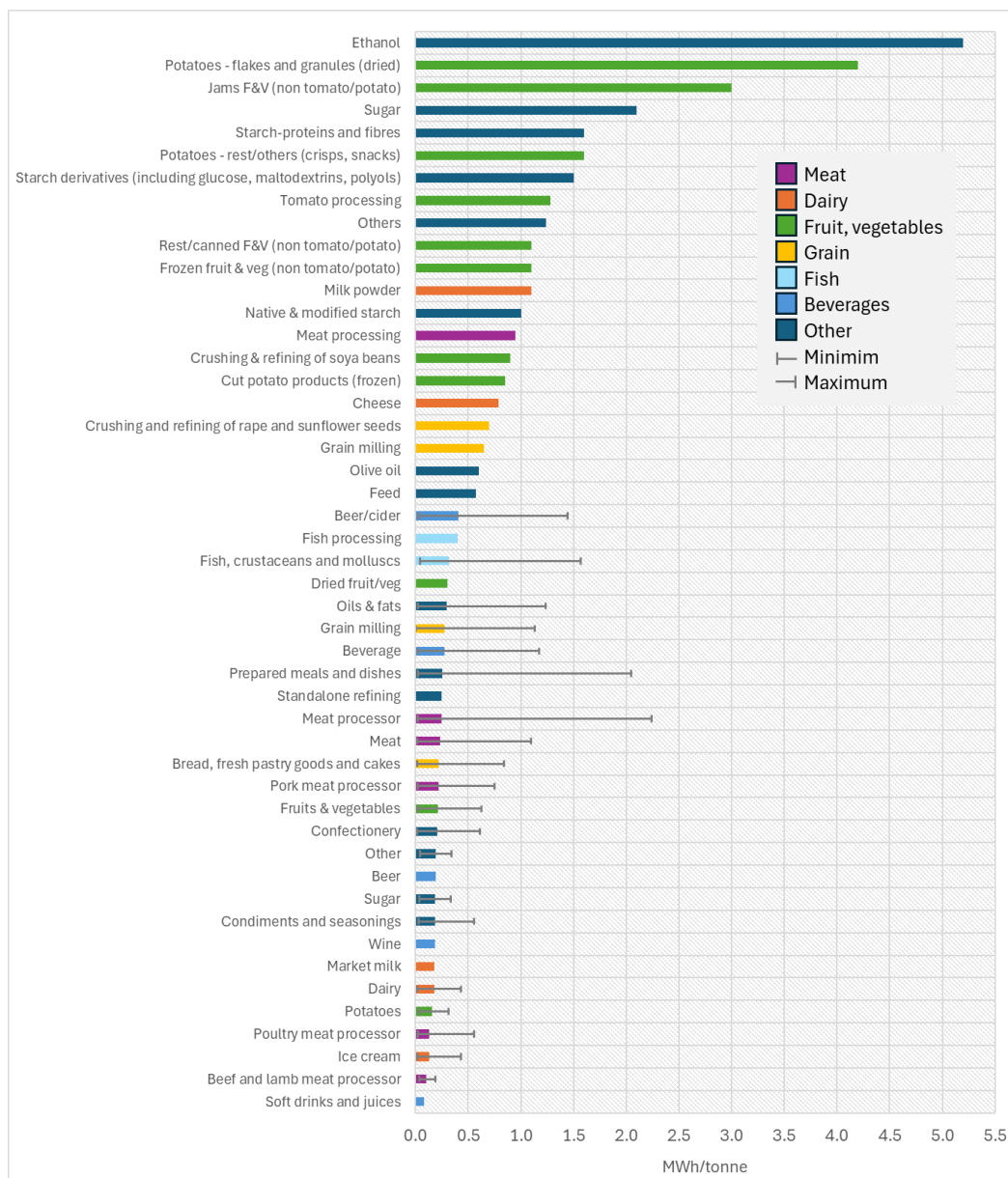


Figure 26. Energy use per tonne of food processed for a range of products.

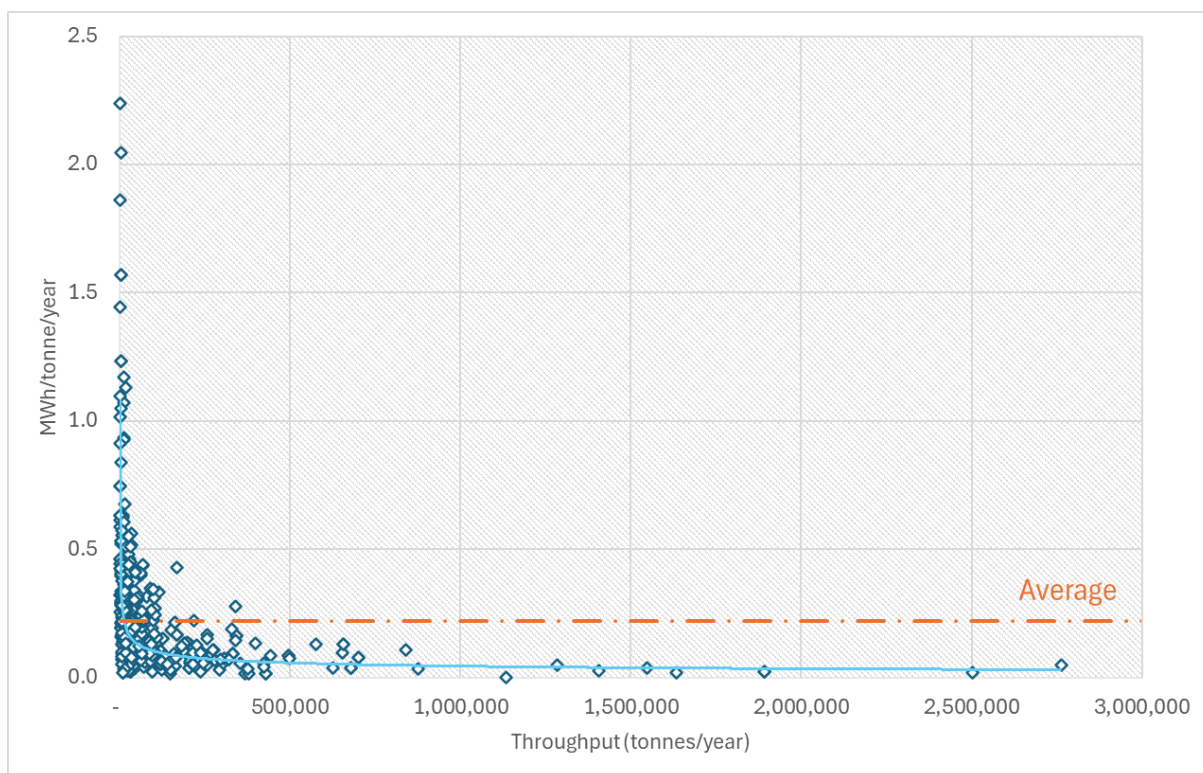


Figure 27. Energy use per tonne of food processed.

6.1.1 Meat processing

6.1.1.1 Metrics

Over time there has been gradual closure of smaller abattoirs and consolidation into larger entities. This results in larger throughputs per facility and theoretical less variable in performance metrics (see Figure 27).

Detailed performance metrics for meat processing are relatively scarce and are complicated by whether they include just chilling or carcasses or also include cutting and deboned and, in some cases, also freezing. In addition, metrics may be presented in different formats. Reported metrics are listed in Table 8. The majority of metrics are reported as kWh/tonne or MJ/tonne. Data compared for kWh/tonne and MJ/tonne are presented in

Table 8. Published metrics for meat processing plants.

Sector	Metric	Value	Value (range)	Notes	Reference
Beef	kWh/head	70	300	Packing plant	Hansen, P., Christiansen, K., and Hummelose, B. (n.d.). Cleaner Production Assessment in Meat Processing. United Nations Environment Programme Division of Technology, Industry and Economics and Danish Environmental Protection Agency (Danish Ministry of Environment and Energy).
Beef	kWh/head	2400		Packing plant	Pagan, R., Renouf, M., and Prasad, P. (2002). Eco-Efficiency Manual for Meat Processing. Queensland: Meat and Livestock Australia.
Red meat	MJ/day	359000		Processing plant	Meat and Livestock Australia (MLA) 2002, Eco-Efficiency Manual for Meat Processing, prepared by the UNEP Working Group for Cleaner Production in the Food Industry, ISBN 174036631X, Meat and Livestock Australia, North Sydney NSW
Red meat	MJ/day	359000		Processing plant	Meat and Livestock Australia (MLA) 2002, Eco-Efficiency Manual for Meat Processing, prepared by the UNEP Working Group for Cleaner Production in the Food Industry, ISBN 174036631X, Meat and Livestock Australia, North Sydney NSW
Red meat	MJ/day	419000		Processing plant	Meat and Livestock Australia (MLA) 2002, Eco-Efficiency Manual for Meat Processing, prepared by the UNEP Working Group for Cleaner Production in the Food Industry, ISBN 174036631X, Meat and Livestock Australia, North Sydney NSW
Beef	MJ/head	252	1080	Energy use of beef packing plants in Denmark	Hansen, P., Christiansen, K., and Hummelose, B. (n.d.). Cleaner Production Assessment in Meat Processing. United Nations Environment Programme Division of Technology, Industry and Economics and Danish Environmental Protection Agency (Danish Ministry of Environment and Energy).
Beef	MJ/head	851		Packing plant	Parker, D., Auvermann, B., Stewart, B., and Robinson, C. (1997). Agricultural energy consumption, biomass generation, and livestock manure value in the southern high plains. In Proceedings Workshop No.1, Livestock Waste Streams:Energy and Environment. Austin, TX: Texas Renewable Energy Industries Association.
Beef	MJ/tonne	70	190	Measured energy consumption, chilling only	Gigiel, A. J., and Collett, P., 1989. Energy consumption, rate of cooling and weight loss in beef chilling in UK slaughterhouses. Journal of Food Engineering, 10, 255-273.
Beef	MJ/tonne	351		Energy use of beef packing plants in Poland	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A., 2013. Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. Food and Bioprocess Technology, 6(10), 2621–2629.
Beef	MJ/tonne	491		Energy use of beef packing plants in Australia	Pagan, R., Renouf, M., and Prasad, P., 2002. Eco-Efficiency Manual for Meat Processing. Queensland: Meat and Livestock Australia.

Sector	Metric	Value	Value (range)	Notes	Reference
Beef	MJ/tonne	626	666	Energy use of beef packing plants in Poland	Kowalczyk, R., and Netter, J., 2008. A new look at the energetic factors consumption in food industry. <i>Postępy Techniki Przetwórstwa Spożywczego</i> , 45–47.
Beef	MJ/tonne	1723		Packing plant	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. <i>Food and Bioprocess Technology</i> , 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.
Beef and sheep	MJ/tonne	878		Dress carcass weight, electricity and fuels and heat consumption	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. <i>Energy Efficiency</i> ; p. 791–810.
Beef, veal, sheep	MJ/tonne	1390		Slaughtering	Aan Den Toorn, S.I., Van Den Broek, M.A. and Worrell, E., 2017. Decarbonising meat: Exploring greenhouse gas emissions in the meat sector. <i>Energy Procedia</i> , 123, pp.353-360. Ramírez, C.A., Patel, M., and Blok, K., 2004
Beef, veal, sheep	MJ/tonne	1390		Dress carcass weight for whole and chilled	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. <i>Food and Bioprocess Technology</i> , 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.
Beef, veal, sheep	MJ/tonne	1390		Whole dressed and chilled, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. <i>Energy</i> , 31(12), pp.2047-2063.
Beef, veal, sheep	MJ/tonne	2110		Dress carcass weight for whole and frozen	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. <i>Food and Bioprocess Technology</i> , 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.
Beef, veal, sheep	MJ/tonne	2110		Whole and frozen, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. <i>Energy</i> , 31(12), pp.2047-2063.
Beef, veal, sheep	MJ/tonne	2146		Dress carcass weight for whole and chilled	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. <i>Food and Bioprocess Technology</i> , 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.
Beef, veal, sheep	MJ/tonne	2146		Cut up deboned and chilled, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. <i>Energy</i> , 31(12), pp.2047-2063.
Beef, veal, sheep	MJ/tonne	2295	3296	Rendering	Aan Den Toorn, S.I., Van Den Broek, M.A. and Worrell, E., 2017. Decarbonising meat: Exploring greenhouse gas emissions in the meat sector. <i>Energy Procedia</i> , 123, pp.353-360. Ramírez, C.A., Patel, M., and Blok, K., 2004.

Sector	Metric	Value	Value (range)	Notes	Reference
Beef, veal, sheep	MJ/tonne	2866		Dress carcass weight for whole and frozen	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. Food and Bioprocess Technology, 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.
Beef, veal, sheep	MJ/tonne	2866		Cut up deboned and frozen, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. Energy, 31(12), pp.2047-2063.
Pig meat	MJ/tonne	90	260	Measured energy consumption, chilling only	Collett, P. and Gigiel, A. J., 1986. Energy usage and weight loss in beef and pork chilling. Recent advances and development in the refrigeration of meat by chilling. In: Proceedings of International Institute of Refrigeration, Commission C2, Bristol (UK) 171-177.
Pork	MJ/tonne	1195		Slaughtering	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. Food and Bioprocess Technology, 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.
Pork	MJ/tonne	1397		Dress carcass weight, electricity and fuels and heat consumption	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. Energy Efficiency; p. 791–810.
Pork	MJ/tonne	1570		Slaughtering	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. Food and Bioprocess Technology, 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.
Pork	MJ/tonne	2093		Whole dressed and chilled, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. Energy, 31(12), pp.2047-2063.
Pork	MJ/tonne	2097		Slaughtering	Aan Den Toorn, S.I., Van Den Broek, M.A. and Worrell, E., 2017. Decarbonising meat: Exploring greenhouse gas emissions in the meat sector. Energy Procedia, 123, pp.353-360. Ramirez, C.A., Patel, M., and Blok, K., 2004
Pork	MJ/tonne	2097		Dress carcass weight for whole and frozen	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. Food and Bioprocess Technology, 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.
Pork	MJ/tonne	2293	3296	Rendering	Aan Den Toorn, S.I., Van Den Broek, M.A. and Worrell, E., 2017. Decarbonising meat: Exploring greenhouse gas emissions in the meat sector. Energy Procedia, 123, pp.353-360. Ramirez, C.A., Patel, M., and Blok, K., 2004
Pork	MJ/tonne	2849		Dress carcass weight for whole and frozen	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. Food and Bioprocess Technology, 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.

Sector	Metric	Value	Value (range)	Notes	Reference
Pork	MJ/tonne	2849		Cut up deboned and chilled, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. <i>Energy</i> , 31(12), pp.2047-2063.
Pork	MJ/tonne	3128		Dress carcass weight for whole and chilled	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. <i>Food and Bioprocess Technology</i> , 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.
Pork	MJ/tonne	3128		Whole and frozen, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. <i>Energy</i> , 31(12), pp.2047-2063.
Pork	MJ/tonne	3884		Cut up deboned and frozen, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. <i>Energy</i> , 31(12), pp.2047-2063.
Pork	MJ/tonne	3884		Dress carcass weight for whole and frozen	Wojdalski, J., Drózd, B., Grochowicz, J., Magryś, A., and Ekielski, A. (2013). Assessment of Energy Consumption in a Meat-Processing Plant-a Case Study. <i>Food and Bioprocess Technology</i> , 6(10), 2621–2629. doi:10.1007/11947-012-0924-4.
Poultry	MJ/tonne	1584		Dress carcass weight, electricity and fuels and heat consumption	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. <i>Energy Efficiency</i> ; p. 791–810.
Poultry	MJ/tonne	2294	3296	Rendering	Aan Den Toorn, S.I., Van Den Broek, M.A. and Worrell, E., 2017. Decarbonising meat: Exploring greenhouse gas emissions in the meat sector. <i>Energy Procedia</i> , 123, pp.353-360. Ramirez, C.A., Patel, M., and Blok, K., 2004
Poultry	MJ/tonne	3096		Whole dressed and chilled, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. <i>Energy</i> , 31(12), pp.2047-2063.
Poultry	MJ/tonne	3096		Slaughtering	Aan Den Toorn, S.I., Van Den Broek, M.A. and Worrell, E., 2017. Decarbonising meat: Exploring greenhouse gas emissions in the meat sector. <i>Energy Procedia</i> , 123, pp.353-360. Ramirez, C.A., Patel, M., and Blok, K., 2004
Poultry	MJ/tonne	3852		Cut up deboned and chilled, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. <i>Energy</i> , 31(12), pp.2047-2063.
Poultry	MJ/tonne	4258	5518	Whole and frozen, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. <i>Energy</i> , 31(12), pp.2047-2063.

Sector	Metric	Value	Value (range)	Notes	Reference
Poultry	MJ/tonne	5014	6274	Cut up deboned and frozen, processed dressed carcass weight	Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. <i>Energy</i> , 31(12), pp.2047-2063.
Processed meat	MJ/tonne	750		Embodied energy use	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. <i>Energy Efficiency</i> ; p. 791–810.
Processed meat	MJ/tonne	4700		Product, electricity and fuels and heat consumption	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. <i>Energy Efficiency</i> ; p. 791–810.
Red meat	MJ/tonne	4108		Processing plant	Meat and Livestock Australia (MLA) 2011 (1), Industry environmental sustainability review 2010, A.ENV.0086, prepared by GHD, June 2011, ISBN 9781741915693, Meat and Livestock Australia, North Sydney, NSW
Rendering	MJ/tonne	234		Raw material	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. <i>Energy Efficiency</i> ; p. 791–810.
Rendering	MJ/tonne	1276		Raw material, electricity and fuels and heat consumption	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. <i>Energy Efficiency</i> ; p. 791–810.
Animal slaughtering	MWh	0.30		Other	Compton, M., Willis, S., Rezaie, B., Humes, K., 2018. Food processing industry energy and water consumption in the Pacific Northwest. <i>Innovative Food Science and Emerging Technologies</i> 47:371–83.
Animal slaughtering	MWh	0.40		Boiler	Compton, M., Willis, S., Rezaie, B., Humes, K., 2018. Food processing industry energy and water consumption in the Pacific Northwest. <i>Innovative Food Science and Emerging Technologies</i> 47:371–83.
Animal slaughtering	MWh	1.00		Process heating	Compton, M., Willis, S., Rezaie, B., Humes, K., 2018. Food processing industry energy and water consumption in the Pacific Northwest. <i>Innovative Food Science and Emerging Technologies</i> 47:371–83.
Animal slaughtering	MWh	1.20		Heating, ventilation, and air conditioning (HVAC)	Compton, M., Willis, S., Rezaie, B., Humes, K., 2018. Food processing industry energy and water consumption in the Pacific Northwest. <i>Innovative Food Science and Emerging Technologies</i> 47:371–83.
Animal slaughtering	MWh	2.00		Lighting	Compton, M., Willis, S., Rezaie, B., Humes, K., 2018. Food processing industry energy and water consumption in the Pacific Northwest. <i>Innovative Food Science and Emerging Technologies</i> 47:371–83.
Animal slaughtering	MWh	5.90		Machine drive	Compton, M., Willis, S., Rezaie, B., Humes, K., 2018. Food processing industry energy and water consumption in the Pacific Northwest. <i>Innovative Food Science and Emerging Technologies</i> 47:371–83.

Sector	Metric	Value	Value (range)	Notes	Reference
Animal slaughtering	MWh	8.20		Cooling and refrigeration	Compton, M., Willis, S., Rezaie, B., Humes, K., 2018. Food processing industry energy and water consumption in the Pacific Northwest. <i>Innovative Food Science and Emerging Technologies</i> 47:371–83.
Meat	MWh/tonne	0.08	0.25	Electricity for chilling	Nunes, J., Silva, P.D.D., Andrade, L.P. and Gaspar, P.D., 2014. Potential of energy savings in Portuguese meat industry. In 8th International Conference on Energy and Development, Environment and Biomedicine. 8th International Conference on Energy and Development, Environment and Biomedicine (EDEB'14).
Meat	MWh/tonne	0.15		Electricity for chilling, average OECD	Nunes, J., Silva, P.D.D., Andrade, L.P. and Gaspar, P.D., 2014. Potential of energy savings in Portuguese meat industry. In 8th International Conference on Energy and Development, Environment and Biomedicine. 8th International Conference on Energy and Development, Environment and Biomedicine (EDEB'14).
Meat	MWh/tonne	0.20	3.1	Electrical energy for slaughter and processing, Germany	Meyers, S., Schmitt, B., Chester-Jones, M., Sturm, B., 2016. Energy efficiency, carbon emissions, and measures towards their improvement in the food and beverage sector for six European countries. <i>Energy</i> 104:266–83.
Meat	MWh/tonne	0.20	0.86	Abattoir and cutting plant	Walsh, C. Resource use in the British beef and lamb processing sector. MLCS Consulting
Meat	MWh/tonne	0.21	0.11	Electricity for chilling	Nunes, J., Silva, P.D.D., Andrade, L.P. and Gaspar, P.D., 2014. Potential of energy savings in Portuguese meat industry. In 8th International Conference on Energy and Development, Environment and Biomedicine. 8th International Conference on Energy and Development, Environment and Biomedicine (EDEB'14).
Meat	MWh/tonne	0.23		Whole plant	UK survey data
Meat	MWh/tonne	0.25		Whole plant	UK survey data
Meat	MWh/tonne	0.39	3.75	Electrical and thermal energy for slaughter, Germany	Meyers, S., Schmitt, B., Chester-Jones, M., Sturm, B., 2016. Energy efficiency, carbon emissions, and measures towards their improvement in the food and beverage sector for six European countries. <i>Energy</i> 104:266–83.
Beef	MWh/tonne	0.01	0.19	Abattoir only	Walsh, C. Resource use in the British beef and lamb processing sector. MLCS Consulting
Beef	MWh/tonne	0.20	0.73	Chill, cutting, retail pack	Walsh, C. Resource use in the British beef and lamb processing sector. MLCS Consulting
Beef	MWh/tonne	0.27	0.28	Packing plant	Kowalczyk, R., and Netter, J. (2008). A new look at the energetic factors consumption in food industry. <i>Postępy Techniki Przetwórstwa Spożywczego</i> , 45–47.
Beef	MWh/tonne	0.38		Abattoir and cutting plant	Walsh, C. Resource use in the British beef and lamb processing sector. MLCS Consulting
Beef	MWh/tonne	0.78		2/3rd electricity, 1/3rd gas or oil	Walsh, C. Resource use in the British beef and lamb processing sector. MLCS Consulting

Sector	Metric	Value	Value (range)	Notes	Reference
Beef and sheep	MWh/tonne	0.10		Whole plant	UK survey data
Beef and sheep	MWh/tonne	2.11		Electrical energy for slaughter and freezing, France, Germany, Netherlands, UK	Meyers, S., Schmitt, B., Chester-Jones, M., Sturm, B., 2016. Energy efficiency, carbon emissions, and measures towards their improvement in the food and beverage sector for six European countries. Energy 104:266–83.
Pork	MWh/tonne	0.22		Whole plant	UK survey data
Pork	MWh/tonne	0.95		Whole plant	UK survey data
Pork	MWh/tonne	3.13		Electrical and thermal energy for slaughter and freezing, France, Germany, Netherlands, UK	Meyers, S., Schmitt, B., Chester-Jones, M., Sturm, B., 2016. Energy efficiency, carbon emissions, and measures towards their improvement in the food and beverage sector for six European countries. Energy 104:266–83.
Poultry	MWh/tonne	0.13		Whole plant	UK survey data
Poultry	MWh/tonne	0.39	3.75	Electrical and thermal energy for slaughter, Germany	Meyers, S., Schmitt, B., Chester-Jones, M., Sturm, B., 2016. Energy efficiency, carbon emissions, and measures towards their improvement in the food and beverage sector for six European countries. Energy 104:266–83.
Poultry	MWh/tonne	0.97	0.67	Electrical and thermal energy for slaughter, Poland	Meyers, S., Schmitt, B., Chester-Jones, M., Sturm, B., 2016. Energy efficiency, carbon emissions, and measures towards their improvement in the food and beverage sector for six European countries. Energy 104:266–83.
Sheep	MWh/tonne	0.20	0.73	Chill, cutting, retail pack	Walsh, C. Resource use in the British beef and lamb processing sector. MLCS Consulting
Sheep	MWh/tonne	0.27		Abattoir only	Walsh, C. Resource use in the British beef and lamb processing sector. MLCS Consulting
Sheep	MWh/tonne	0.28		Abattoir and cutting plant	Walsh, C. Resource use in the British beef and lamb processing sector. MLCS Consulting
Sheep	MWh/tonne	0.69		2/3rd electricity, 1/3rd gas or oil	Walsh, C. Resource use in the British beef and lamb processing sector. MLCS Consulting
Meat	MWh/year	73.00		Electric energy for motors	Sheets, E.B., eurostat. Luksemburg, Roczniki. INE, 2018. Dados Macroeconómicos [WWW Document]. Fipa, URL https://www.fipa.pt/estatisticas/dados-macroeconomicos-industria-alimentar .
Meat	MWh/year	92.00		Electric energy for refrigeration	Sheets, E.B., eurostat. Luksemburg, Roczniki. INE, 2018. Dados Macroeconómicos [WWW Document]. Fipa, URL https://www.fipa.pt/estatisticas/dados-macroeconomicos-industria-alimentar .
Meat	MWh/year	105.00		Natural gas	Sheets, E.B., eurostat. Luksemburg, Roczniki. INE, 2018. Dados Macroeconómicos [WWW Document]. Fipa, URL https://www.fipa.pt/estatisticas/dados-macroeconomicos-industria-alimentar .

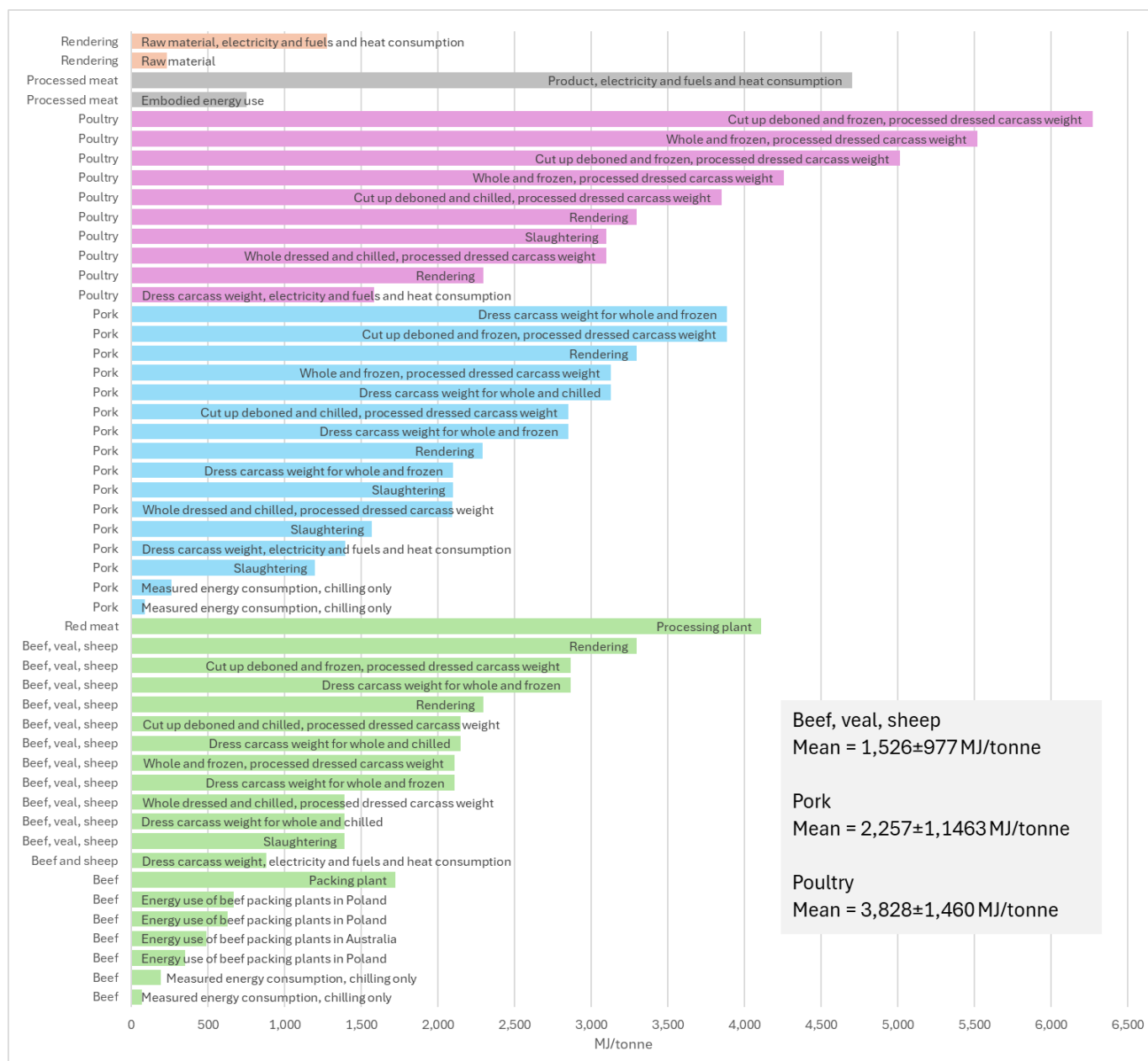


Figure 28. Metrics for meat processing in MJ/tonne.

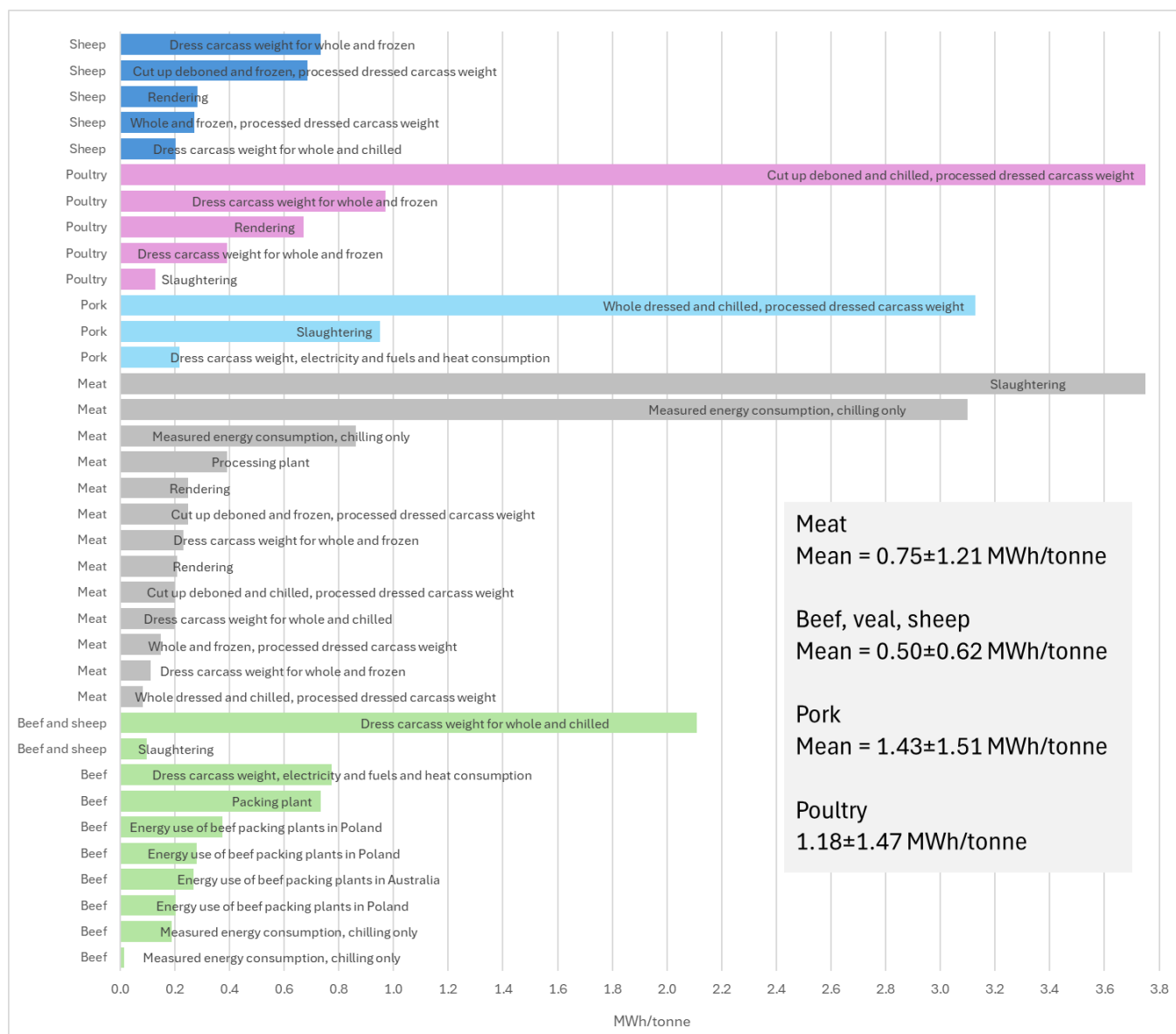


Figure 29. Metrics for meat processing in kWh/tonne.

6.1.1.2 Energy usage across meat processing processes

In abattoirs and cutting plants approximately 20-50% of the total energy is thermal energy from combustion of fuels for on-site boilers (provided by gas, liquid petroleum gas LPG or oil). Thermal energy used to heat water for cleaning, knife sterilisation, washing tripe, heating, blood drying and rendering. Rendering sometimes also occurs in abattoirs and cutting plant facilities (to typically provide edible oils or biodiesel raw materials) and also required thermal energy. Electricity provides 50-80% of the energy which is used for operating equipment in the slaughter and boning areas, for by-product processing, and for refrigeration and compressed air as well as for ventilation, lighting, powering the operating equipment in the slaughter, boning and by-product processing areas, e.g. saws, hoists, conveyors, packing machines, and electrical stimulation. Electricity consumption can be higher in plants where there is electrical stimulation, rapid chill and processing edible co-products.

Differences are reported between countries in terms of the fuels sources they utilise but also basic efficiencies. Ramirez et al (2006)¹⁷⁵ provide details of beef, pork and poultry processing in 4 European countries (France, Germany, the Netherlands and the UK). In the Netherlands, Germany and the UK gas is the predominant fuel used whereas in France electricity dominates (due to a focus on using electricity for heat by the French government). The use of ‘other fuels’ has either been low or has generally decreased over time. Electricity and gas tend to dominate the fuels used.

The division of energy varies between different types of plant. Cattle and sheep abattoirs need less hot water than pig plants which can use 80% of the total energy as thermal energy for heating scalding tanks, raising steam and singeing. Cattle and lamb abattoirs generally use less energy for thermal processes (30-50%). Lamb abattoirs use the least energy due to smaller carcasses that require less energy/kg for cooling and the fact that carcasses are not usually aged for long periods. Sheep abattoirs also rarely process stomachs and ship product whole (rather than cutting and deboning)¹⁷⁶. Poultry abattoirs are reported to use the greatest energy¹⁷⁷

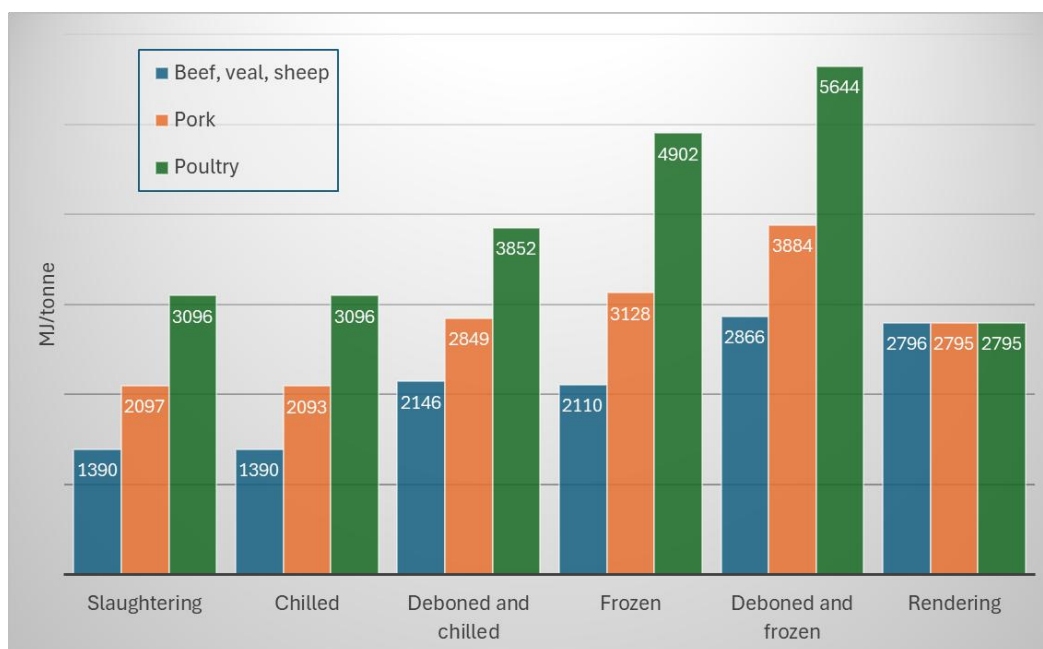


Figure 30. Energy used various processes in beef/veal/sheep, pork and poultry abattoirs¹⁷⁷.

Limited detailed information on how energy is divided between the various thermal processes in a meat processing plant are available. The division in electrical energy is reported by Iten et al¹⁷⁸ but this excludes energy from other sources (Figure 31). More comprehensive information on all thermal

¹⁷⁵ Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. *Energy*, 31(12), pp.2047-2063.

¹⁷⁶ Walsh, C. Resource use in the British beef and lamb processing sector. MLCS Consulting.

¹⁷⁷ Aan Den Toorn, S.I., Van Den Broek, M.A. and Worrell, E., 2017. Decarbonising meat: Exploring greenhouse gas emissions in the meat sector. *Energy Procedia*, 123, pp.353-360.

Ramírez, C.A., Patel, M., and Blok, K., 2004.

¹⁷⁸ Iten, M., Fernandes, U. and Oliveira, M.C., 2021. Framework to assess eco-efficiency improvement: Case study of a meat production industry. *Energy Reports*, 7, pp.7134-7148.

processes is provided by Colley¹⁷⁹ (Figure 32). Colley identified that 59% of the energy was associated with steam, 33% with electricity and 8% with hot water. Energy associated with different processes do vary quite considerably between reports with for example Iten et al claiming that 48% of electricity is used for refrigeration whereas Colley claims this to be 68%.

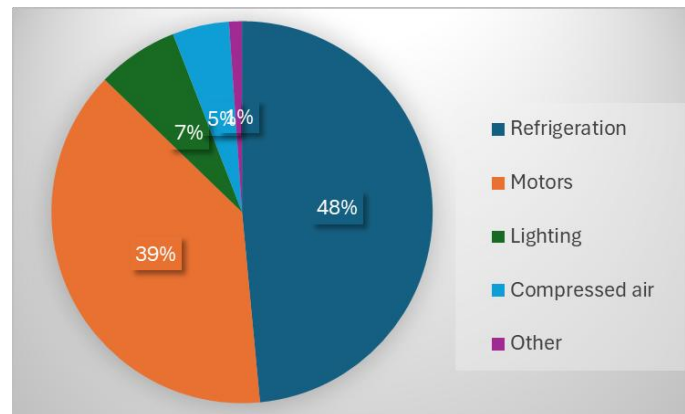


Figure 31. Division of energy in a typical slaughterhouse in Portugal¹⁷⁸.

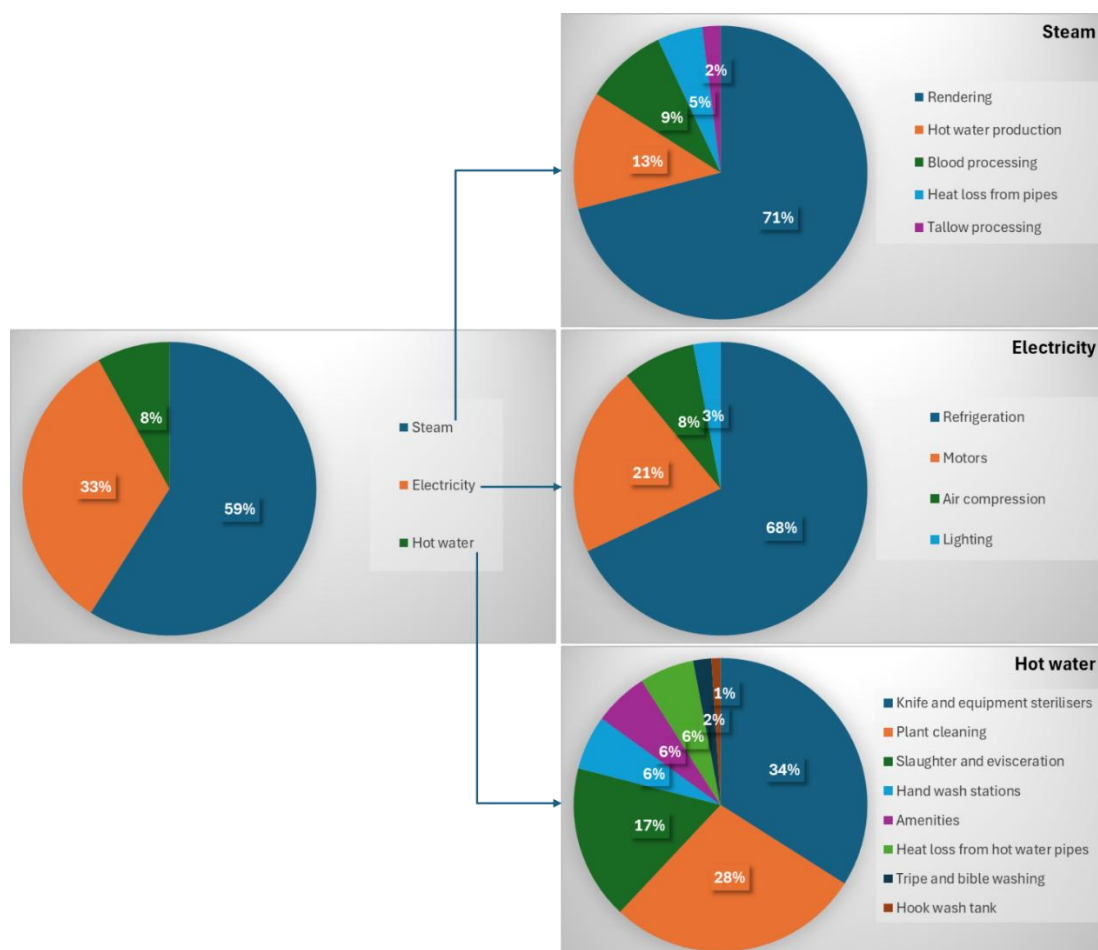


Figure 32. Division of energy in a slaughterhouse in Australia¹⁷⁹.

¹⁷⁹ Colley, T. Heat Integration and Renewable Energy in Meat Processing Plants - a strategy for minimising the impact of a carbon price. 2012.

6.1.2 Fish processing

When it comes to fish processing, there is a diversity in the production of seafood products, with some facilities specializing in a single type of production, while others are configured to handle a broad range of products. This flexibility is often dictated by the availability of raw material, which is influenced by seasonal variations, fish migration patterns and even political regulations (fishing quotas). Additionally, market dynamics and shifts in consumer preferences also impact the outputs from the different product groups. In a recent project, an attempt was made to estimate energy usage in the production across various seafood products, based on the Norwegian seafood industry (add ref). The results are summarised in Table 9, presenting value ranges that reflect 1) uncertainties when compiling this type of data, 2) variation between facilities due to differences in e.g. technical condition and operating practices, and 3) variation within the same facility caused by shifts in product portfolios and raw material availability.

Table 9. Current energy usage in fish processing

Sector	Metric	Value	Notes
Pelagic production ^A	kWh/tonne (r.m.)	116-235	Varies with degree of filleting, production throughput. Values are annually.
Fishmeal- and oil production ^A	kWh/tonne (r.m.)	El.: 30-60 Gas: 320-530	Varies with species, seasonality and variations in processing equipment
Salmon processing plant ^B	kWh/tonne (pr.)	190	Based on annual energy consumption and production values
Clipfish production ^C	kWh/tonne (r.m.)	84-209	Highly dependent on species (cod vs saithe) and fish size
Saltfish production ^C	kWh/tonne (r.m.)	20-119	Low range: theoretical estimation. High range: based on measurements
Stockfish production ^C	kWh/tonne (r.m.)	33-293	The variation reflects differences between traditional/manual and modern production (climate-controlled storage). Also, higher value includes diesel use for transport to/from outdoor drying frames
Whitefish/demersal processing ^C	kWh/tonne (r.m.)	31–324	Low range: theoretical estimation, mix of fresh/frozen r.m input and fresh/frozen pr. Output. High range: based on measurements
^A Svendsen, E.S., Widell, K.N., Moen, O.M., Bless, M., Sæther, F., Patanou, E., Lunde, M., Einhjellen, L., Bjerkvik, K., 2025b. Veikart for energieffektivisering i pelagisk sektor (No. 2025:00039). SINTEF. ^B Slette, H.T., Svendsen, E.S., Bless, M., Moen, O.M., Sæther, F., Patanou, E., Lunde, M., Hansen, G.T., 2025. Veikart for energieffektivisering i norsk havbruksnæring (No. 2025:00042). SINTEF. ^C Svendsen, E.S., Nordtvedt, T.S., Bless, M., Moen, O.M., Sæther, F., Patanou, E., Lunde, M., Berger, G., 2025a. Veikart for energieffektivisering i hvitfisk- og rekesektoren (No. 2025:00041). SINTEF. pr. = product basis, r.m = raw material basis			

Excluding the fishing stage, most of the energy used in the Norwegian fish processing industry is electricity, with the exception of fishmeal and oil production. Other countries may have a higher share of thermal energy use across sectors due to differing conditions related to energy availability and

pricing. Fishmeal processing has a high demand for heat, typically supplied as steam, for heating raw materials, evaporation, and drying processes. This heat has traditionally, and still is, produced by gas- or oil-fuelled boilers rather than electricity, due to factors such as energy costs or electrical grid restrictions. However, as HTHP technology has advanced in recent years, there is now significant potential to reduce the reliance on thermal energy in this sector as well.

Across all sectors of the fish processing industry, refrigeration systems are typically the primary energy consumers. This is largely attributable to the highly perishable nature of fish, which requires a range of thermal processes such as chilling, freezing, drying, thawing, and ice production. In the processing of pelagic species, i.e. Atlantic mackerel which are typically frozen, refrigeration systems can account for as much as 75% of a plant's total energy consumption (Figure 33). This is primarily driven by the intensive use of tunnel freezers during production.

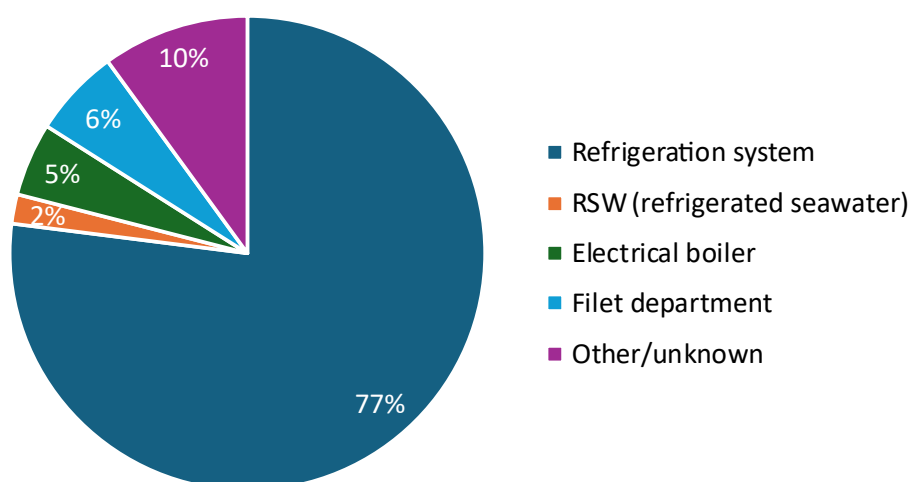


Figure 33: Division of energy in a typical pelagic production plant in Norway. Reproduced from Widell et al. (2022)¹⁸⁰.

In other sectors, such as whitefish processing, there is typically a broader product range, resulting in greater variation in energy consumption across facilities. The energy profile of a plant is therefore highly dependent on its product portfolio. For instance, a facility focused solely on fresh products will generally have significantly lower energy use compared to one producing frozen goods. The production of clipfish involves drying wet salted fish in energy-intensive drying tunnels over several days, resulting in high energy consumption. In contrast, the production of stockfish—also a dried product—relies on natural drying under ambient conditions and therefore requires substantially less energy. Figure 34 presents energy division of a whitefish processing plant producing both fresh and frozen, consumer ready products.

¹⁸⁰ Widell, K.N., Svendsen, E.S., Selvnæs, H., Sevault, A., Hafner, A., Ståle Nordtvedt, T., 2022. Energy flow analysis of an industrial ammonia refrigeration system and potential for a cold thermal energy storage. <https://doi.org/10.18462/iir.gl2022.0034>.

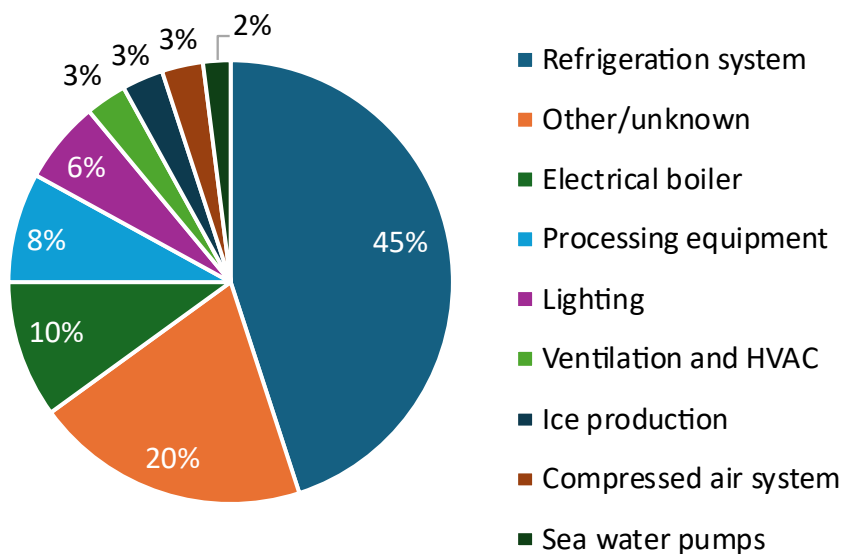


Figure 34: Division of energy in a whitefish processing plant in Norway¹⁸¹

6.1.3 Dairy processing to product cheese

Dairy operations are energy-intensive, with approximately 80% of consumption attributed to thermal energy. This thermal energy, generated primarily through the combustion of fossil fuels, provides the steam and hot water necessary for heating processes and cleaning. The remaining 20% of energy use is electrical, powering machinery, refrigeration, ventilation, and lighting. Evaporation and drying of milk are the most significant energy drains, according to Giner et al (2019¹⁸²), followed by pasteurisation, which requires substantial energy for heating and cooling. However, heat recovery via heat exchangers can mitigate this. Evaporation processes often incorporate vapor recompression for increased efficiency. Energy consumption data within the European dairy sector varies widely. Table 5 reports specific energy consumption based on the primary product (drinking milk, cheese, powder, and fermented milk), where the primary product constitutes at least 80% of total production.

Table 5. Current energy usage in dairy processing

Sector		Metric (kWh/tonne)	Value	References
Milk processing	Reception	700-970	2%	Giner et al 2019 ¹⁸²
	Storage		7%	
	Pasteurisation		17-26%	
	Centrifugation and homogenisation		12%	
	Cooling		19%	
	Cleaning in place		9.5%	

¹⁸¹ Svendsen, E.S., Nordtvedt, T.S., Bless, M., Moen, O.M., Sæther, F., Patanou, E., Lunde, M., Berger, G., 2025a. Veikart for energieffektivisering i hvitfisk- og rekesektoren (No. 2025:00041). SINTEF.

¹⁸² Giner Santonja, Germán, Karlis, Kristine Panagiotis, Stubdrup Raunkjær, Brinkmann Thomas, Roudier Serge (2019) "Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries" JRC Science for Policy Report European Commission.

	Sector	Metric (kWh/tonne)	Value	References
Milk powder	Drying	831-2077	45-51%	Xu and Flapper (2011) ¹⁸³
Cheese	Reception	1080.30-1191	7-19%	Xu and Flapper (2009) ¹⁸⁴ Ramirez et al 2004 ¹⁸⁵
	Cheese processing		14%	
	Treatment/storage		12-32%	
	Ripening		9-65%	
	Cooling/refrigeration		8-19%	
	Compressed air		5%	
	Cleaning in place		19%	
Butter	Cooling	277-1495.8	66%	
	Compressed air		8%	
	Cleaning in place		26%	
Ice cream		249	n/a	
Yoghurt		1319	n/a	

6.2 KPIs

Being able to compare performance of a facility with others is a useful first step in reducing energy consumption and emissions. Benchmarking provides a method to determine the relative efficiency of comparable food plants and also to monitor their performance over time. Benchmarks are usually averaged over a long period (usually a year) but can also be used to compare performance over comparable periods of usage and ambient conditions to see if there is fall off in performance that might be related to operation and maintenance.

7 SELECTED PRODUCTS/LOCATIONS/FUELS

7.1 Why products/processes were selected

7.1.1 Meat Processing

Beef, pork and poultry were selected as the case study products due to their high levels of consumption in Europe. Approximately 96% of the meat (excluding fish) consumed in Europe is pork, poultry or beef (Figure 3). Additionally, each product has slightly different slaughtering and processing characteristics as described in section 8.1.1.

7.1.2 Fish processing

Mackerel was selected as the focus species, due to its significant share of total fish production in Europe. In 2021, mackerel accounted for nearly 6% of the total world produced volume. In the EU production was at maximum in 2017 (423,000 tonnes) but has decreased since. The main producers in

¹⁸³ Xu, T. and Flapper, J., 2011. Reduce energy use and greenhouse gas emissions from global dairy processing facilities. *Energy policy*, 39(1), pp.234-247.

¹⁸⁴ T. Xu, J. Flapper. Energy use and implications for efficiency strategies in global fluid-milk processing industry. *Energy Policy*, 37 (12) (2009), pp. 5334-5341.

¹⁸⁵ C. Ramirez, M. Patel, K. Blok. From fluid milk to milk powder: Energy use and energy efficiency in the European dairy industry. *Energy*, 31 (12) (2006), pp. 1984-2004.

the EU-27 are Ireland, Spain, the Netherlands, Denmark, Portugal, and Lithuania. Consumption of mackerel in the EU was 272.741 tonnes live weight equivalent in 2021. The main markets for mackerel are Poland, France, Spain, Romania, Lithuania, Italy, and the Netherlands¹⁸⁶.

7.1.3 Dairy processing

Cheese was selected as the focus dairy product as 36% of raw milk is used to produce cheese¹⁸⁷.

According to a recent US Department of Agriculture (USDA) World Markets and Trade report¹⁸⁷, EU cheese production is poised for growth in 2024, with an anticipated increase of nearly 1%, reaching approximately 10.5 million tons. This expansion is fuelled by strong domestic consumption and consistent export demand, with key producers like Germany, France, Italy, the Netherlands, and Poland collectively accounting for nearly three-quarters of the EU's total output. As a reliable source of revenue and a product of high market demand, cheese production remains a pivotal focus for the European dairy sector. Concurrent with increased production, EU cheese exports are projected to rise by 1% to 1.4 million tons, building on the previous year's upward trend, with notable early-2024 surges in exports to the UK and the United States, particularly for hard cheeses. Furthermore, domestic cheese consumption within the EU is expected to accelerate, bolstered by economic recovery and the revival of the hospitality and tourism sectors. After a temporary decline in 2022 due to decreased consumer purchasing power, consumption stabilised in 2023 and is now projected to climb in 2024, driven by rising incomes and the resurgence of pre-COVID tourism and dining out levels.

7.1.4 Secondary processing to produce composite products

Beef casserole and breaded fish fingers were selected as representative products based on potential GHG emission reduction in the food industry due to their moderate complexity, which allows for meaningful analysis without excessive processing detail. These meals involve both primary and secondary food processing stages, providing a comprehensive view of emissions across the production chain. Additionally, their widespread recognition and consumption across Europe make them suitable benchmarks for evaluating environmental performance and potential improvements.

7.2 Fuels used and their carbon intensities

The food and drink industry's scope 1 GHG emissions are largely attributable to fossil fuels used by manufacturing facilities and offices¹⁸⁸. The use of solid fuels (e.g. coal) has steadily declined in the food industry, however, the industry is still reliant on natural gas for cooking and heating and petroleum for transport¹⁸⁹. In the UK in 2023, 56% of the gross calorific value of the energy used from the food and drink sector came from natural gas, 34% from electricity, 5% petroleum products, 3% bioenergy, and each of 1% coal and imported heat (Figure 35)¹⁹⁰.

¹⁸⁶ EUMOFA (European Market Observatory for Fisheries and Aquaculture Products). Mackerel in the EU. <https://eumofa.eu/documents/20124/90048/PTAT+mackerel+in+ES+PT+NL.pdf/b7c12eb7-c7cb-a65b-6b0d-35c13fb53f9d?t=1707750223695>.

¹⁸⁷ USDA. Dairy: World Markets and Trade. 2024. <https://apps.fas.usda.gov/psdonline/circulars/dairy.pdf>.

¹⁸⁸ A TIME TO ACT Climate Action and the Food and Drink Industry. FoodDrinkEurope. June 2015.

¹⁸⁹ Ladha-Sabur, A., Bakalis, S., Fryer, P.J. and Lopez-Quiroga, E., 2019. Mapping energy consumption in food manufacturing. Trends in food science and technology, 86, pp.270-280.

¹⁹⁰ The Digest of UK Energy Statistics (DUKES). Aggregate energy commodity balance: gross calorific values basis. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fmedia%2F66a79dd2a3c2a28abb50d8b6%2FDUKES_1.1.xlsx&wdOrigin=BROWSELINK.

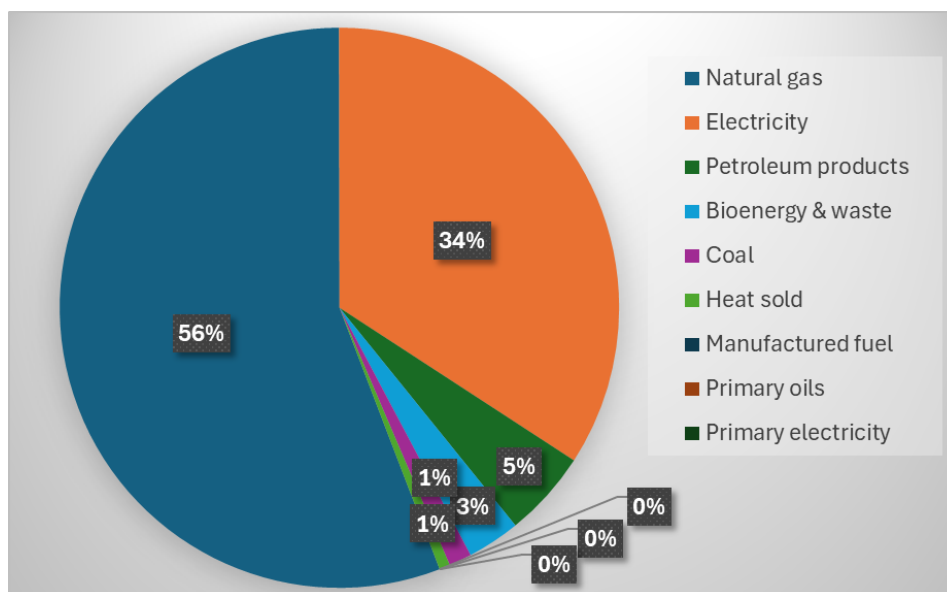


Figure 35. Breakdown of fuel from DUKES for food and beverage manufacturing in the UK (2023)¹⁹⁰.

Food processes that already use electricity, will decarbonise naturally with the electricity grid. Figure 36 shows GHG emissions emission factors for national electricity for EU member states from 1990 to 2021. The electrical grid conversion factors over time are predicted to decrease considerably, as renewable energy generation becomes more widespread. In many countries the grid intensity factors will reach almost zero by 2050. This will significantly reduce carbon emissions naturally. However, efficiency options cannot be ignored as these will aid more rapid decarbonisation. In addition, as the sector begins to transition to greater use of electricity there are potential issues with access to the grid and the grid being able to cope with increased demand. Many factories are constrained by the kVA available to a site. Adding extra capacity is an option (if the grid can provide that power) but is often a very costly option. Reducing the need for energy is one way to be able to operate using existing kVA supplies whilst at the same time reducing operational costs.

Grid carbon intensities vary considerably between European countries. In 2021 grid carbon intensities varied from zero in Iceland to 0.779 kgCO₂e/kWh in Poland (Figure 36). Natural gas and solid fuels have a carbon intensity of 0.243 and 0.264 kgCO₂e/kWh respectively.

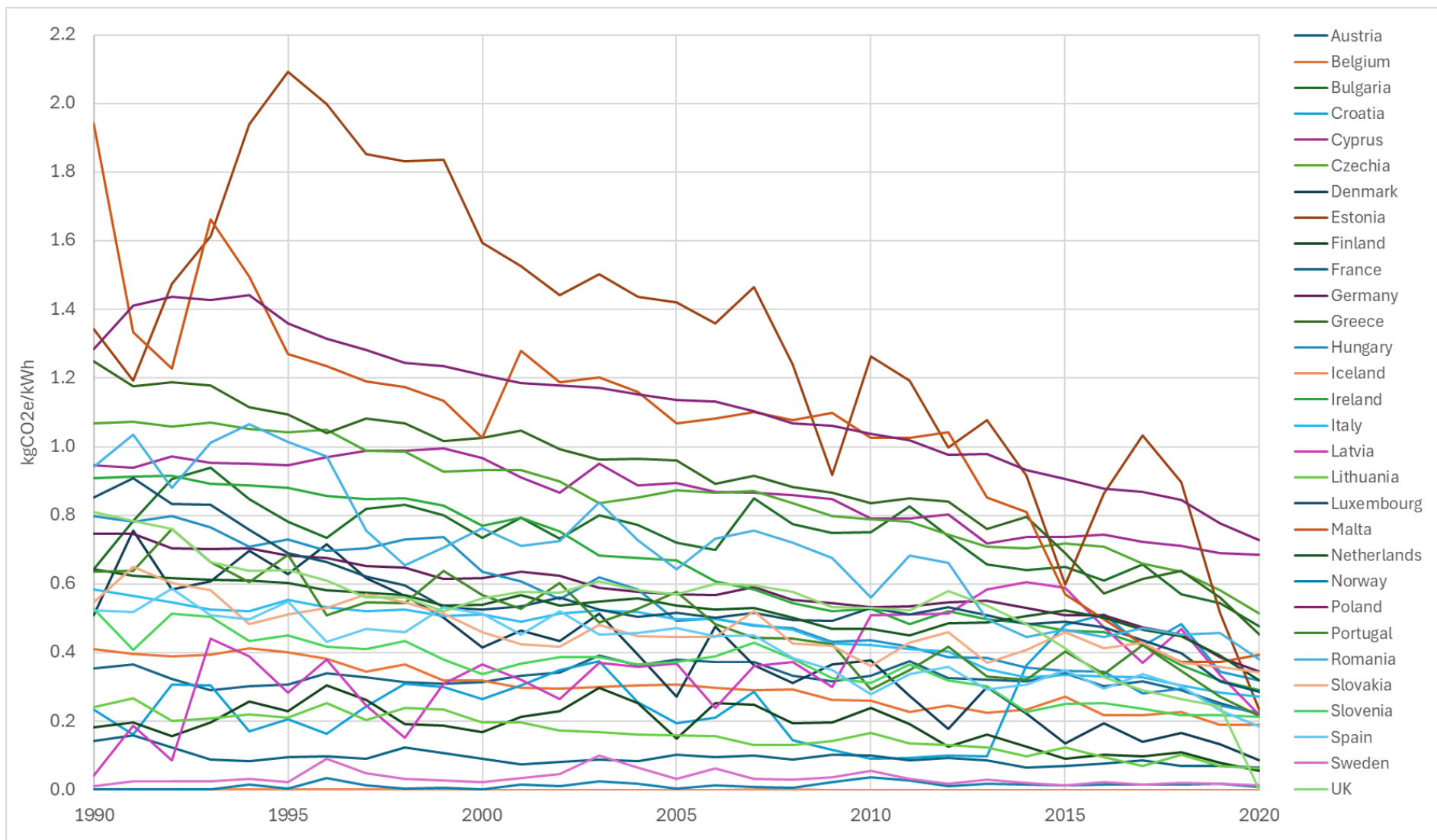


Figure 36. GHG emissions emission factors for national electricity for EU member states in kgCO₂e/kWh.

The share of electricity and heating used by different food processing sectors varies considerably (Table 10)¹³. Most chilling and freezing processes use more electricity (assumed to be for refrigeration) whereas processes more reliant on cooking, drying or further processing require more heat. A few products such as olive oil and grain are claimed to be 100% electrically processed, whereas the sugar sector is the lowest user of electricity at only 3%. As the sugar sector has the second highest annual energy usage (after feed), this makes the transition away from fossil fuels for sugar production critical to decarbonising the food and drink sector. Other industries with low levels of electricity use include dried potato products and frozen and canned fruit and vegetables.

Table 10. Share of energy use in the European food and drink sector.

	Share of energy	
	Electricity	Heating
Sub-sector	%	%
Feed	30	70
Beer	30	70
Market milk	30	70
Cheese	80	20
Milk powder	30	70
Ethanol	30	70
Fish processing	70	30
Frozen F&V (non-tomato/potato)	12	88
Rest/canned F&V (non-tomato/potato)	12	88
Jams F&V (non-tomato/potato)	30	70
Dried fruit/veg	50	50
Cut potato products (frozen)	25	75
Potatoes - flakes and granules (dried)	5	95
Potatoes - rest/others (crisps, snacks)	20	80
Tomato processing	20	80
Grain milling	100	0
Meat processing	70	30
Crushing and refining of rape and sunflower seeds	20	80
Crushing and refining of soya beans	25	75
Standalone refining	30	70
Olive oil	100	0
Soft drinks and juices	80	20
Native and modified starch	30	70
Starch-proteins and fibres	30	70
Starch derivatives (including glucose, maltodextrins, polyols)	30	70
Sugar	3	97
Others	30	70
Average	38	62

8 TYPICAL (STANDARD) PROCESSES INVESTIGATED

8.1.1 Meat processing

Typical processes in the slaughterhouse for poultry, beef and pork are shown in Figure 37, Figure 38 and Figure 39.

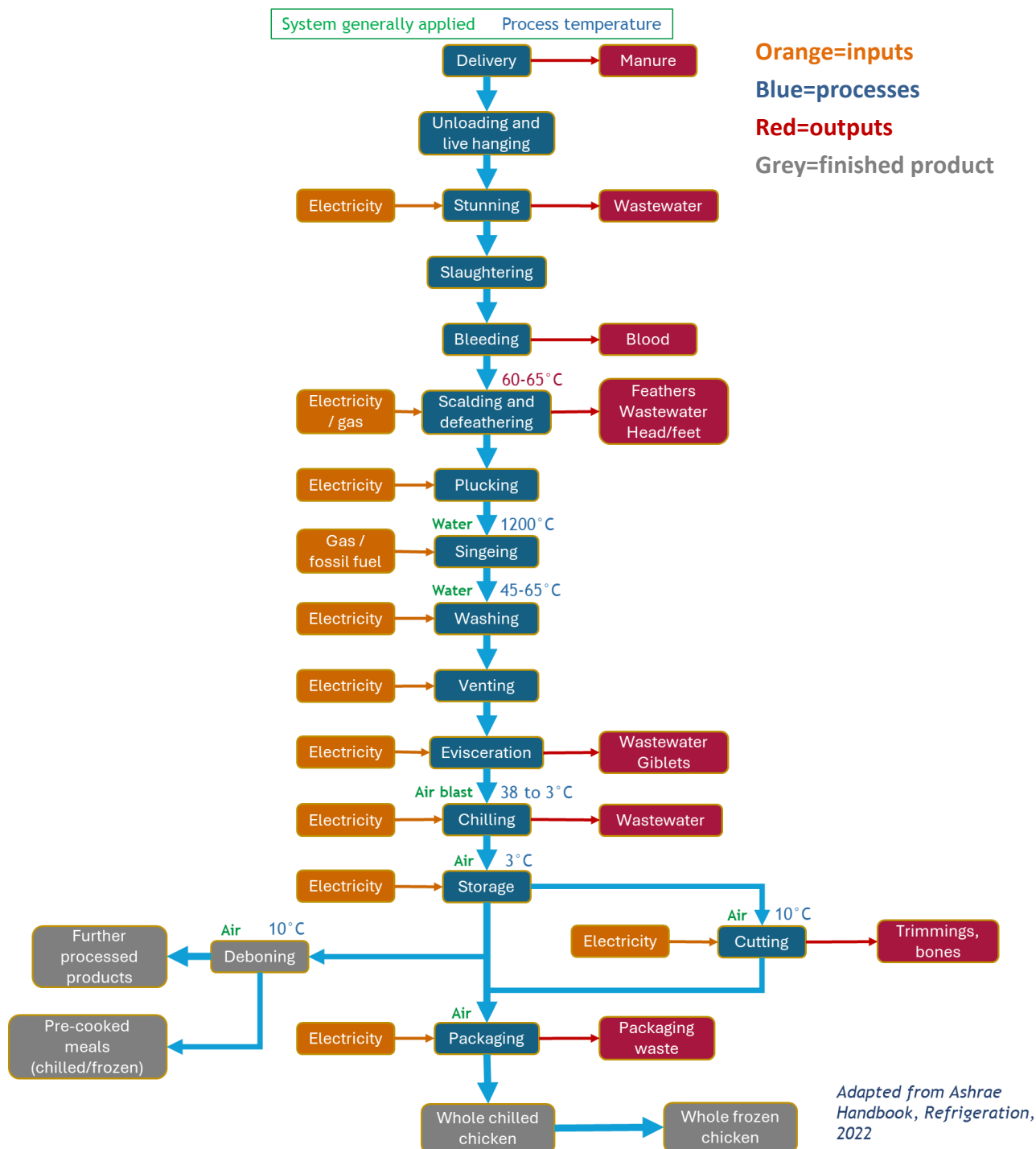


Figure 37. Typical poultry primary processing steps.

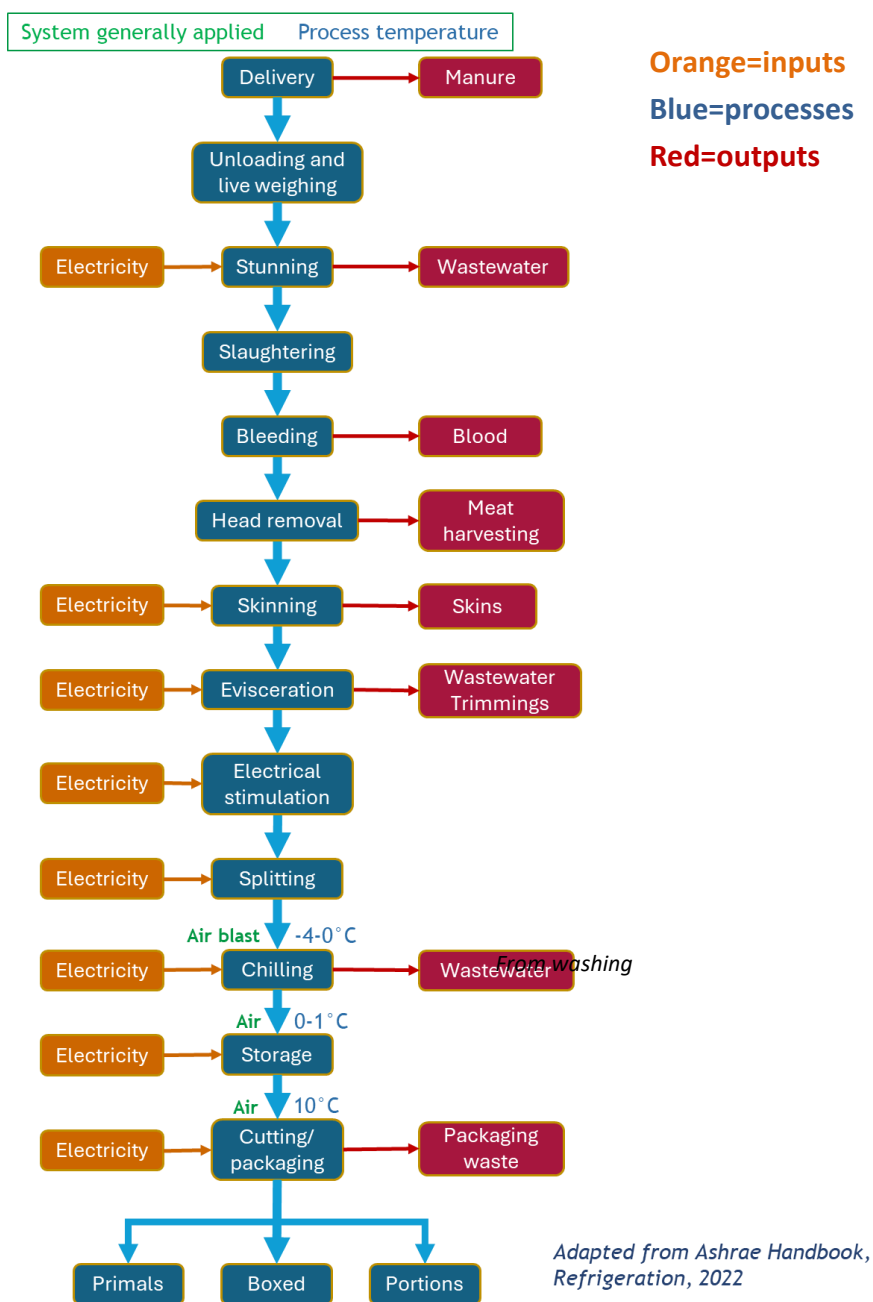


Figure 38. Typical beef primary processing steps.

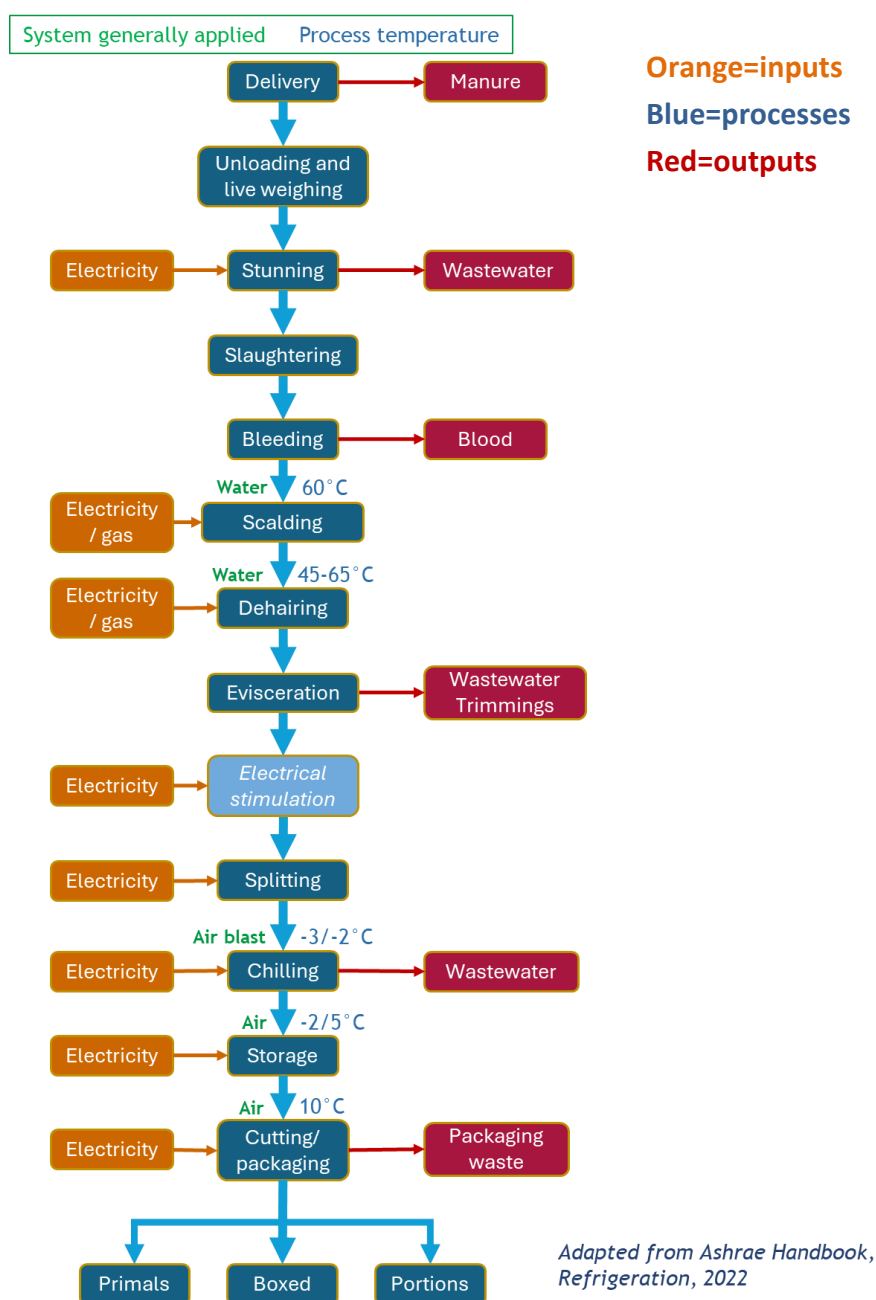


Figure 39. Typical pork primary processing steps.

8.1.2 Fish processing

The typical primary processing steps for Atlantic mackerel are illustrated in Figure 40. This includes the delivery of fresh catches from fishing vessels and the subsequent production of frozen, whole (round) mackerel packed in 20 kg cardboard boxes. Figure 40 presents the processing steps for canned mackerel in tomato sauce, based on frozen raw material sourced from a primary processing facility.

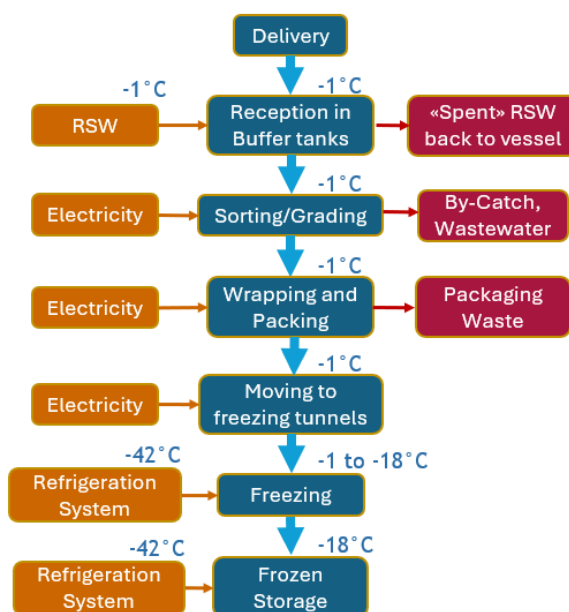


Figure 40: Typical primary processing of Atlantic mackerel.

8.1.3 Dairy processing to produce cheese

Generally raw milk is received in the dairy transferring it in a bulk storage. The milk can be separated from cream to standardise the content in terms of fat content. Milk will follow a precise heat treatment according to the type of milk that will be processed: High temperature short time (HTST), UHT, pasteurised etc. Homogenisation is the next unit operation, where the fat globules need to be reduced to a size < than 0.7µm. For pasteurised milk the process is presented in Figure 41.

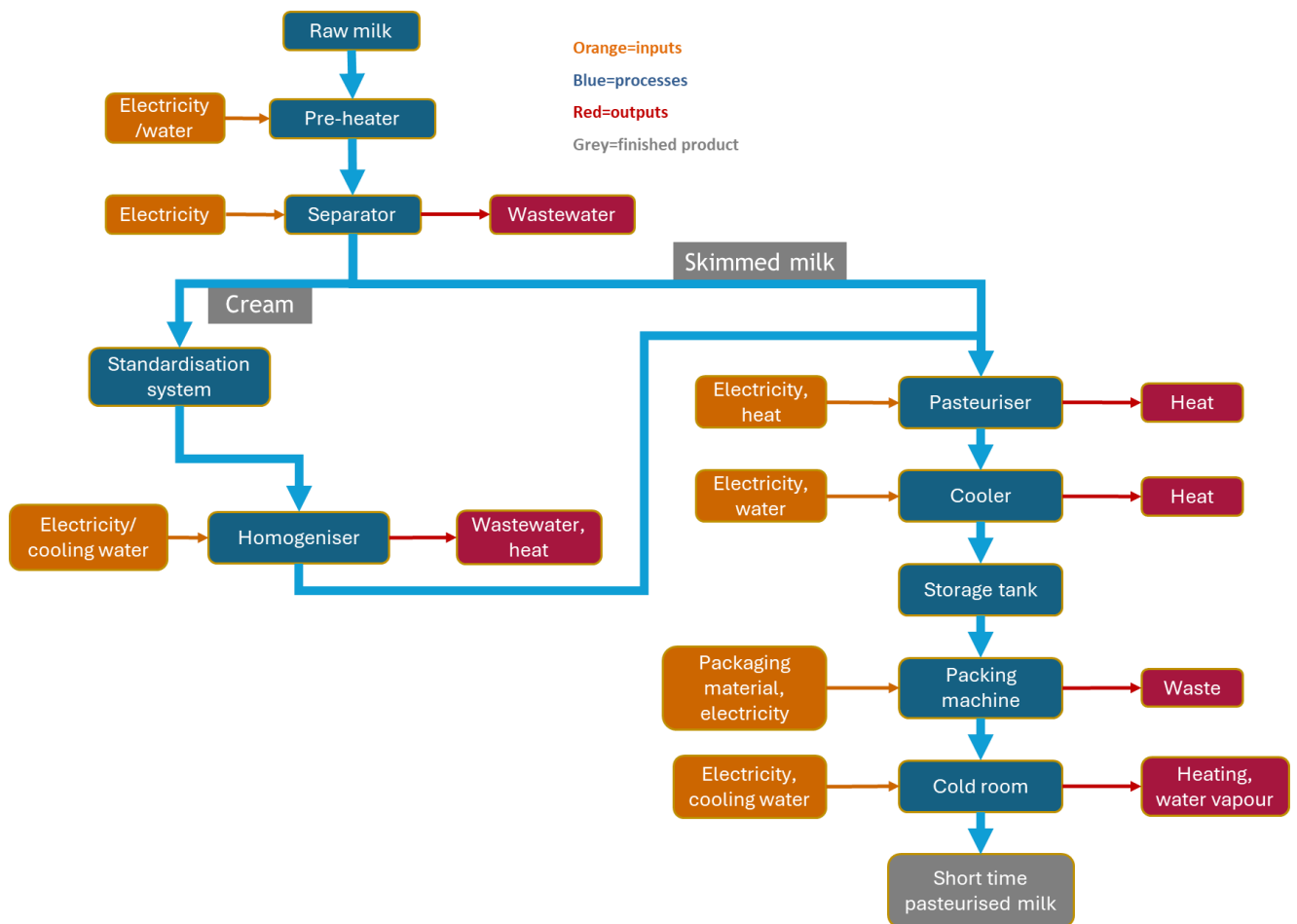


Figure 41. Short-time pasteurised milk process.

When manufacturing cheese there are a very wide range of processes according to the type of cheese. Typically, the process entails production of a coagulum thanks to the action of rennet and acid lactic, separation of the resulting curds from the whey, manipulation of the curds to produce the desired characteristics of the type of cheese (Figure 42). Traditionally cheese manufacture was a manual process but now is more automatised. After adding starter cultures to the milk, lactic acid is generated, and rennet is used to coagulate the protein. The curd is then cut into pieces and treated in a different way according to the recipe. The blocks are salted and wrapped to protect them from losing moisture. The cheese is placed in a room with controlled temperature for ripening to generate taste and flavour.

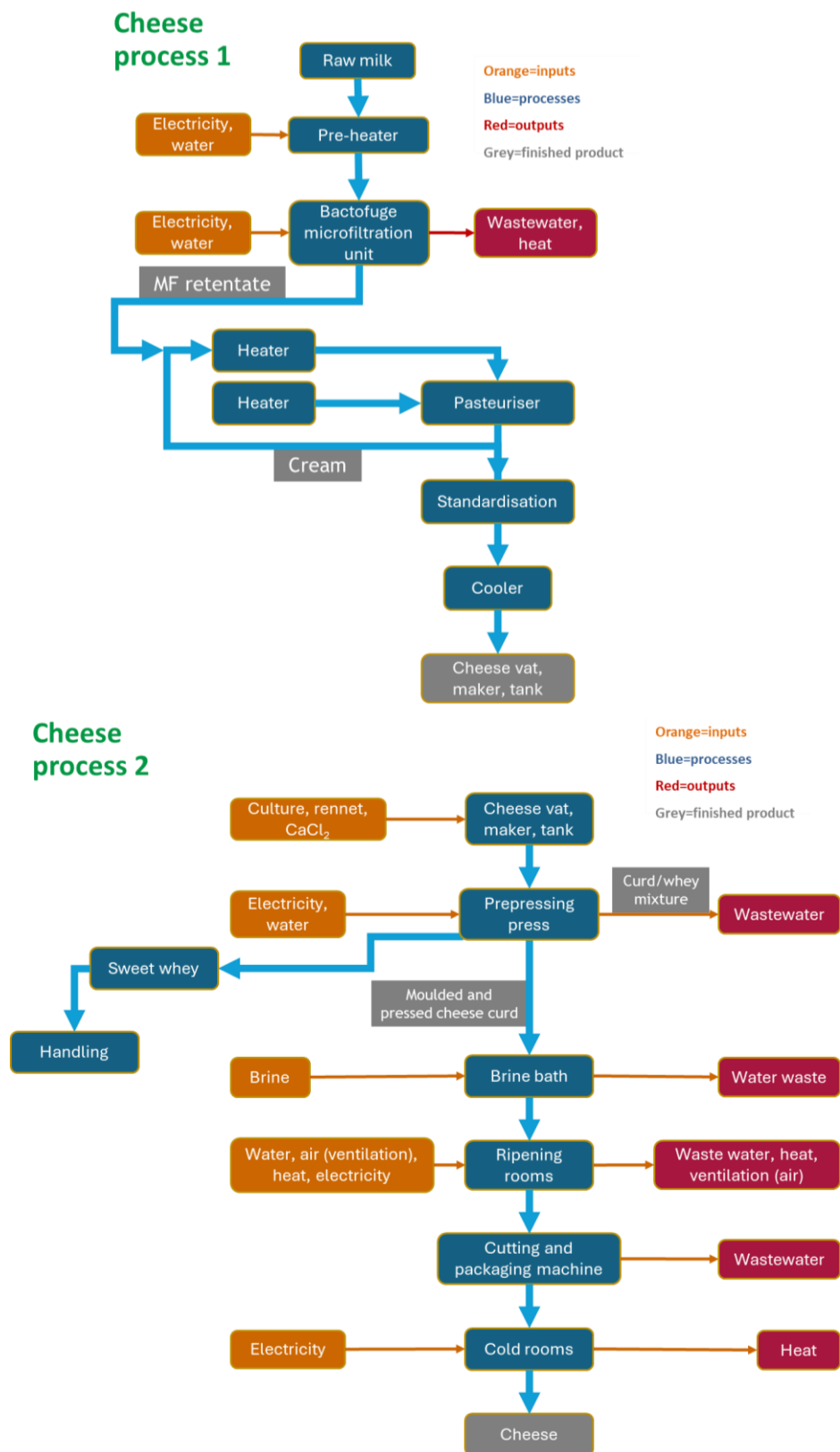


Figure 42. Manufacture of Cheese part 1 and part 2. Source German Dairy Association¹⁹¹.

¹⁹¹ German Dairy Association, Translation of extracts and additions made 2001. VDM., 1999.

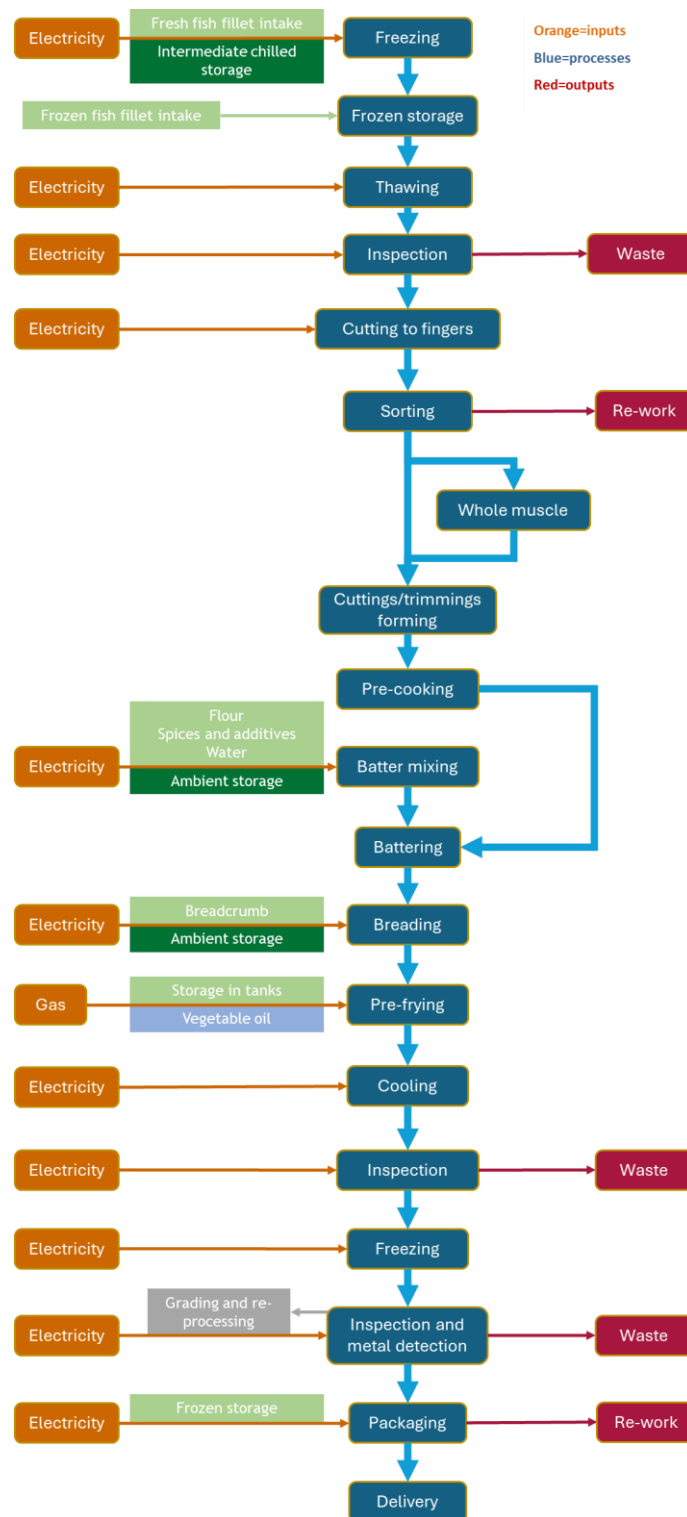


Figure 43. Flow diagram for the manufacturing of quick-frozen breaded fish fingers.

8.1.4 Secondary processing to produce composite products

For demonstrating GHG emission reduction in secondary processing, two specific composite products have been selected: breaded fish fingers and beef casserole. These products represent well-known, widely consumed meals across Europe. Their manufacturing process is neither too simple nor too complex, making them ideal for analysing the secondary food processing stages. Additionally, their popularity ensures that the findings will be relevant and applicable to a broad audience.

8.1.4.1 Fish fingers

Fish fingers are in the category of composite fish products, defined as meal or food products containing fish flesh which have undergone numeral changes such as standard scaling, gutting, filleting, freezing or brining. Such products may be manufactured from a single species of fish or from a combination of several species of fish or from mixtures of fish and other ingredients. At present the former represents about 95% of all composite fish products manufactured in Norway.

The flow diagram shown in Figure 43 illustrates the typical manufacturing of quick-frozen breaded fish fingers. Fish fingers are typically made from various species of whitefish, including cod, haddock, pollock, and hake. High quality products are cut from fresh or frozen de-boned fish fillers while the economy range is produced from frozen blocks of minced fish for forming, slicing and pre-cooking for setting the texture before battering. Breaded fish fingers are usually deep-fried in vegetable oil for a short period to set the coating and partially or fully cook the product. The fingers are subsequently cooled, inspected for defects, quick frozen with high velocity air at around -40°C in a tunnel or on a belt.

8.1.4.2 Beef casserole ready meal

The industrial manufacturing process of a chilled beef casserole ready meal (Figure 44) begins with the preparation of vegetables (onions, carrots, potatoes) which are washed, peeled, and diced. Onions, garlic, and sometimes carrots are sautéed to develop flavour. Beef, if delivered frozen, is thawed and prepared for cooking which involves cutting, seasoning, dusting with flour and browning in kettles or browning pans using oil. Meat, vegetables, stock, tomato paste, herbs, and seasonings are combined in steam-jacketed kettles and simmered for a controlled time to achieve desired tenderness and flavour infusion. Cooked casserole is hot-filled and portioned using automated filling systems, then sealed still under aseptic conditions. After seal inspection, metal detection and labelling, the product is cooled rapidly to safe temperatures, stored chilled or frozen and distributed via the cold chain.

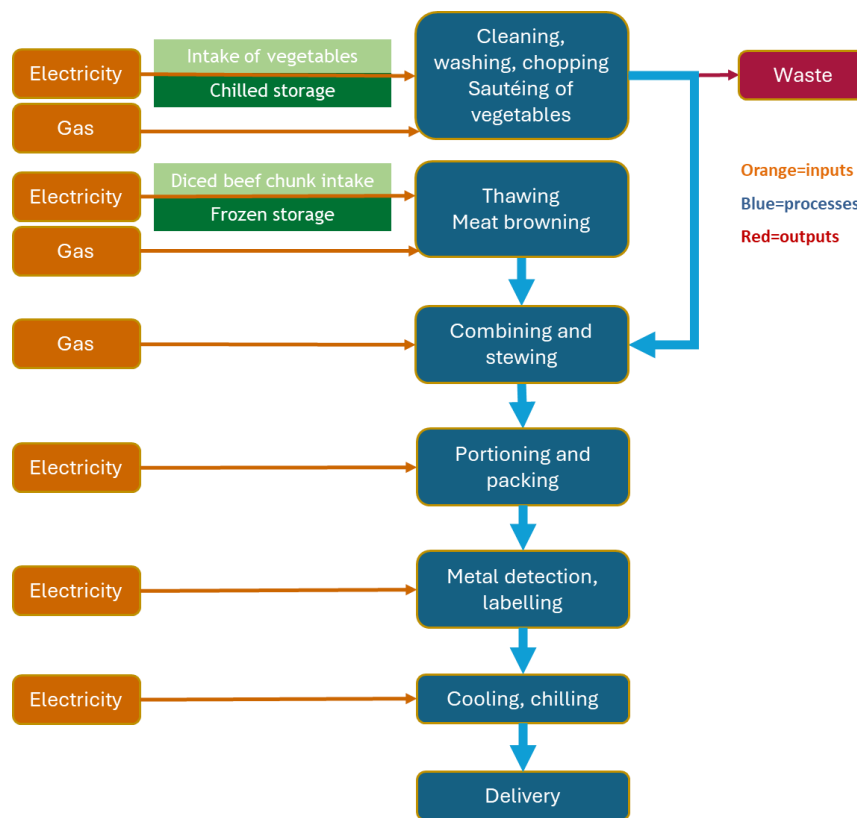


Figure 44. Flow diagram for the industrial manufacturing of chilled, ready to eat beef casserole.

9 TECHNOLOGIES/STRATEGIES

The focus of this report is to assess the technologies and strategies available to the food processing sector to reduce their carbon emissions. This covers the emissions that they generate today and also how emissions moving forward to 2050 could be reduced to ultimately assess how a processing facility could reduce their carbon emissions. This covered technologies that could be applied to the refrigeration, heating and other processing systems.

GHG saving technologies/strategies were identified and listed. In total 54 technologies and strategies were reviewed (see [Detailed technology/strategy reviews](#)). Technologies/strategies were only included if they had the potential to reduce GHG emissions. A comprehensive review of each technology was carried out and any references listed. The reviews included published information (peer reviewed papers, conference papers, grey literature) and information obtained directly from manufacturers of the equipment and personal experience and provided a critical assessment of the validity of the information. The proportion of GHG emissions that a technology could save and any constraints around the use/application of the technology were reported. In addition, the cost for application of the technology and the technology readiness level (TRL) level were listed if available. If a technology was not currently available, the approximate time until it could be deployed was estimated (Table 11).

Table 11. Review summary information included at the end of each review.

Information	Comments
Scope 1 emissions savings (% or another quantifiable metric)	Overall savings that the review indicated.

Information	Comments
Quality of scope 1 emissions information	How robust is the available information?
Scope 2 emissions savings (% or another quantifiable metric)	Overall savings that the review indicated.
Quality of scope 2 emissions information	How robust is the available information?
TRL level	Marked as: TRL1-4 TRL5-7 TRL8-9 TRL 1 - basic principles observed TRL 2 – technology concept formulated TRL 3 – experimental proof of concept TRL 4 – technology validated in lab TRL 5 – technology validated in relevant environment TRL 6 – technology demonstrated in relevant environment TRL 7 – system prototype demonstration in operational environment TRL 8 – system complete and qualified TRL 9 – actual system proven in operational environment
Maintainability issues	Any relevant issues are listed.
Legislative concerns	Any relevant issues are listed.
Payback time (years)	Time to recover cost of technology. This is equal to the saving in electrical energy per year divided by the cost of the technology. It does not include other ongoing costs, e.g., maintenance, cost of finance etc.

Table 12. List of technologies/strategies assessed, when they can be applied and the type of emission saving.

Ref	Technology	TRL level	MEAT Where applied:		FISH Where applied:		DAIRY Where applied:		2ndry PROCESS Where applied:		Carbon savings		
			Retrofit	New	Retrofit	New	Retrofit	New	Retrofit	New	Scope 1	Scope 2	Scope 3
	Refrigeration												
12.1.1	Air cycle (reverse Brayton cycle) refrigeration (low temperature only)	7		✓		✓		✓		✓	✓	✓	
12.1.2	Ambient cooling	9							✓	✓	✓ (only if remove refig. equip)	✓	
12.1.3	Antifreeze proteins	4-5						✓ (ice cream)				✓	
12.1.4	Cold recovery on LNG driven fishing vessels (fish)	8-9				✓					✓	✓	
12.1.5	Dehydrofreezing	9								✓		✓	
12.1.6	Electrostatic field freezing	5-6		✓		✓		✓		✓		✓	
12.1.7	Heat pipes	4		✓		✓		✓		✓		✓	
12.1.8	Hydrofluidisation	9		✓		✓				✓		✓	
12.1.9	Ice bank chilling	9						✓				✓	
12.1.10	Ice nucleation proteins (INPs)	7-8						✓ ice cream)				✓	
12.1.11	Impingement cooling/freezing	9		✓		✓		✓		✓		✓	
12.1.12	Localised cooling	9		✓		✓		✓		✓		✓	
12.1.13	Magnetic field freezing/ Cell Alive System (CAS)	5-6		✓		✓		✓		✓		✓	
12.1.14	Superchilling	7-9		✓		✓		✓		✓		✓	

Ref	Technology	TRL level	MEAT Where applied:		FISH Where applied:		DAIRY Where applied:		2ndry PROCESS Where applied:		Carbon savings		
			Retrofit	New	Retrofit	New	Retrofit	New	Retrofit	New	Scope 1	Scope 2	Scope 3
12.1.15	Supercooling	3-5		✓		✓		✓		✓		✓	
12.1.16	Ultrasound assisted freezing	6-7		✓		✓				✓		✓	
12.1.17	Vascular perfusion / infusion	7-8		✓								✓	
	Heating												
12.2.1	Automatic shutdown	8-9								✓	✓	✓	
12.2.2	Drying – novel systems	7-9						✓			✓	✓	
	Efficient oven design	1-4								✓	✓	✓	
12.2.3	Frying - efficiency improvements, novel options	6								✓	✓	✓	
12.2.4	High-pressure freezing and thawing	1-3								✓	✓	✓	
12.2.5	High-temperature heat pumps	Up to 9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
12.2.6	HPP (High Pressure Processing)	8		✓		✓		✓		✓	✓	✓	
12.2.7	High-Temperature Short-Time (HTST)	7-9								✓	✓	✓	
12.2.8	Impingement of air jets	5-9		✓		✓		✓		✓	✓	✓	
12.2.9	Improve combustion efficiency (gas/oil)	8-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
12.2.10	Improved oven control e.g. active exhaust control	4-9							✓	✓	✓	✓	
12.2.11	Keeping oven loaded	8-9							✓	✓	✓	✓	
12.2.12	Microwave/ultrasonic combination cooking	8-9							✓	✓	✓	✓	
12.2.13	Motor efficiency (fans and conveyors)	8-9	✓	✓	✓	✓	✓	✓	✓	✓		✓	

Ref	Technology	TRL level	MEAT Where applied:		FISH Where applied:		DAIRY Where applied:		2ndry PROCESS Where applied:		Carbon savings		
			Retrofit	New	Retrofit	New	Retrofit	New	Retrofit	New	Scope 1	Scope 2	Scope 3
12.2.14	Ohmic heating	6-7							✓	✓	✓	✓	
12.2.15	Recovery of exhaust heat	8-9							✓	✓	✓	✓	
12.2.16	Reduce heating up time	8-9							✓	✓	✓	✓	
12.2.17	Reduce thermal mass of tins	5-7							✓	✓	✓	✓	
12.2.18	Retorts (variable temperature control)	6							✓	✓	✓	✓	
12.2.19	Roasting - efficiency and innovative methods	9							✓	✓	✓	✓	
12.2.20	Steaming - efficiency improvements, novel options	9							✓	✓	✓	✓	
	Other												
12.3.1	Advanced evaporation technologies	8-9								✓	✓	✓	
12.3.2	Alternative fuels for fishing vessels (fish)	4-7			✓	✓					✓	✓	
12.3.3	Centrifugation	9								✓	✓	✓	
12.3.4	Compressed air optimisation	9	✓	✓	✓	✓	✓	✓	✓	✓		✓	
12.3.5	Efficient conching	7-9							✓	✓	✓	✓	
12.3.6	Efficient grinding	7-9							✓	✓	✓	✓	
12.3.7	Hot boning (meat)	8-9		✓								✓	
12.3.8	Internet of Things (IoT) and Artificial Intelligence (AI)	4-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12.3.9	Milling	7-9							✓	✓	✓	✓	
12.3.10	Polygeneration	8		✓		✓		✓		✓	✓	✓	

Ref	Technology	TRL level	MEAT Where applied:		FISH Where applied:		DAIRY Where applied:		2ndry PROCESS Where applied:		Carbon savings		
			Retrofit	New	Retrofit	New	Retrofit	New	Retrofit	New	Scope 1	Scope 2	Scope 3
12.3.11	Refining and extraction	8-9								✓	✓	✓	
12.3.12	Reverse osmosis	9						✓		✓	✓	✓	
12.3.13	Smoking	8-9		✓		✓		✓		✓	✓	✓	
12.3.14	Solar power	8-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12.3.151 2.3.15.1	Thermal energy systems (TES):												
12.3.15.1	TES integration at processing plants; low, medium and high temperature	4-9		✓		✓		✓		✓	✓	✓	✓
12.3.15.2	TES integration on fishing vessels (fish)	4-9		✓		✓		✓		✓	✓	✓	✓
12.3.16	Utilisation of processing wastes	3-9		✓		✓		✓		✓	✓	✓	✓
	Ancillaries												
12.4.1	Building fabric optimisation	7-9		✓		✓		✓		✓	✓	✓	✓
12.4.2	Building lighting efficiency	8-9	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

10 AVAILABLE TECHNOLOGIES/STRATEGIES WE COULD APPLY TO REDUCE ENERGY AND DECARBONISE PROCESSING FACILITIES?

The opportunities to reduce emissions from large industrial refrigeration plant are similar to those for large cold stores. Greater background information on operation of refrigeration plant and opportunities for refrigeration energy saving and carbon reduction can be found in the [Cold storage road map](#). Therefore, readers should refer to this road map for general information on how to optimise refrigeration plant performance.

10.1 Meat processing

A number of technologies are available to reduce GHG emissions from primary meat processing. These include:

- More efficient chilling – improving overall efficiency of refrigeration systems through optimised components, better maintenance and operation practices and also alternative chilling operations such as 2-stage chilling, hot boning and rapid chilling (see 12.1 and 12.3).
- Heat pumps to provide hot water for space heating, cleaning and washing that replace fossil fuels. There is also potential to use the waste heat from many meat slaughterhouses to improve the COP of heat pumps. HTHPs are also being developed and becoming more widespread on the market. The International Energy Agency (IEA) estimate that heat pumps that can achieve temperatures of 160°C will be commercially available in the next 5 years (Figure 24).
- Some slaughterhouses use air compressors and there is considerable potential to apply strategies to reduce energy and carbon emissions (see 12.3.4).
- For more challenging processes such as singeing (used in pork and poultry processing) there is less potential to electrify systems. Therefore, sustainable fuels such as green hydrogen or biomethane could be used to replace part of the natural gas (see 5.2).
- Solar power generated on site also has potential to provide heat or electricity to meat processing plants as a means to also mitigate GHG emissions (see 12.3.14).

The above technologies/strategies were applied to pork, beef and poultry slaughterhouses (excluding any rendering) in 6 European countries (France, Italy, Lithuania, Norway, Poland and the UK) to assess the potential to reduce emissions in each country. The methods by which the GHG emissions were attributed and the methods and justifications for the technologies applied are listed below. It should be noted that the model provides a general overview of the potential savings achievable across a sector of the primary meat processing industry in each country and that individual facilities may vary in their baseline fuels used, their current processes and proportion of energy attributed to each individual process.

10.1.1 Assumptions applied to carbon reduction model

Overall emissions for food processing sector in each country were obtained from the ENOUGH top-down model developed in work package 1 (

Table 13). Based on data from FoodDrinkEurope an assumption was made that the meat industry is responsible for 4.3% of the total food processing emissions¹⁹².

¹⁹² Decarbonisation road map for the European food and drink manufacturing sector. A report for FoodDrinkEurope. ED14569, Issue number 1, Date 07/07/2021.

Table 13. Carbon emissions of food processing sector from the ENOUGH top-down model.

	France	Hungary	Italy	Lithuania	Norway	Poland	UK
	Total in MtCO ₂ e						
Scope 1 (ex.fugitive)	8.56	0.81	5.14	0.24	0.41	4.88	6.05
Scope 1 fugitive	0.85	0.08	1.30	0.08	0.00	0.73	0.51
Scope 2	2.02	0.64	4.90	0.06	0.11	5.70	2.5

Ramírez et al¹⁹³ state that pigs, chicken and cattle together are the source of 88% of all boned meat. Therefore, total emissions were attributed according to the figures of Aan Den Toorn et al¹⁹⁴ with scope 1 and 2 emissions attributed between species as 33.2% being associated with pork, 42.4% with poultry and 12.4% with beef.

Data from Infomil¹⁹⁵, European Commission¹⁹⁶, Pontoppidan et al¹⁹⁷ and Ramirez et al¹⁹³ was averaged to create a percentage of energy used for each individual process. Processes were divided into those that used electricity (scope 2) and those that used other fuels (scope 1) which were assumed to be fossil fuels as a baseline (Figure 45).

A carbon intensity of 0.184 kgCO₂e/kWh was assumed for LPG and electrical grid carbon intensities for all countries from the ENOUGH top-down model were projected through to 2050 using the projections from Enerdata (EnerBlue scenario) (Figure 46).

Fugitive emissions were calculated by applying the current European F-gas phase down requirements.

An assumption was made that facilities had already transitioned to LED lights, and so further efficiencies were not considered.

Each process for each meat species was assessed and an alternative technology applied with the assumptions shown in Table 14.

Predicted carbon reductions were compared to a 1990 baseline. This was generated from UNFCCC data¹⁹⁸ using all industrial (2) for scope 1 emissions and public electricity and heat (1.A.1.a) for scope 2 emissions. Data from 1990 and 2019 were compared and the pro rata difference in emissions for each country was applied to the baseline top-down model data used in the model.

¹⁹³ Ramirez, C.A., Patel, M. and Blok, K., 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. *Energy*, 31(12), pp.2047-2063.

¹⁹⁴ Aan Den Toorn, S.I., Van Den Broek, M.A. and Worrell, E., 2017. Decarbonising meat: Exploring greenhouse gas emissions in the meat sector. *Energy Procedia*, 123, pp.353-360.

¹⁹⁵ Infomil, 1996. Meat industry (vleesindustrie). Informatieblad. De Haag: Infomil [in Dutch].

¹⁹⁶ European Commission - EC., 2003. Integrated pollution prevention and control. Draft reference document on best available technologies in the slaughterhouses and animal by-products industries. Final draft. Brussels. See also: <http://eippcb.jrc.es/pages/BActivities.cfm>.

¹⁹⁷ Pontoppidan, O., Hansen, P., 2001. Cleaner technology in the poultry and cattle slaughtering branch. Project report (renere teknologi på svine-og kreaturslagterier Resume-rapport). Environmental report No. 9, Danish EPA [in Danish]. See also: <http://www.mst.dk/udgiv/publikationer/2000/87-7944-306-0/html/>.

¹⁹⁸ https://di.unfccc.int/detailed_data_by_party.

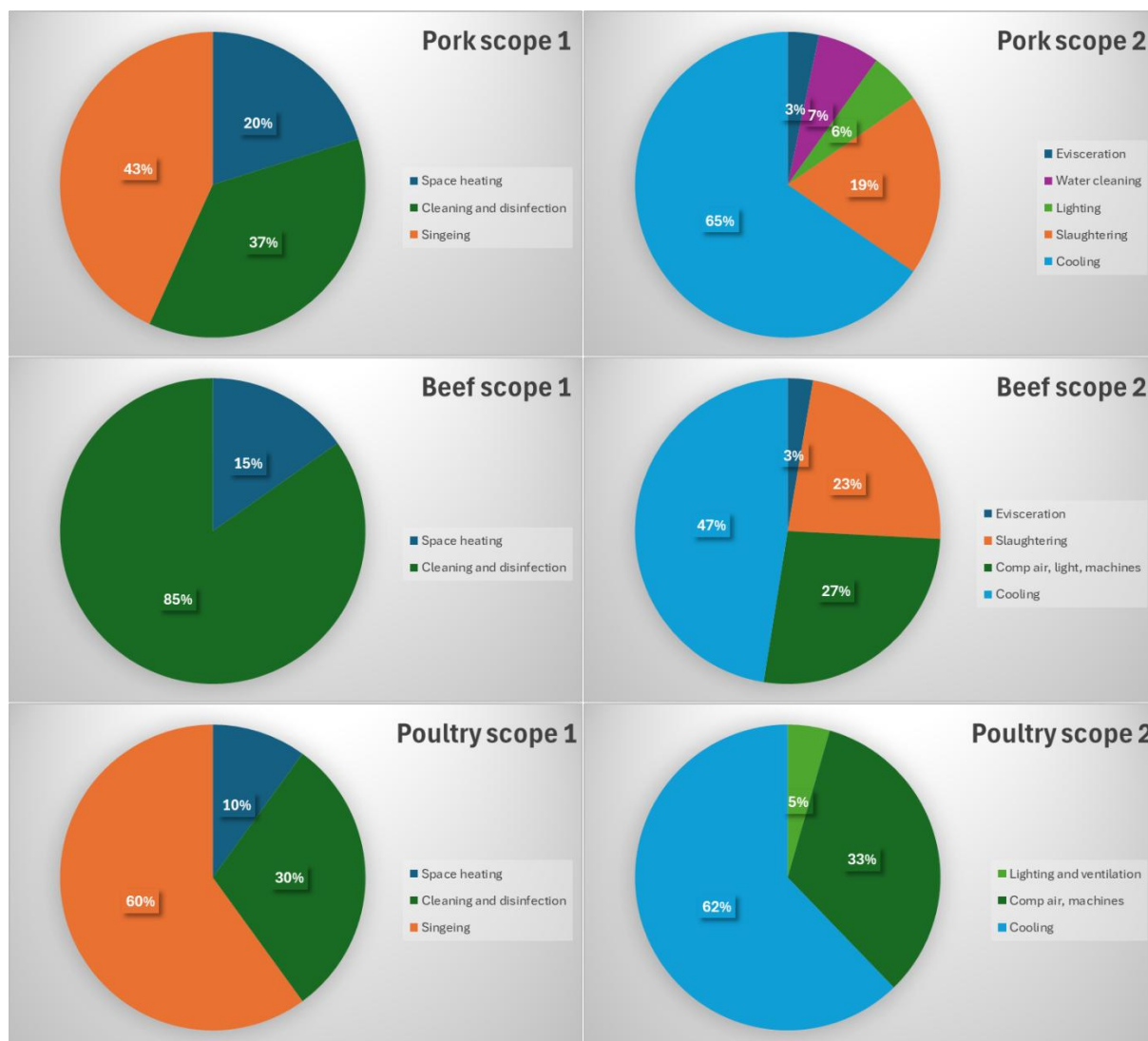


Figure 45. Proportion of carbon attributed across each process for each meat type.

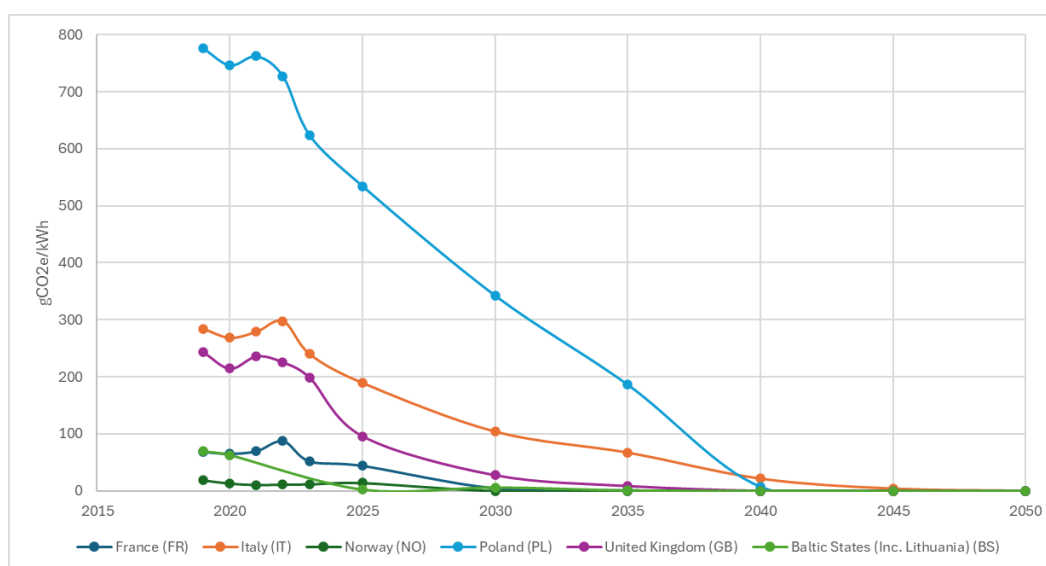


Figure 46. Grid carbon intensity for the 6 countries considered.

Table 14. Assumptions applied to each meat process in model.

Assumptions apply to all meats in all countries unless stated. All lighting assumed to already be LED and so further efficiencies were not considered.

Process	Where applied	Fuel baseline/replacement	Assumptions
More efficient chilling	Pork, poultry and beef	Electricity	2% saving/year up to total of 30%, starting in 2020
Standard heat pumps for cleaning and disinfection and water cleaning	Pork, poultry and beef cleaning and disinfection Pork water cleaning	Electricity to replace LPG in cleaning and disinfection. Electricity to replace resistive heating in water cleaning.	COP of 2.2 applied (temp lift of 70°C, from Annex 57) LPG oiler efficiency of 90% Replacement over 10 years starting in 2020
Standard heat pumps with heat reclaim (as above)	Pork, poultry and beef cleaning and disinfection Pork water cleaning	Electricity to replace LPG	COP of 4 applied (temp lift of 40°C, from Annex 57) LPG oiler efficiency of 90% Replacement over 10 years starting in 2020
Standard heat pumps for space heating	Pork, poultry and beef	Electricity to replace LPG	COP of 5 applied (temp lift of 30°C, from Annex 57) LPG boiler efficiency of 90% Replacement over 10 years, 20% application in 2019 with 10% increase in uptake/year
Air compressors	Poultry and beef	Electricity	12% relatively simple to apply immediately (in 2020), more advanced additional savings of 4% increase/year up to a maximum of 40% savings
Green hydrogen (20% mix) to replace singeing	Pork and poultry	Hydrogen to replace LPG	20% H ₂ added to natural gas from 2030 ¹⁹⁹ Green hydrogen emissions of 0.011 kg CO ₂ e/kWh applied ²⁰⁰ Biomethane emissions (generation from AD) of 0.012 kg CO ₂ e/kWh applied ²⁰¹

¹⁹⁹ Zhao, Y., McDonell, V. and Samuelson, S., 2019. Influence of hydrogen addition to pipeline natural gas on the combustion performance of a cooktop burner. International Journal of Hydrogen Energy, 44(23), pp.12239-12253.

²⁰⁰ Rivera, X.C.S., Topriska, E., Kolokotroni, M. and Azapagic, A., 2018. Environmental sustainability of renewable hydrogen in comparison with conventional cooking fuels. Journal of cleaner production, 196, pp.863-879.

²⁰¹ Bakkaloglu, S. and Hawkes, A., 2024. A comparative study of biogas and biomethane with natural gas and hydrogen alternatives. Energy and Environmental Science, 17(4), pp.1482-1496.

Process	Where applied	Fuel baseline/replacement	Assumptions												
Biomethane to replace singeing	Pork and poultry	Biomethane to replace LPG	5% now substituted into gas network, 1% increase/yr up to a maximum according to the country Marconi²⁰². The following maximums were applied: <table><tr><td>FR</td><td>IT</td><td>NO</td><td>POL</td><td>UK</td><td>LITH</td></tr><tr><td>15%</td><td>15%</td><td>8%</td><td>35%</td><td>10%</td><td>20%</td></tr></table> Biomethane generation from AD (mean emissions of 0.1 kg CO₂e/kWh applied²⁰³	FR	IT	NO	POL	UK	LITH	15%	15%	8%	35%	10%	20%
FR	IT	NO	POL	UK	LITH										
15%	15%	8%	35%	10%	20%										
Solar photovoltaic (PV) to mitigate electricity use	Pork, poultry and beef	Electricity	Solar panel output values for the six locations from RETscreen, based on a 15° slope, 0° azimuth, and 15% efficiency. The following figures were used: <table><tr><td>Paris (France)</td><td>154.21 kWh/year.m²</td></tr><tr><td>Rome (Italy)</td><td>226.45 kWh/year.m²</td></tr><tr><td>Kaunas (Lithuania)</td><td>162.44 kWh/year.m²</td></tr><tr><td>Oslo (Norway)</td><td>142.18 kWh/year.m²</td></tr><tr><td>Warsaw (Poland)</td><td>156.1 kWh/year.m²</td></tr><tr><td>London (UK)</td><td>144.8 kWh/year.m²</td></tr></table> Number of abattoirs in each country estimated from Passantino²⁰⁴ Abattoir roof size from measurements of a range of UK abattoirs 50% of roof used for solar panels Replacement over 10 years, 30% application in 2019 with 10% increase in uptake/year (based on industry data)	Paris (France)	154.21 kWh/year.m ²	Rome (Italy)	226.45 kWh/year.m ²	Kaunas (Lithuania)	162.44 kWh/year.m ²	Oslo (Norway)	142.18 kWh/year.m ²	Warsaw (Poland)	156.1 kWh/year.m ²	London (UK)	144.8 kWh/year.m ²
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Warsaw (Poland)	156.1 kWh/year.m ²														
London (UK)	144.8 kWh/year.m ²														

²⁰² Marconi, P. and Rosa, L., 2023. Role of biomethane to offset natural gas. Renewable and Sustainable Energy Reviews, 187, p.113697.

²⁰³ Guilera, J., Filipe, M., Montesó, A., Mallol, I. and Andreu, T., 2021. Carbon footprint of synthetic natural gas through biogas catalytic methanation. Journal of Cleaner Production, 287, p.125020.

²⁰⁴ https://www.researchgate.net/publication/225136367_Welfare_of_animals_at_slaughter_and_killing_A_new_regulation_on_the_protection_of_animals_at_the_time_of_killing.

10.1.2 Potential carbon reductions

Overall carbon savings for pork, poultry and beef processing in all 6 countries between 2019 and 2050 are presented in Figure 47. Compared to 1990 (obtained from https://di.unfccc.int/detailed_data_by_party, scope 1 from all industrial (2), scope 2 from public electricity and heat (1.A.1.a)), the overall potential carbon reductions in 2050 are at least 75% (Figure 47). Each individual process was assessed and applied cumulatively. Results for pork are shown in Figure 48, poultry in Figure 49 and beef in Figure 50.

Of the 3 meat sectors examined, beef processing can potentially decarbonise most simply, mainly due to the limited need for natural gas and high temperature processes. Most gas processes can be transferred to an electrical process. Pork and poultry which have high temperature gas processes (singing, scalding) and are more difficult to decarbonise unless greater levels of low carbon gas substitutes can be applied to the gas grid or alternative processes are developed. For example, it may be possible to dehair pigs and using a plucking mechanism or using an electric process. However, these are not processes that are currently available and so were not assessed in the road map.

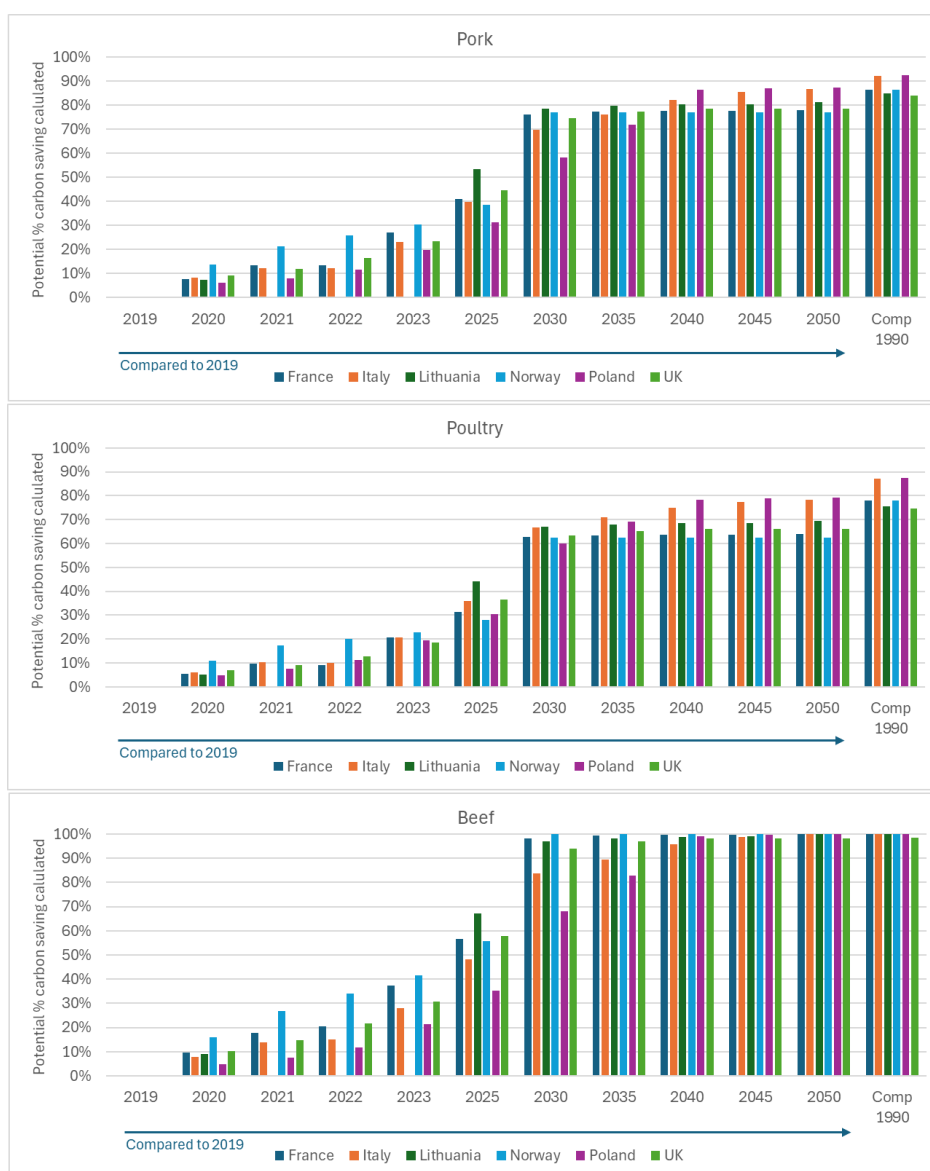
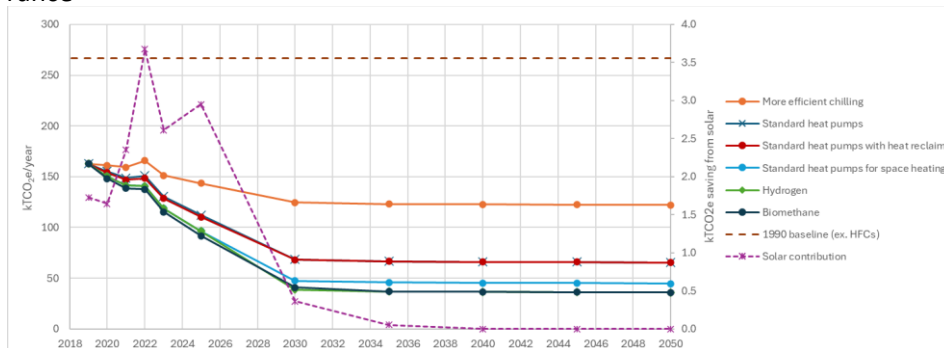
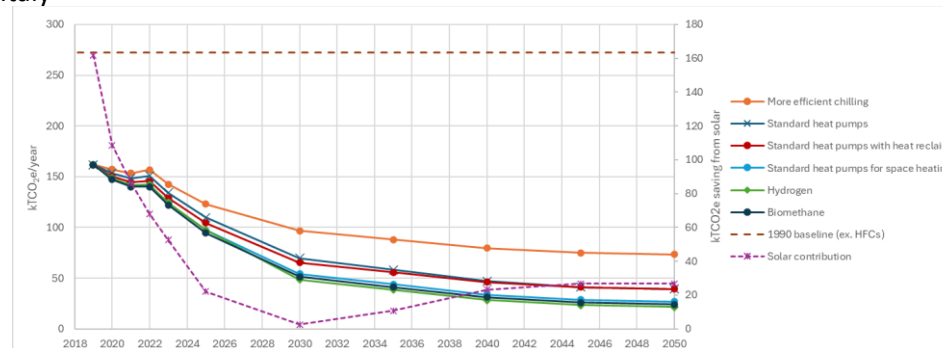


Figure 47. Carbon reduction potential for meat processing (Note: solar contribution is not included).

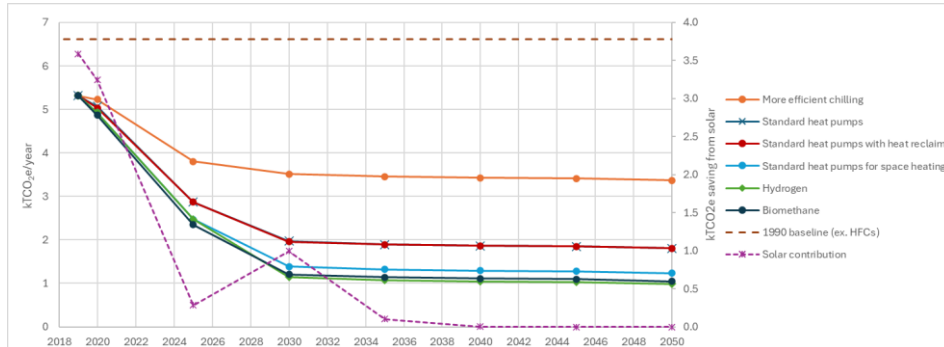
France



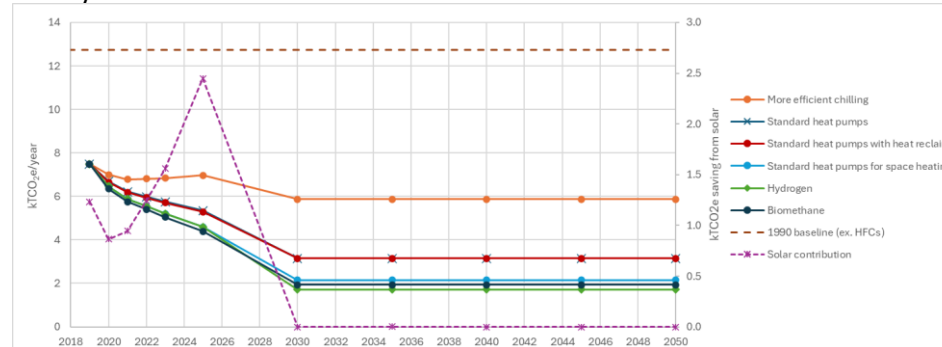
Italy



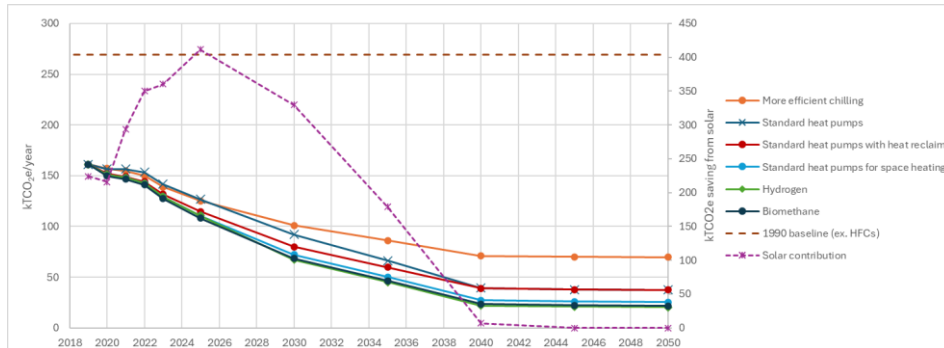
Lithuania



Norway



Poland



UK

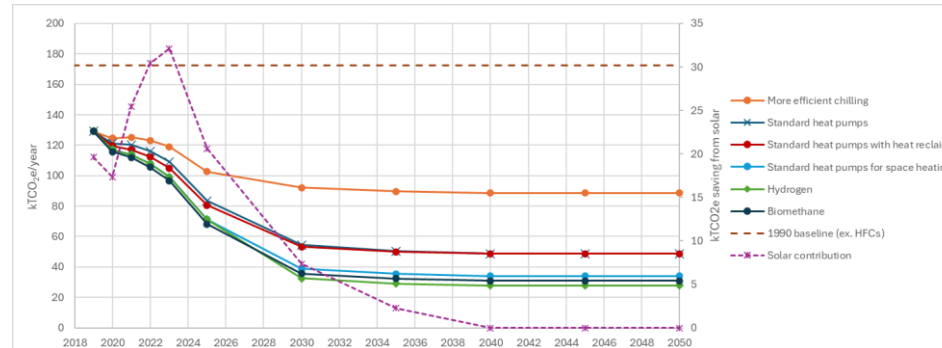
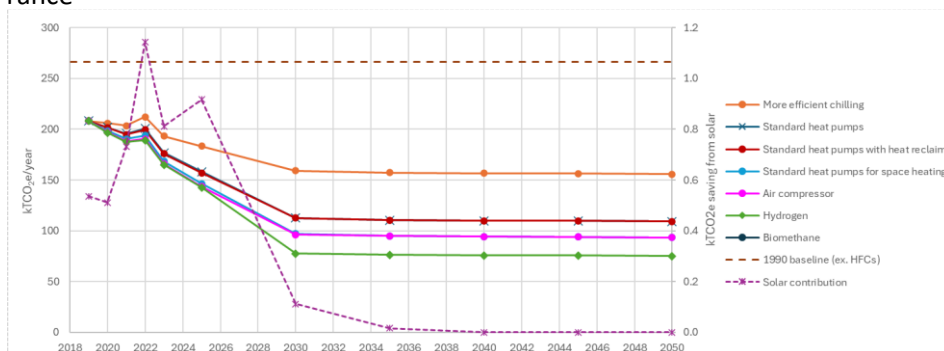
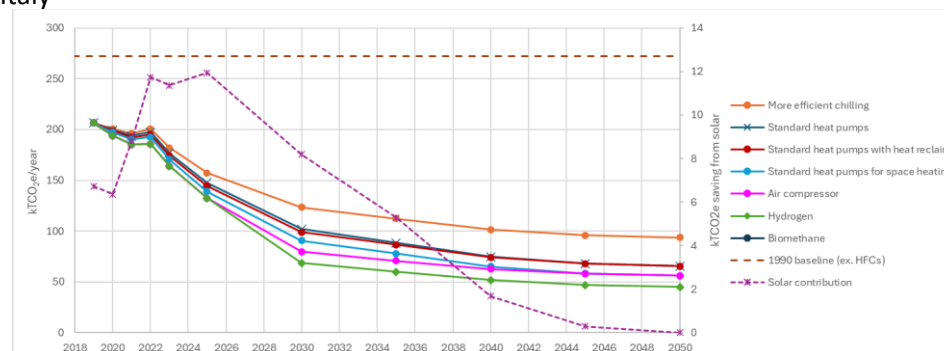


Figure 48. Potential carbon reduction for pork processing (2019 baseline).

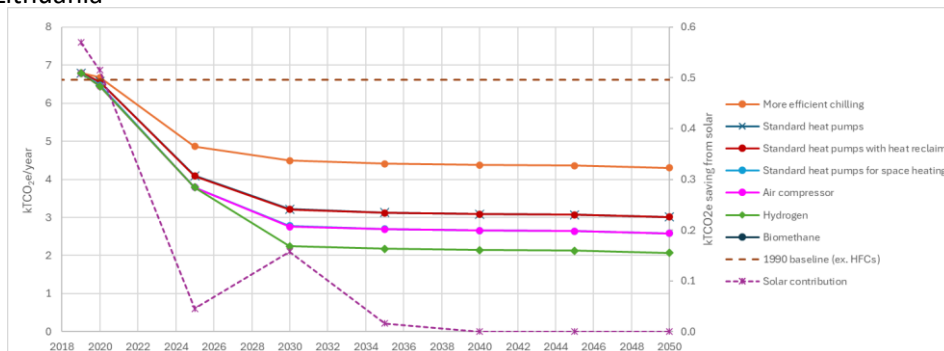
France



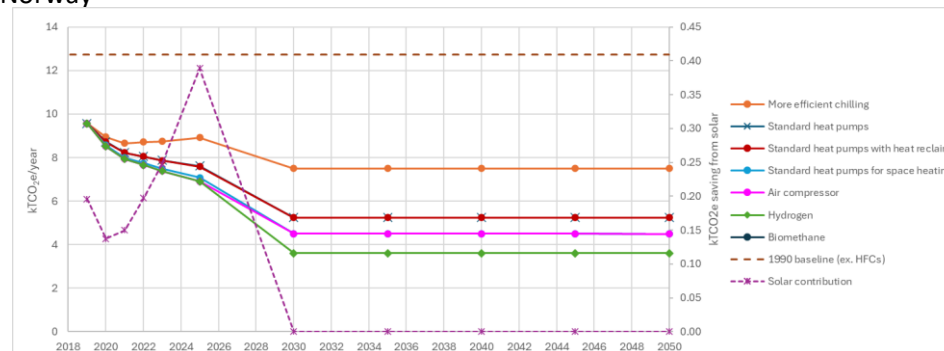
Italy



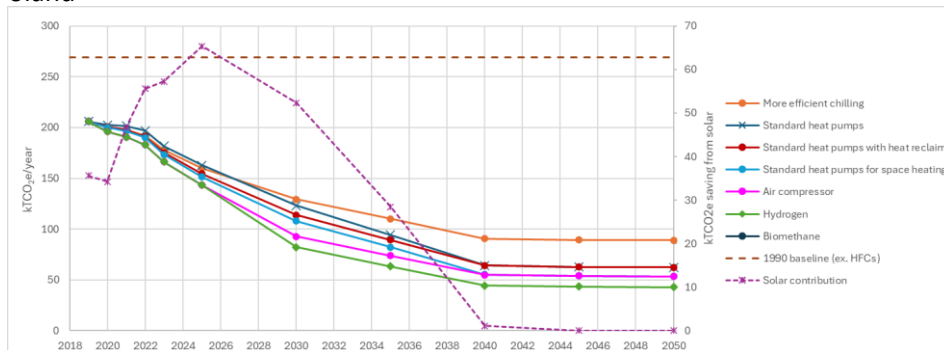
Lithuania



Norway



Poland



UK

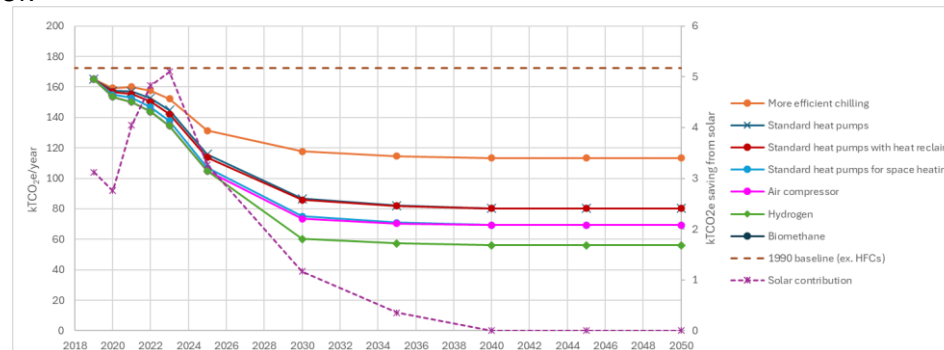
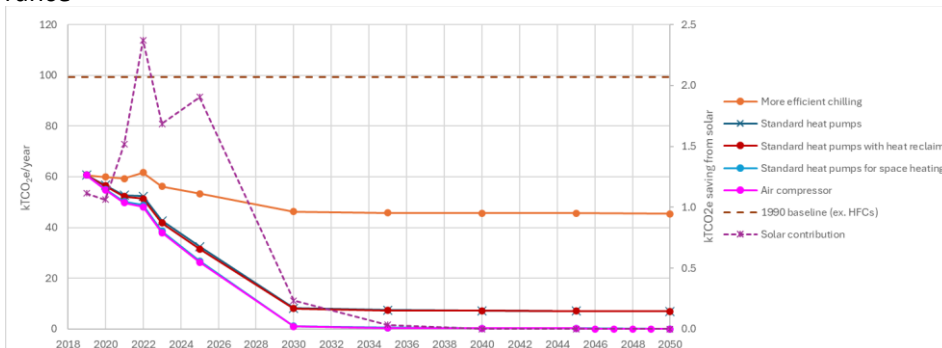
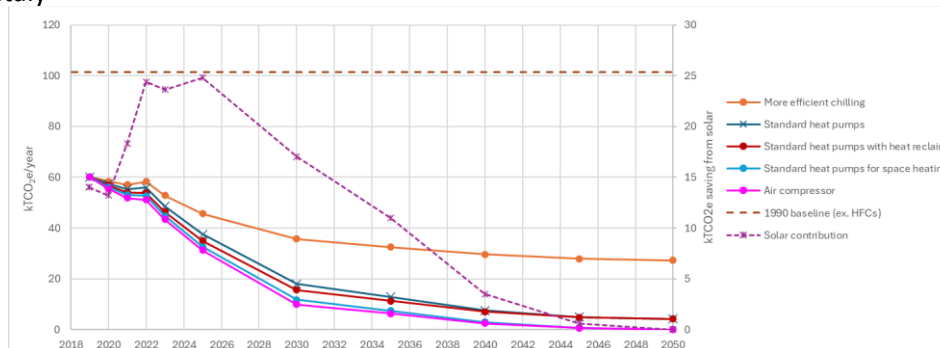


Figure 49. Potential carbon reduction for poultry processing (2019 baseline).

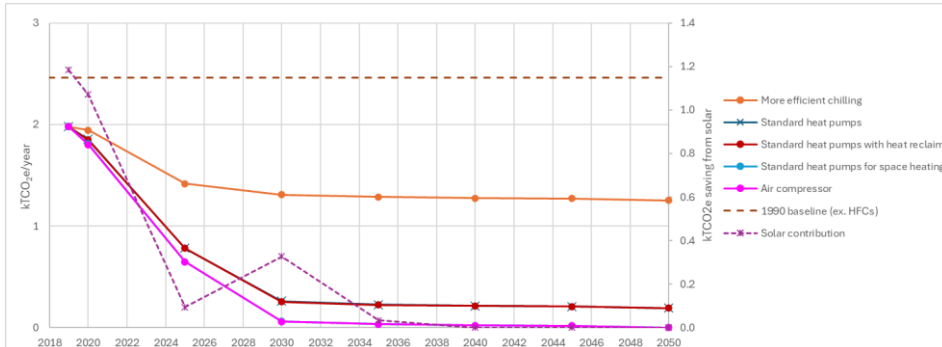
France



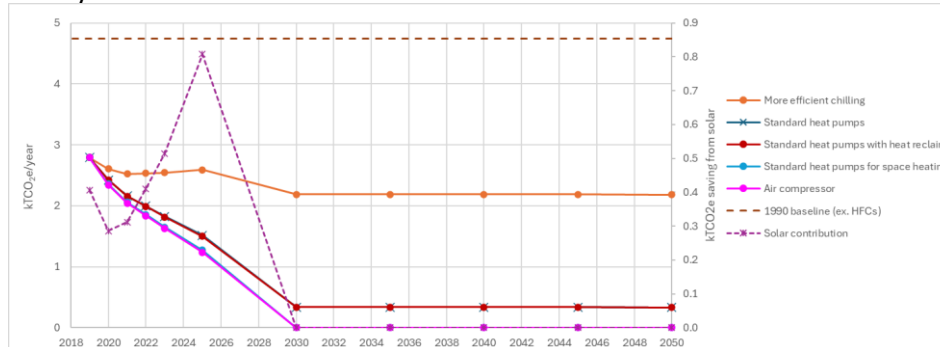
Italy



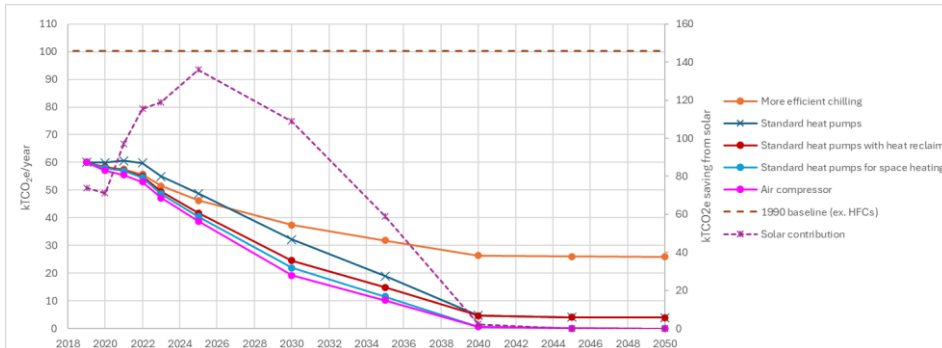
Lithuania



Norway



Poland



UK

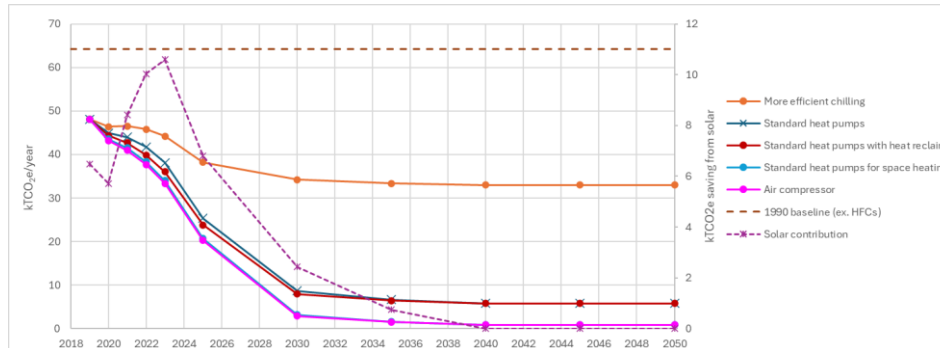


Figure 50. Potential carbon reduction for beef processing (2019 baseline).

10.2 Fish processing

Given the perishable nature of fish and the extensive thermal processing required to preserve quality and extend shelf life, it is both logical and necessary to investigate energy efficiency measures within refrigeration systems and to optimise thermal processes. Such improvements can contribute significantly to reducing overall energy consumption and associated GHG emissions. In addition, increasing the utilisation of by-products and rest raw materials (RRM) represents a key strategy, not only for improving resource efficiency, but also for reducing specific energy use. By valorising parts of the fish that would otherwise be discarded, processing plants can maximise yield, minimise waste, and improve the overall sustainability of the value chain.

A specific measure applicable to a limited number of pelagic fishing vessels involves recovering “cold energy” from onboard liquid nitrogen gas (LNG) systems, as described in chapter 12.1.4. This approach has the potential to increase the COP of the onboard refrigerated sea water (RSW) systems by 4.5–8%, which directly reduces LNG consumption and associated GHG emissions. However, the current applicability is limited, as only three fishing vessels in the fleet are equipped with dual-fuel engines capable of operating on LNG (known to the authors). Consequently, the overall energy efficiency potential at fleet level remains modest. Increased contracting of new vessels with LNG propulsion systems would enhance the future potential of this measure. Moreover, switching from marine gas oil (MGO) to LNG alone can reduce emissions by up to 20%. Table 15 presents the fuel use intensity (FUI) and specific emission factors (SEF) for European and Norwegian pelagic fishing fleet. With an average SEF of 292 g CO_{2eq}/kg fish and 1.53 MT of pelagic landings (see Table 1), a transition to LNG could result in an emissions reduction of approximately 81 kt CO_{2eq} annually. It is important to note, however, that LNG is generally considered a transitional fuel, and ongoing research and development efforts are directed toward identifying more climate-friendly alternatives as part of the broader green transition in maritime operations²⁰⁵.

Table 15: Fuel use intensity (FUI) for different fleets, gear and target species. From Jafarzadeh et al. (2016)²⁰⁶; SEF are self-calculated

Region	Gear	Target species	FUI ^A	SEF ^B
Europe	Pelagic trawl	Small pelagic	0.144	456
Norway	Trawl	Pelagic fish	0.09	285
Norway	Pelagic trawl	Blue whiting, Atlantic herring etc.	0.087	276
Norway	Purse seine	Atlantic herring, capelin etc.	0.09	285
Norway	Purse seine	Atlantic herring, capelin etc.	0.085	269
Unspecified	Coastal seiner	Atlantic herring, mackerel etc.	0.056	178

^A Fuel use intensity: kg fuel / kg fish (whole). Assumed to be 100% MGO

^B Specific emission factor: g CO_{2eq} / kg fish (whole). Calculated assuming an emission factor of 3.17 kg CO_{2eq}/kg MGO.

²⁰⁵ Gabriellii, C., Jafarzadeh, S., 2020. Alternative fuels and propulsion systems for fishing vessels (No. 2020:00977). SINTEF. <https://hdl.handle.net/11250/2684524>.

²⁰⁶ Jafarzadeh, S., Ellingsen, H., Aanondsen, S.A., 2016. Energy efficiency of Norwegian fisheries from 2003 to 2012. Journal of Cleaner Production 112, 3616–3630. <https://doi.org/10.1016/j.jclepro.2015.06.114>.

10.2.1 Pelagic processing plants

For the primary processing of mackerel and herring, freezing has been identified as the most energy-intensive operation, with refrigeration systems accounting for up to 75% of the total energy consumption in such facilities (see Figure 33). It is therefore logical to explore measures aimed at improving the refrigeration systems, the freezing process itself, or both, in order to enhance energy efficiency and reduce associated emissions.

In large-scale plants, high freezing capacity demands call for robust industrial refrigeration systems. These systems are typically based on ammonia (NH₃) and are designed for continuous, high-load operation.

Facilities with daily production capacities of around 1 kton often require installed refrigeration capacities in the range of 4–7 MW. These systems commonly use multiple compressors—usually screw compressors for base loads and reciprocating units for peak demand. Depending on the plant design, the cooling capacity may be distributed across several interconnected or independently operating systems. Evaporating temperatures can reach as low as -40°C, while condensation typically occurs around 20–25°C, with heat rejected to seawater or via rooftop evaporative condensers. Overall, these refrigeration systems are central to the plant's energy use and represent a key target for efficiency improvements. These improvements could be, but not limited to:

- **Optimised components.** For ammonia system in particular, air and water purgers are critical for maintaining high efficiency. Ammonia freezing operate under sub-atmospheric pressure, making them susceptible to air ingress, which reduce heat transfer efficiency and this overall efficiency.
- **Improved regulation/capacity control.** Several compressors are typically employed to meet the freezing demand and requires coordinated control of the compressor pack/group to allow for optimised load distribution and staging. Additionally, high-capacity screw compressors operating under variable load conditions should be regulated using VFDs rather than integrated slide valve control, which is less efficient at partial load (see Figure 51 right).
- **Pressure ratio.** The pressure ratio at which such systems operate has a significant impact on its COP. Efficiency gains can be achieved by either increasing suction pressure or lowering the condensing pressure – but possibilities are also limited and governed by process requirements and ambient conditions (see Figure 51).
- **Maintenance.** Continuous monitoring and maintenance of refrigeration systems is necessary to sustain efficiency over time, as performance tends to deteriorate gradually. Heat exchangers require periodic cleaning, pipe and wall insulation degrades and must be replaced, and refrigerant leaks may occur, all contributing to reduced system performance if not addressed.
- **Cold stores.** With daily production capacities exceeding 1,000 tons, the facilities also have large cold stores for frozen products, which could contribute significantly to overall energy consumption and related emissions. Measures to improve energy efficiency and reduce these emissions can be found in the [Cold storage road map](#).

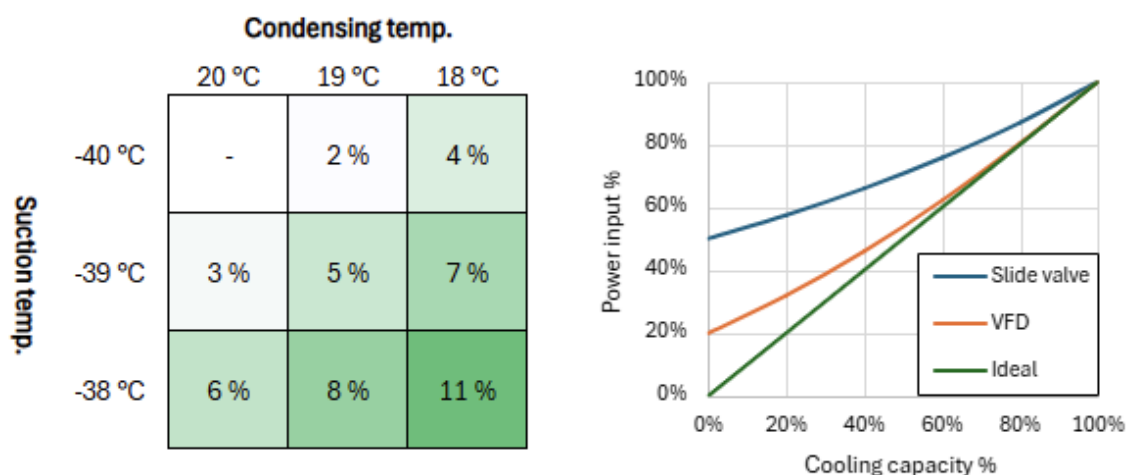


Figure 51: Left: Effect of adjusting pressure conditions on the COP of an ammonia refrigeration system (single-stage, 70% isentropic efficiency, baseline -40/+20°C). Right: Part-load efficiency of a screw compressor using slide valve or VFD regulation. Reproduced from Svendsen et al. (2025)²⁰⁷

Tunnel freezers (explained in more detail in 3.2.5.1.1) are the most commonly used freezing technology in these plants, capable of freezing large volumes of pelagic fish at a time. However, as explained in Chapter 3.2.1, air blast systems tend to have high energy consumption due to high fan loads. Potential improvements in such systems include boosting efficiency by:

- **Optimising air flow distribution.** It is assumed that a wide variety of tunnel designs are used across the industry; even within a single facility, there may be up to 10 tunnels, each with a freezing capacity of around 100 tons per day. The design of these tunnels—such as the placement of guide vanes, ceiling structures (e.g., false ceilings), air flow direction, and fan placement—significantly influences air flow distribution. Proper distribution is essential to achieve maximum heat transfer, thereby reducing freezing time and ultimately lowering energy consumption
- **Utilise full capacity.** Heat load of the product can account for about 65% of the total heat load in air blast tunnels, meaning that there is a high base load due to other sources (fans, heat ingress). This base heat load must be covered regardless of how much of the tunnels capacity is utilised, meaning that operating below full loading results in higher specific energy consumption. Therefore, ensuring full tunnel loading could improve energy efficiency (see Figure 52 right)
- **Packaging.** Pelagic fish, mackerel and herring in particular, are wrapped in plastic and frozen whole packed in standardised 20 kg cardboard boxes. Packaging in itself acts as a barrier for heat transfer, and improving the packaging in that regard could lead to lower freezing times and energy usage. A study conducted by Magnussen and Nordtvedt (2006)²⁰⁸ shows that freezing time could be reduced significantly by modifying packaging, and most so by completely removing the lid (see Figure 52 left).

²⁰⁷ Svendsen, E.S., Widell, K.N., Moen, O.M., Bless, M., Sæther, F., Patanou, E., Lunde, M., Einhjellen, L., Bjerkvik, K., 2025. Veikart for energieffektivisering i pelagisk sektor (No. 2025:00039). SINTEF (NOR).

²⁰⁸ Magnussen, O.M., Nordtvedt, T.S., 2006. ENØK i kuldeanlegget (Technical report No. TR A6287). SINTEF Energy Research (NOR).

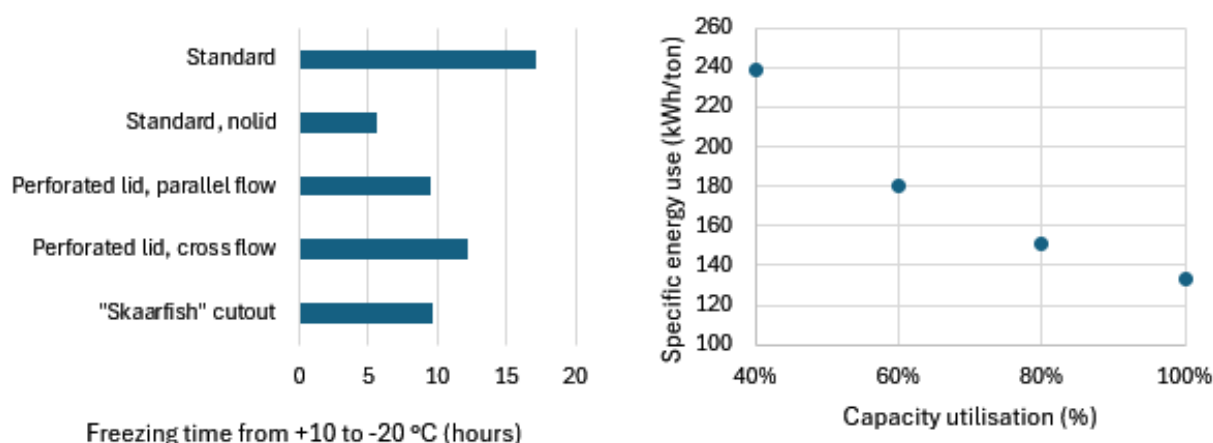


Figure 52: Left: Freezing times of mackerel in tunnel freezer by packaging modifications. Right: Theoretical calculation of specific energy use in tunnel freezer as function of capacity utilisation of the tunnel.

Another approach is to partially or fully replace tunnel freezing with alternative methods. As shown in Table 16, both plate freezing and brine freezing (explained in more detail in 3.2.5.7) enable more efficient energy use compared to tunnel systems. However, as previously mentioned, one of the main reasons tunnels are commonly used is their ability to handle large batches, which can be challenging for other freezing technologies. Horizontal plate freezers are also used in some pelagic plants, but they typically account for only a small share of the total freezing capacity. Moreover, they are more or less only suitable for filleted products, as whole round fish are prone to mechanical deformation during the process.

Table 16: List of specific energy consumption by freezing method from various literature sources.

Method	Sources	Description	SEC (kWh/ton)
Tunnel	1: Magnussen, O.M., Nordtvedt, T.S., 2006. ENØK i kuldeanlegget (Teknisk rapport No. TR A6287). SINTEF Energiforskning. 2: Cleland, D.J., Valentas, K.J., 1997. Prediction of Freezing Time and Design of Food Freezers, in: Handbook of Food Engineering Practice (ISBN 0-8493-8694-2) 3: Kolbe, E., Kramer, D., 2007. Planning for Seafood Freezing. Alaska Sea Grant.	Theoretical calculations	106-158
Tunnel	1: Unpublished results, anonymised plants.	Measured at pelagic plants (n=3)	130
Plate	1: Kolbe, E., Kramer, D., 2007. Planning for Seafood Freezing. Alaska Sea Grant. 2: Cleland, D.J., Valentas, K.J., 1997. Prediction of Freezing Time and Design of Food Freezers, in: Handbook of Food Engineering Practice (ISBN 0-8493-8694-2). 3: Verpe, E.H., Tolstorebrov, I., Sevault, A., 2019. Cold thermal energy storage with low-temperature plate freezing of fish on offshore vessels. https://doi.org/10.18462/iir.icr.2019.1168 .	Theoretical calculations	64-79
Brine	1: Kolbe, E., Kramer, D., 2007. Planning for Seafood Freezing. Alaska Sea Grant. 2: Larssen, W.E., Barnung, T., Bjørkevold, I., 2022: «Lakefrysing av hvitfisk», https://www.fhf.no/prosjekter/prosjektbasen/901580/ .	Theoretical calculations	77-80
Brine	Østvik, S.O. m.fl., 2018. Utvikling av teknologi og metode for lakefrysing av makrell (FHF 901290).	Measured, freezing of mackerel	53

Brine freezing is a particularly efficient method in which the fish is immersed in a chilled salt brine (commonly NaCl or CaCl₂), offering excellent heat transfer due to the close contact between the brine and the product, as well as the superior thermal conductivity of liquids compared to air. As part of the ENOUGH project, a demonstrator activity was conducted to adapt a brine freezing concept for mackerel, as described in Svendsen et al. (2024)²⁰⁹. A two-stage freezing process was proposed, where the first stage involved chilling mackerel from a chilled state to -5 °C in brine, followed by packing and completing the freezing cycle in a tunnel. Calculations from the study indicated that approximately 2.1 MWh of energy could be saved per 100-ton batch of mackerel, representing a total energy reduction of about 14% compared to the conventional freezing process.

10.2.2 Potential carbon reductions

To quantify the potential carbon reductions achievable in pelagic processing, the following measures have been modelled, and Table 17 outlines the assumptions and premises involved for each. Overall emissions for each country related to food manufacturing have been sourced from work carried out in WP1. According to FoodDrinkEurope, the fish processing industry accounts for 0.7% of total emissions; this figure was applied to all countries except Norway. For Norway, this share was adjusted based on energy use estimates: a recent study indicates that the energy consumption in the Norwegian fisheries sector suggests a significantly higher proportion relative to total national food production. The energy distribution within such plants is assumed to align with the breakdown shown in Figure 33. Lastly, there is assumed no change in production portfolio or volumes. The results are shown in Figure 53.

Table 17. Assumptions and premises applied for pelagic processing.

Measure	Description
BAU	Business as usual – no measures are implemented on the plant side; however, the electric grid is decarbonised in accordance with the Enerdata Blue scenario, in combination with aggressive F-gas regulations.
Efficiency of refrigeration systems	It is assumed that the current Carnot efficiency of refrigeration systems used in the European pelagic processing industry is 45%, and that this can be increased to 55% through various measures described in this section. Furthermore, it is expected that this improvement will be implemented gradually over a 20-year period, starting in 2020.
Improved freezing process	Improving the design and operation of tunnel freezers can reduce energy use by at least 5%. Modifying the current standard cardboard box could enhance heat transfer and lead to a 10% reduction in energy consumption. In this model, it is assumed that both measures will be fully adopted across the industry over a 10-year period.
Brine freezing	Replacing the current freezing process with a two-stage freezing system, including brine freezing in the first stage, could reduce energy use by 14%. It is assumed that this will become the industry standard within 10 years in this model.

²⁰⁹ 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. International Institute of Refrigeration (IIR). <https://doi.org/10.18462/IIR.ICCC2024.1029>.

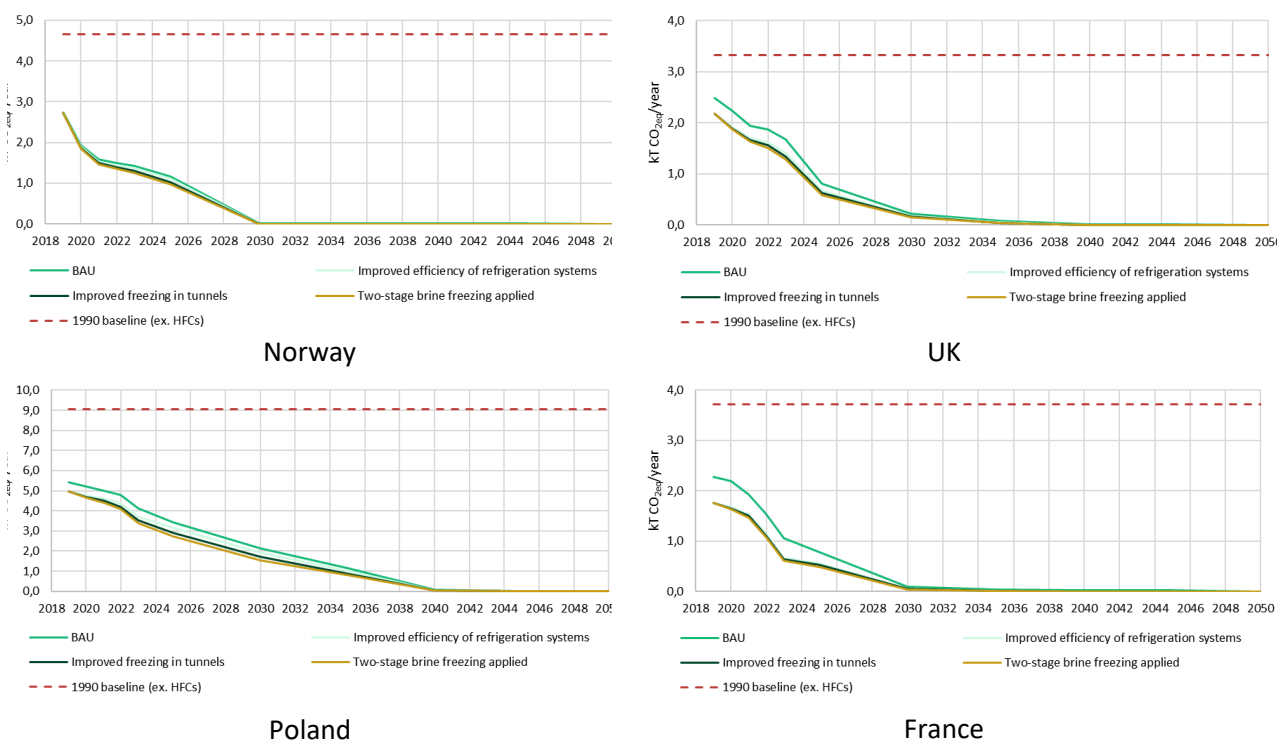


Figure 53: Potential carbon reduction for pelagic processing plants in Norway, UK, Poland and France.

When assessing the carbon reduction potential across the selected countries, results indicate that pelagic processing could be nearly fully decarbonised by 2050. This outcome is primarily attributed to the fact that such facilities are already fully electrified, combined with the use of a scenario in this model that projects full decarbonisation of national electricity grids over the coming decades. The analysis shows that grid decarbonisation is by far the most significant driver of emissions reduction, with the cumulative impact of additional measures contributing seemingly marginal in comparison. However, from a more proactive and risk-aware perspective, it is important to recognise that the projected supply-side decarbonisation embedded in this model is largely beyond the control of individual plant operators. As such, demand-side measures should still be pursued to ensure emissions reductions in this sector. Figure 54 illustrates the cumulative effect of all measures for each country, assuming no change in grid emissions.

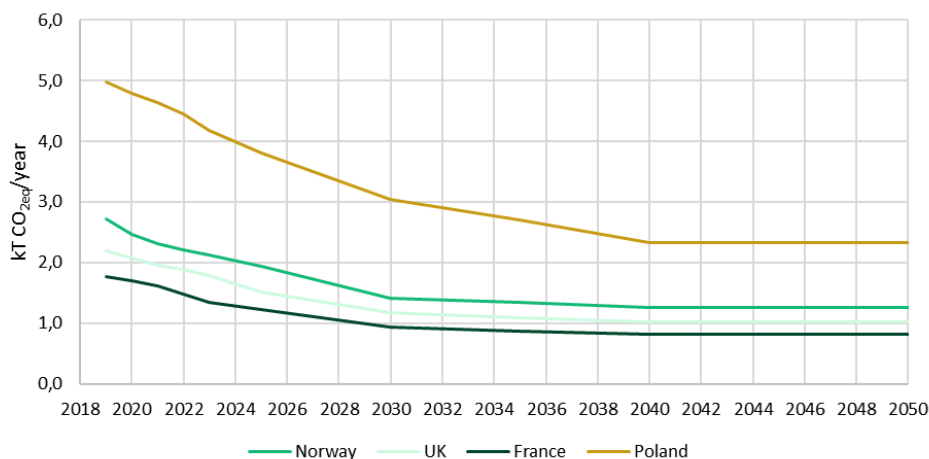


Figure 54: Potential carbon reduction for selected countries assuming no change in grid emissions.

10.2.3 HTHP in fishmeal processing

In fishmeal processing, a significant proportion of the total energy demand is attributed to thermal energy used for steam production, typically generated by burning fossil fuels such as gas or oil. Two main technological alternatives could replace these fossil-based systems: electric boilers and industrial HTHPs. Both technologies offer a direct pathway to eliminate combustion-related emissions, provided that the electricity supply is low-emission. Additionally, electric boilers offer high energy efficiency, with near 100% conversion efficiency, compared to conventional gas boilers, which typically operate at 90–95% efficiency. This makes electric boilers a technically straightforward and potentially impactful solution for decarbonising steam production in fishmeal plants. Such boilers are also commercially available and technically mature. However, their limited uptake can primarily be attributed to two key constraints: energy costs and limited grid capacity. Most Norwegian fishmeal plants have a processing capacity of 1200–1500 tonnes of raw material per day, which translates into a continuous power demand in the range of 20–30 MW for steam generation alone. This level of demand places substantial pressure on the local electricity infrastructure. In many cases, there is simply insufficient grid capacity to support the connection of high-power equipment such as electric boilers.

A more viable approach is the use of HTHPs (see chapter 12.2.5). These systems are capable of delivering heat at temperatures above 100 °C. This makes them particularly relevant for applications such as steam production in the pelagic sector, where steam pressure levels in the range of 2–10 bar are common. In recent years, there has been significant technological development in this area, and a wide range of suppliers are now offering or developing climate-friendly HTHPs designed to deliver heat at temperatures between 120 °C and 150 °C, with some systems capable of reaching up to 250 °C. Several of these technologies have reached commercial maturity (TRL 7–9) and are available on the market today, making them a promising alternative for decarbonising industrial thermal processes where direct electrification via electric boilers is constrained by limited grid capacity.

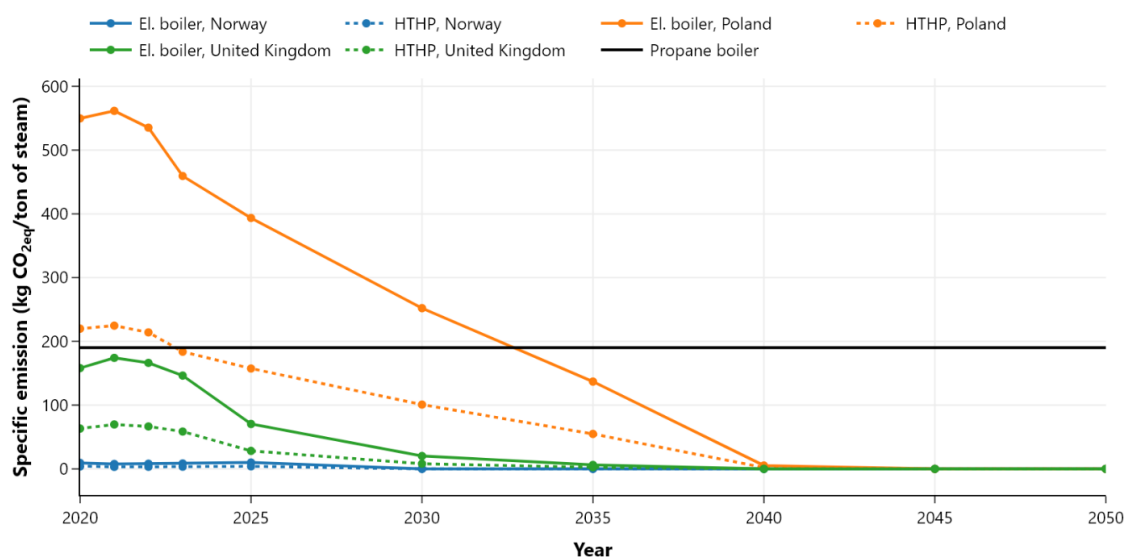


Figure 55: Specific emissions for generating 1 ton of steam with propane boiler, electrical boiler and HTHP, for Norway, UK and Poland

Figure 55 compares the emissions associated with generating 1 tonne of steam using either an electric boiler or a HTHP, based on projected grid emission factors for Norway, the UK and Poland from 2025

to 2050²¹⁰. A propane-fuelled boiler emits approximately 190 kg CO_{2e} per ton of steam, assuming a boiler efficiency of 90%. Switching to electric boilers (with 100% efficiency) would reduce emissions in regions with low-emission electricity grids. However, this is not yet the case for Poland, where current grid emissions exceed those from propane combustion, and are expected to remain higher for at least the next decade. In contrast, an HTHP with an assumed COP of 2.5 would already produce lower emissions than propane combustion for all three countries, with particularly significant reductions in Norway and the UK. For reference, in fishmeal processing plants handling 1,000 tons of raw material per day, the cooking process could require as much as 7 tons of steam per hour.

10.3 Dairy processing to produce cheese

In this section we identify the best available technologies to decarbonise the dairy cheese industry through three key levers; advanced energy management systems, high-efficiency equipment, and waste heat recovery to improve energy efficiency; renewable electricity, biomass, and alternative fuels for fossil fuel substitution; and natural refrigerants (CO₂, ammonia), improved refrigeration systems, and enhanced leak detection for refrigerant reduction. The aim is to collect and evaluate effective technologies and practices to achieve dairy industry's decarbonisation objectives.

We summarised the key general Best Available Techniques (BATs) for dairy processing as falling into the following categories.

10.3.1 Techniques to improve efficiency

Dairy manufacturers are a significant energy consumer. The processing phase is energy-intensive due to operations like pasteurisation, sterilisation, cooling, and drying. The implementation of BAT can significantly reduce this energy consumption, leading to cost savings, environmental benefits, and improved sustainability.

The key BATs for dairy processing are as follows:

10.3.1.1 Heat recovery and energy integration:

- A. Heat recovery from cooling systems: heat recovery systems in dairy processing capture thermal energy from cooling compressors, utilising heat exchangers and storage tanks to produce warm water at approximately 50-60°C.
- B. Precooling of ice water: the energy consumption for ice water production can be significantly reduced by implementing a two-stage cooling system. If the dairy is near to a river or lake which has a suitable temperature, cold water from a river or lake can be effectively used for precooling ice water.
- C. Enhanced regenerative efficiency using advanced heat exchangers: recovering heat from processes like pasteurisation and sterilisation to preheat incoming water or other process streams using advanced heat exchangers. For instance, the incoming milk is preheated with the hot milk flowing from the pasteurisation section using plate heat exchangers or other efficient designs to optimise heat transfer.

²¹⁰ These figures are based on theoretical calculations. Assumptions include the production of saturated steam at 4 bara using fresh water at 20°C. Projected grid emission factors were provided by Enerdata (EnerBlue scenario).

10.3.1.2 Efficient equipment:

- A. HTHPs (see 12.2.5): utilising waste heat to generate medium-temperature heat for cleaning and sanitisation.
- B. Efficient biomass boiler: the replacement of traditional boilers with more efficient biomass boilers can bring significant energy savings and reduce CO₂ emissions. Modern biomass boilers can achieve better efficiency than older fossil fuel boilers due to advancements in their design and the use of standardised, dry fuels like wood pellets. The key to high efficiency in any boiler type lies in good design, proper installation, and regular maintenance. The primary advantage of biomass boilers often lies in their use of a renewable fuel source, which can have environmental benefits in terms of carbon emissions, especially when the biomass is sourced sustainably.
- C. Frequency converter: utilising a frequency converter to adjust pump speeds. This approach allows for precise control of the pump impeller speed to match the required flow rate, optimising power consumption and preserving product quality by minimising excessive mechanical treatment.
- D. VFDs: vary the frequency supply to the motor, allowing precise control of motor speed and matching the speed to the actual load demand, thereby significantly reducing energy consumption. Even small reductions in speed can lead to substantial energy savings.

ENOUGH DEMONSTRATORS: DAIRIES AT RØROSMEIERIET, YEO VALLEY AND ENNSTALMILCH

Rørosmeieriet (Norway): as part of the demonstration equipment was installed to enable a more detailed monitoring of energy use, particularly for the heating and cooling systems. This allowed the dairy to better understand where and how energy was consumed across different processes beyond just tracking total energy. The key benefit of this insight was that it enabled identification of inefficiencies more easily and to implement targeted improvements. A number of efficient options were identified:

1. Replacing the electrical boiler with a heat pump will improve both specific energy use (and emissions as a consequence) and freshwater use.
2. Installing a TES system on the cold side does not reduce energy/carbon but allows short-term peaks in cooling demand to be managed (and prevents the need for upsizing the current installed cooling capacity, which could lead to suboptimal part-load operation).

The demonstration activities identified that the specific energy consumption could be reduced by ~36%.

Ennstalmilch (Austria): A HTHP was used to increase the temperature of the waste heat from the chiller to a temperature of up to 90°C. This was used to heat cleaning fluids (lye and acid) for the cleaning-in-place (CIP) systems of the dairy (used to clean process equipment such as tanks, filling machines, pasteurisers, milk collecting trucks, etc). The system was more recently upgraded to supply parts of the cheese dairy as well.

With a nominal heating capacity of 500 kW the demonstrator could supply 2-3 MWh of process heat per day. This reduced natural gas fired processes resulting in an annual GHG emission reduction of ca. 160 tonnes CO₂e.

Yeo Valley (UK): a new chilled water system was installed at a yoghurt factory. The ammonia chiller replaced the original HFC chillers. The rejected heat from the chiller was used to preheat milk prior to pasteurisation, reducing natural gas use. The rejected heat was stored in a 40m³ tank allowing for future expansion to the rejected heat use. Further opportunities to reduce energy and GHG emissions were identified.

The initial phase 1 replacement of the chiller system with an ammonia chiller with heat recovery to preheat milk ahead of pasteurisation is expected to provide an annual saving of 4,400 MWh of gas use and 400 MWh electricity use. This

10.3.1.3 Process optimisation and control:

- A. Partial homogenisation: only the cream and a small portion of skimmed milk (optimally with a 12% fat content) are homogenised, while the majority of the skimmed milk bypasses the homogeniser and goes directly to the pasteurisation section. The homogenised cream is then reintroduced into the skimmed milk stream before the final heating stage.
- B. Reducing the operation of air compressors during periods of inactivity: by turning off compressors during periods of inactivity or low demand, dairy facilities can significantly reduce energy consumption and operational costs.
- C. Reducing head (high) refrigeration system pressure: some refrigeration systems work with unnecessarily high head pressure. Reducing the system's minimum head pressure setting point can lead to huge energy savings. See the [Cold storage road map](#) for further information on optimisation of industrial refrigeration plant.
- D. Minimising product recirculation in pasteurisation lines: adapting the size or number of packaging tanks to match pasteuriser output and optimising product changeovers can prevent interruptions in continuous operation.

10.3.1.4 Building and infrastructure efficiency:

- A. Insulation: Improving insulation of buildings, pipes, and equipment to reduce heat loss.
- B. Lighting upgrades: replacing traditional lighting with LED or other energy-efficient options (if not already applied).
- C. Occupancy sensors: occupancy sensors detect the presence or absence of people in a space and automatically control lighting and sometimes HVAC systems accordingly.
- D. Air and water leak detection: identifying and sealing leaks to reduce energy consumption.

Table 18 shows energy savings potential and payback period for employing these technologies in dairy processing from literature sources.

Table 18. Identified BATs for dairy processing.

Best available technologies		Saving potential (%)	Payback	Source
Heat recovery and energy integration	Heat recovery from cooling systems	n/a	6.3 years	TemaNord, 2001 ²¹¹
	Precooling of ice water from rivers/lakes	20% electricity savings	2 years	TemaNord, 2001 ²¹¹
	Advanced heat exchangers	From 85% to 91% energy savings	3.6 years	TemaNord, 2001 ²¹¹
Efficient equipment and machinery	Heat pumps	27% electricity savings (compared to resistive, otherwise is a carbon saving)	3.2 years	Becker et al.2011 ²¹²
	Introducing efficient biomass boiler	29% (dependent on country)	2.3 years	Josijević et al. 2020 ²¹³
	Frequency converter	10% pump output reduction leads to 28% reduction in power consumption.	3.45 years	TemaNord, 2001 ²¹¹

²¹¹ TemaNord 2001 Nordic Council of Ministers, BAT for Nordic dairy industry, 586, 2001.

²¹² Becker, Helen, Maréchal, François Vuillermoz, Aurélie; 2011 Process Integration and Opportunities for Heat Pumps in Industrial Process, International Journal of thermodynamics; Vol 14 (2) P. 59.

²¹³ Josijević, M.M., Šušteršič, V.M. and Gordić, D.R., 2020. Ranking energy performance opportunities obtained with energy audit in dairies. Thermal Science, 24(5 Part A), pp.2865-2878.

Best available technologies		Saving potential (%)	Payback	Source
	VFDs	40% electricity savings	2 years	JRC 2009 ²¹⁴
	Two-Stage Compression	15%-25%	1-3 years	CII-Sohrabji ²¹⁵
Process optimisation and control	Patial homogenisation	68% electricity savings	2.5 years	Tetra Pak 2015 ²¹⁶
	Reducing the operation of compressors	Estimated 26% electricity savings	0.06 years	Josijević et al. 2020 ²¹³
	Resetting floating head pressure control	5%-20% (12% average)	Immediate	HVAC&R 2017 ²¹⁷
	Minimising of product recirculation in pasteurisation lines	About 5%	>4 years	TemaNord, 2001 ²¹¹
Building and infrastructure efficiency	Pipe-line insulation	Estimated 4% energy savings	0.22 years	TemaNord, 2001 ²¹¹
	Lighting upgrades	50% electricity savings	1.8 years	Josijević et al. 2020 ²¹³
	Occupancy sensors	Estimated 10% electricity savings	1.67 years	Josijević et al. 2020 ²¹³
	Air and water leak detection and elimination	Estimated 17% electricity savings	0.06 years	Josijević et al. 2020 ²¹³

Identifying the most important systems and processes where significant energy-efficiency improvements can be achieved can help related shareholders make decisions. By defining 2.5 years as the payback period threshold and 25% as the savings potential threshold, we can categorise the options into four groups (Figure 56):

Quadrant 1: high saving with short paybacks

The first quadrant includes technologies that offer significant carbon savings and have a short payback period, typically under two years. These technologies are highly attractive for organisations seeking quick financial returns while also achieving substantial reductions in carbon emissions. Key technologies in this quadrant include:

- Reducing operation of compressors: this measure offers 26% carbon savings with a payback period of 0.06 years.
- VFDs: results in roughly 40% carbon savings with a payback period of around 2 years.
- Lighting upgrades: provides about 50% carbon savings with a payback period of 1.8 years.
- Advanced heat exchangers: offers a substantial 90% carbon saving potential with a payback period of 3.6 years.
- Introducing efficient biomass boiler: can contribute to about 29% energy savings with a payback period of 2.3 years.
- Patial homogenisation: leads to 68% electricity in homogenisation with moderate payback period of 2.5 years estimated.

²¹⁴ JRC IPTS EIPPCB, 2009. Best Available Techniques (BAT) Reference Document for Energy Efficiency (ENE BREF), European Commission.

²¹⁵ CII-Sohrabji Godrej Green Business Centre 2019 Energy Efficiency in Compressed System Air

²¹⁶ Tetra Pak, Energy-efficient homogenisation device, 2015.

²¹⁷ HVAC& Workshop /September 2017 | www.airah.org.au/nation | HVAC&R Nation | Variable float heat pressure.

These measures are particularly well-suited for manufacturers that prioritise both immediate cost savings and environmental benefits.

Quadrant 2: high saving with long paybacks

The second quadrant focuses on measures that deliver high carbon savings but require longer payback periods, typically over two years. While these measures are effective in significantly reducing carbon emissions, they involve a longer-term financial commitment. Key measures in this quadrant include:

- Frequency converter: offers around 50% carbon savings with a payback period of 3.5 years.
- Heat pump: results in roughly 30% carbon savings with a payback period of around 3 years.

Manufacturers that have a long-term sustainability focus and are willing to invest in measures with longer payback periods may find these options particularly beneficial.

Quadrant 3: medium saving with short paybacks

The third quadrant represents measures that provide moderate carbon savings with short payback periods, making them suitable for organisations seeking a balance between savings and investment recovery time. A key measure in this quadrant includes:

- Eliminating air leaks: results in around 20% carbon savings with a payback period of under 1 month.
- Pipeline insulation: provides about 5% carbon savings with a payback period of less than 3 months.
- Occupancy sensors: results in approximately 25% carbon savings with a payback period of around 1.5 years.
- Precooling of ice water: brings 20% energy savings with a payback period of approximate 2.5 years.

These measures can be ideal for organisations looking to achieve reasonable environmental benefits without extending the payback period too long.

Quadrant 4: medium saving with long paybacks

The fourth quadrant includes measures that offer moderate carbon savings but have longer payback periods, generally over two years.

- Minimising of product recirculation in pasteurisation lines: provides about 5% energy saving with payback period of more than 4 years.



Figure 56. Comparison of payback periods (years) and energy savings (%) for identified Best Available Techniques (BATs).

10.3.2 Milk processing case studies/demonstrations

The effect of the BATs identified in the previous sections in terms of energy and CO₂ emissions have been described in a case study by Josiyević et al (2020)²¹⁸. They studied a medium-sized dairy company that employs 230 workers, with 70% in production roles. The dairy processes approximately 100 tons of raw milk daily through various energy-intensive operations such as pasteurisation, cooking, cooling, separation, and homogenisation. The company produces a diverse range of dairy products including cheese, cream, yogurt, and sour milk. The production process involves multiple stages of milk treatment, each requiring significant energy input to transform the raw milk into the final consumer products (Figure 57).

²¹⁸ Josiyević, M.M., Šušteršič, V.M. and Gordić, D.R., 2020. Ranking energy performance opportunities obtained with energy audit in dairies. Thermal Science, 24(5 Part A), pp.2865-2878.

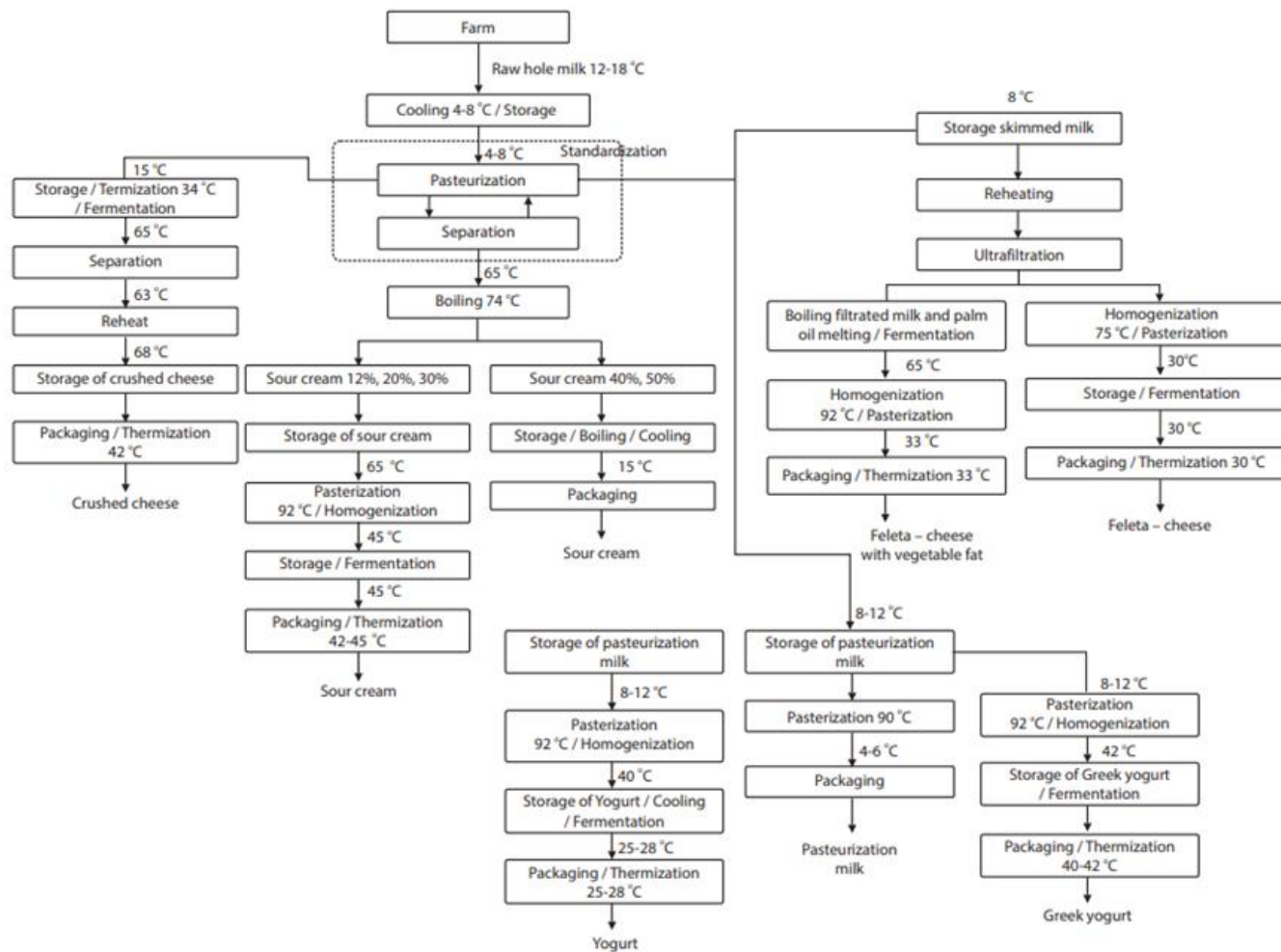


Figure 57. Production-lines and processes in the analysed dairy case (Josijević et al. 2020)²¹⁸.

Electricity consumption was, on average about 200,000 kWh per month. Most of the electricity was used for cooling processes and final products (60%). For heating, 38 tons of briquettes with lower thermal power (18 MJ/kg) were used for space heating for the facility, which was 3% of its total heat consumption. This implies that the energy needed for other heating processes was 377,000 kWh per month (97%) (Figure 58).

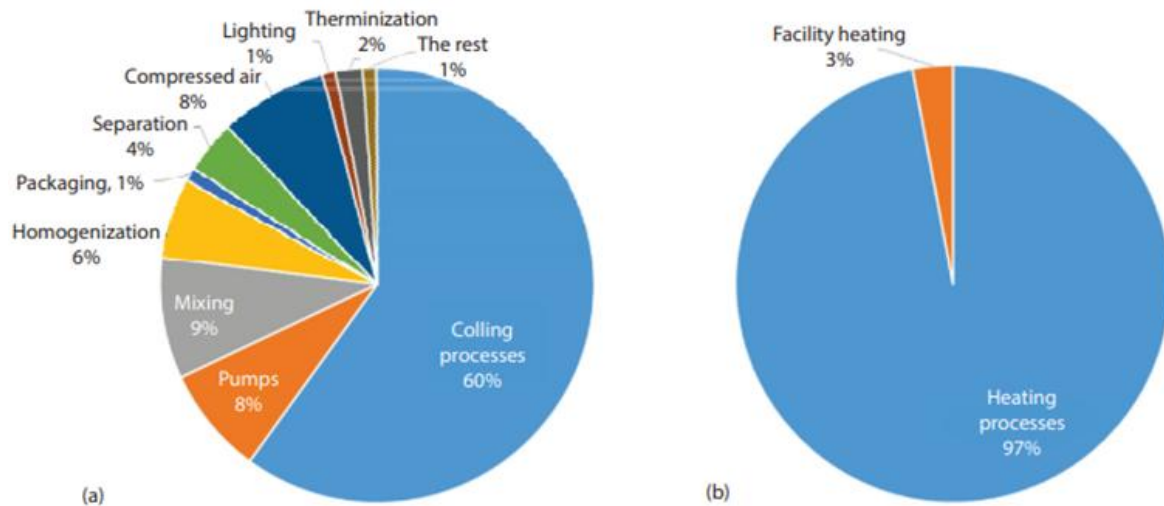


Figure 58. The share of (a) electricity and (b) heat energy users. (Josijević et al. 2020)²¹⁸.

The value of specific energy consumption with respect to product mass and raw milk mass was calculated for every product. The average specific energy consumption of final energy was 0.12 kWh/kg of processed milk. The results are presented in Table 19.

Table 19. Data on energy consumption for all the products (Josijević et al. 2020)²¹⁸.

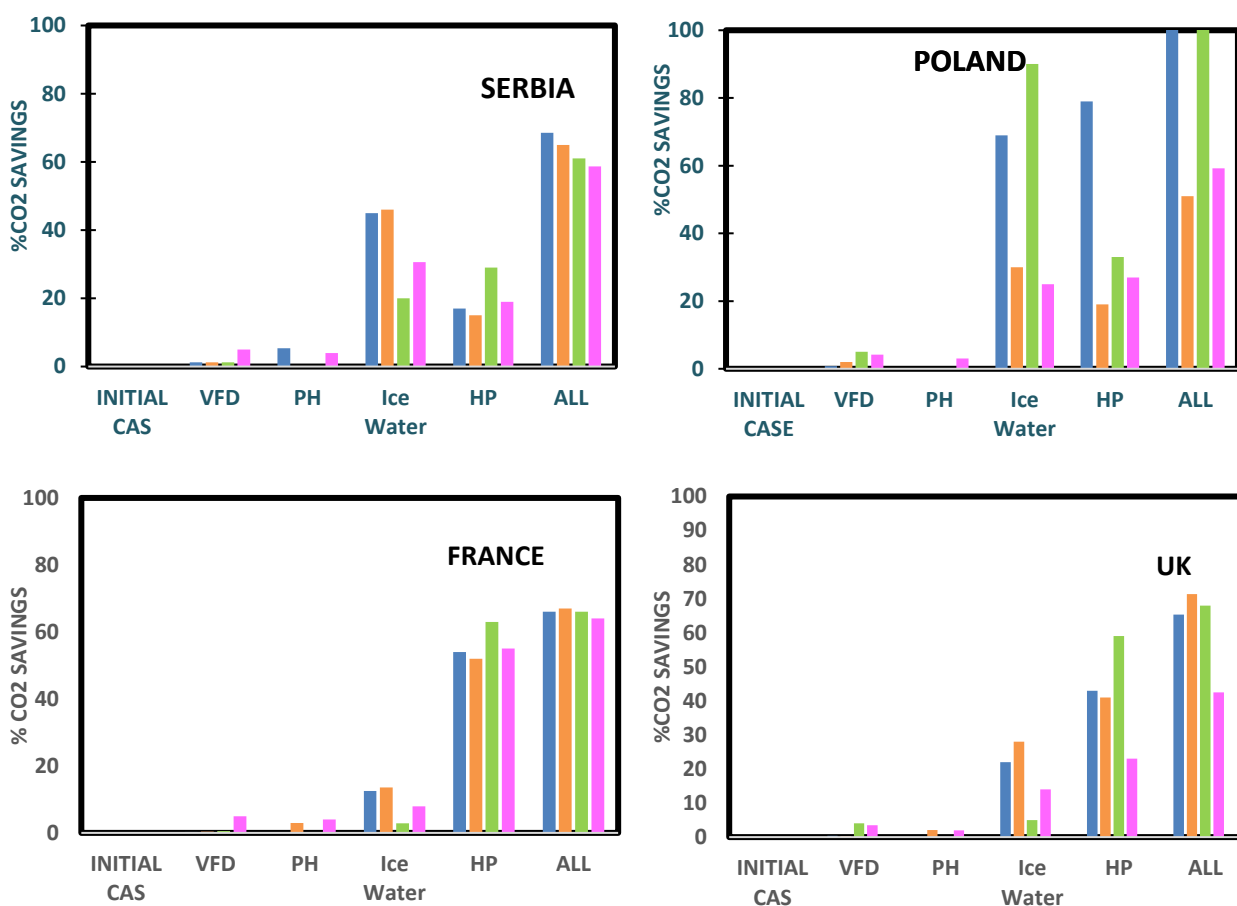
Product	Pasteurisation milk		Yoghurt		Sour cream 40-55%		Sour cream 12-30%		Crushed cheese		Feta cheese		Fetela cheese		Greek yoghurt	
Daily energy consumption	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
Pumps	15	2	34	1	2.8	3	4	1	38	2	167	9	183	8	9	1
Mixing	18	3	90	3	6.8	7	26	8	35	1	109	6	142	7	34	5
Separation	20	3	26.7	1	26.7	26	27	9	81	3	26.7	1	26.7	1	26.7	4
Homogenisation	-	-	140	5	-	-	30	10	-	-	75	4	72.3	3	56	8
Packing	4.5	1	10.5	-	5.4	5	8	3	11	-	17.6	1	19.8	1	4.2	1
Process cooling	288	43	1391	45	35	35	128	42	340	20	545	28	731	33	297	43
Process heating	324	48	1404	45	24.3	24	83	27	1927	74	988	51	1016	47	265	38
Total		100		100												
Indicators of SEC																
SEP kWh/kg of product	0.0877		0.1896		0.0808		0.0971		0.6120		0.6882		0.3759		0.1199	
SEP kWh/kg of raw milk	01.0877		0.1826		0.0060		0.0184		0.1307		0.1835		0.1504		0.1170	

Based on the daily energy consumption figures in Table 19, in particular the energy audits that provide data for each electrical process and heating process, we can integrate the selected BATs into the each process. Knowing the energy saving potential for technology we can calculate the energy saving potential of suitable technologies with the corresponding CO₂ emissions. These data were then assessed to determine their impacts on CO₂ emissions for each dairy products for the selected countries: Norway, France UK, Italy, Poland, Lithuania and in some cases Serbia. An assumption was made that the same energy was used in total and same percentages across all countries.

Four technologies were selected to study: enhanced precooling with ice water, partial homogenisation (PH), VFDs and integration of heat pumps (HP) for heating.

10.3.2.1 Energy performance

Figure 59 presents CO₂ emissions for several dairy products using various BATs. Baseline values are the current processing performance. The savings from PH, VFDs, HP, ice water, and their combination were compared.



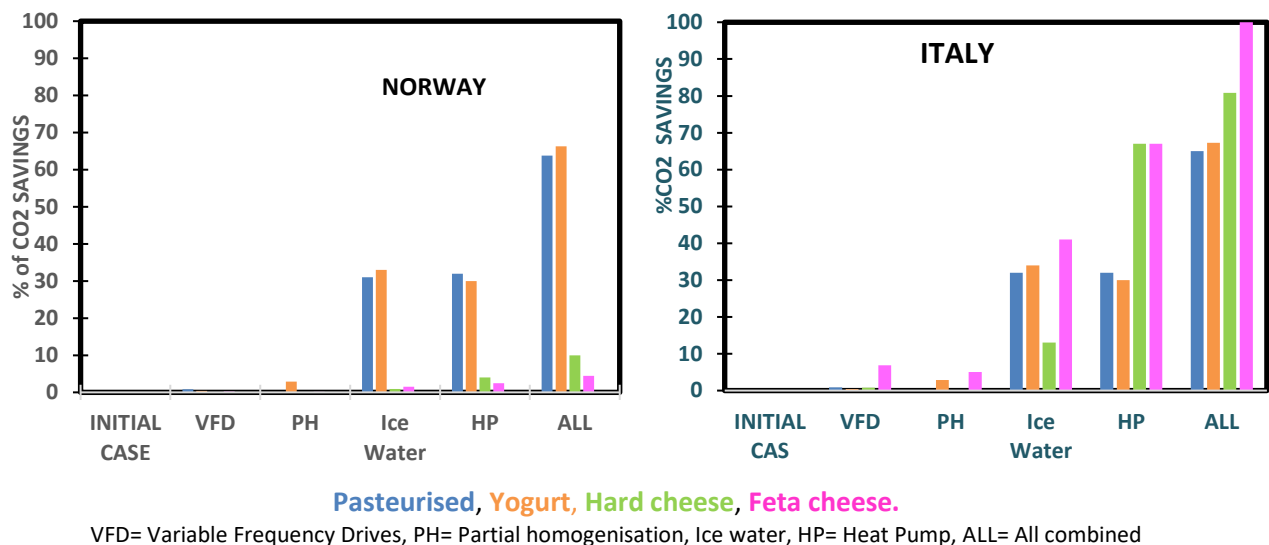


Figure 59. CO₂ savings for each product implementing various BATs.

For some products (e.g., yogurt and cheese), individual BATs show as expected a significant CO₂ emissions savings, in particular in heating and chilling. Improved chilling shows notable reductions, especially for cheese products. HP are effective but provide less reduction compared to combined BATs and chilling technologies.

Environmental performance

Figure 59 displays the of percentage of CO₂ emissions savings for the same set of products and BATs applied for different countries. Some of the technologies BATs are more appropriate for r some of the products such as yoghurt and hard cheese. Combined BATs as expected yield the highest CO₂ emissions savings for most products, highlighting the effectiveness of integrating multiple technologies. For products such as yoghurt and various cheeses, individual BATs such as HP and ice chilling also significantly reduce CO₂ emissions.

Projected CO₂ emission evolution (2025-2050)

Projected reduction in CO₂ emissions to 2050 are shown in Figure 60 and Figure 61. The projections are based on constant total energy consumption (electricity + heating) and the change in grid carbon emissions actors as explained for other products.

Scenario 1 assumed constant heating emissions (Figure 60). Assuming current heating technologies persist, decarbonisation efforts reach a plateau, with CO₂ emissions remaining constant. This trend is consistent across most countries, with the exception of Norway, which already predominantly utilises electric heating.

Scenario 2 assumed a transition to electric heating by 2035 (Figure 61). This scenario quantifies the impact of widespread electric heating adoption on national decarbonisation pathways and demonstrates that emissions from heating can almost be eliminated in all countries.

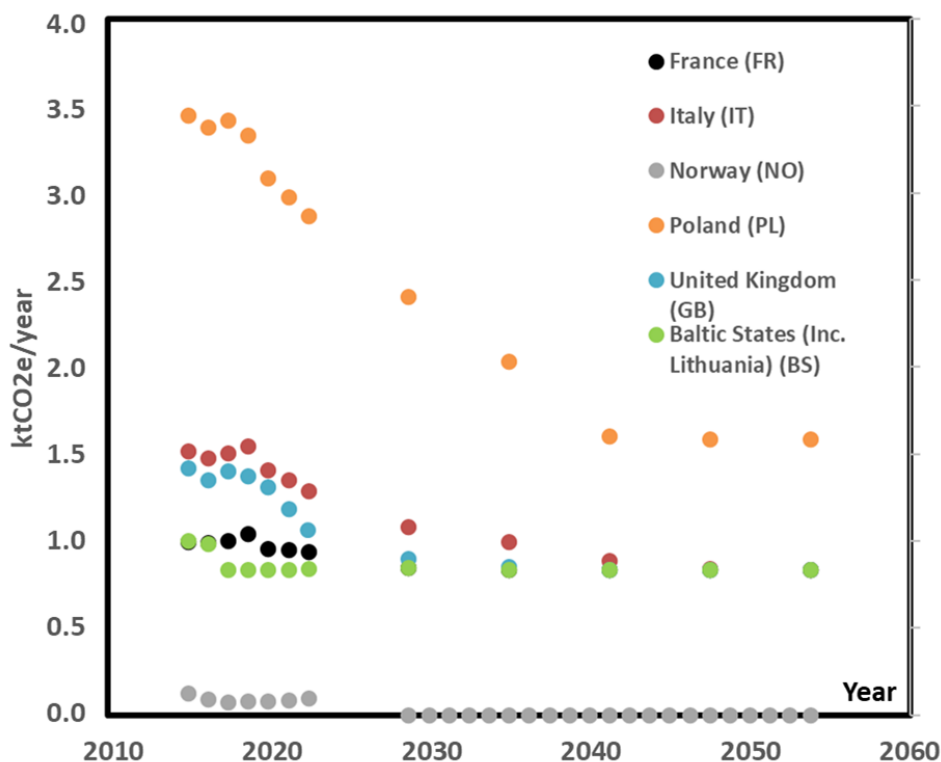


Figure 60. CO₂ emissions evolution per year in a dairy plant keeping the same process heating up to 2050.

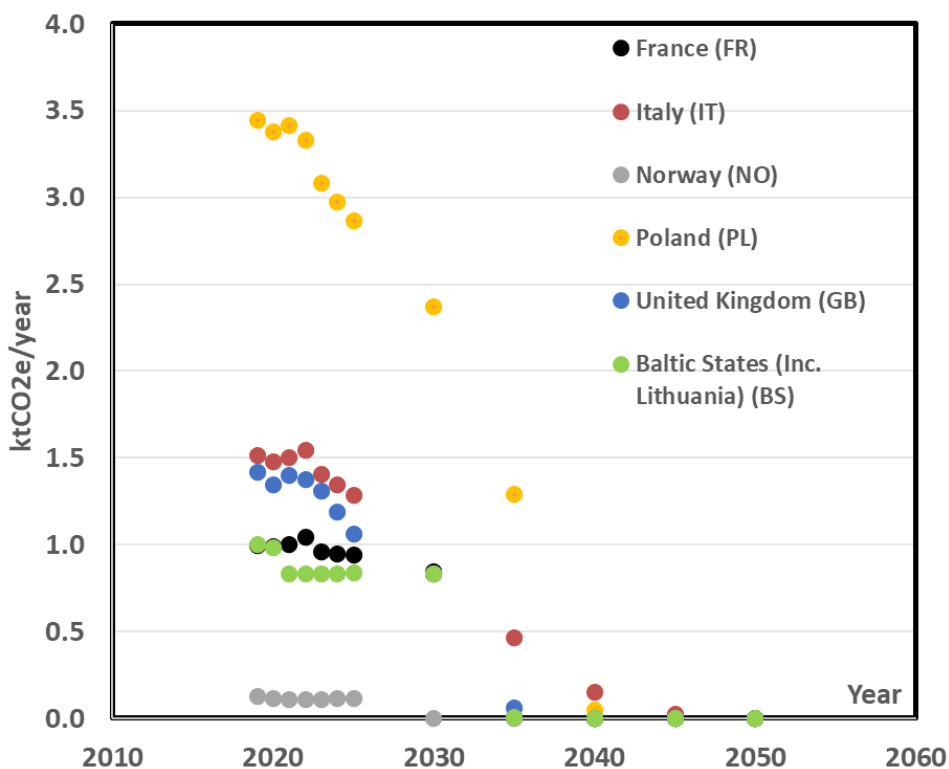


Figure 61. CO₂ emissions evolution per year in a dairy plant changing to electrical heating in 2035 the same process heating up to 2050.

10.4 Secondary processing to produce composite products

10.4.1 Fish fingers

Fish products are subjected to multiple processing stages before becoming a final product. Fish, before being processed, are subjected to filleting, cooking, frying, and freezing. These processes consume a significant quantity of electrical energy. Of the products studied, fish fingers were not only the largest produced fish product²¹⁹ but also the one having the highest energy demand²²⁰.

The breaded finger fish product is composed of six processing stages; raw material thawing to texture fit for processability, forming, pre-cooking, breading, frying, and freezing. A preliminary estimate from a number of compiled sources of fish fingers production energy consumption showed that 23% of energy is consumed in (pre-)cooking, 27% in frying, 38% in cooling and freezing processes²²¹, 5% by batter mixing and handling and 4% by indirect industrial services (e.g. lighting, transportation, vapour extraction). The major energy use is in cooking and frying procedures. The steam cooking procedure requires rapid cooling after the texture has been set, to avoid dripping losses and texture deterioration before battering. The oil frying batch has a typical size of 400 to 800 litres of frying oil that has to be filtered after each pass to remove loose meat and breading particles that burn rapidly and contaminate the bulk quantity of frying oil. The whole procedure contains a number of energy loss points. The cooking stage possesses very high energy saving potential, the extent of cooking stage energy saving opportunities is to be assessed through the identified technology/strategy options in Appendix: Detailed technology/strategy options.

Given the current and anticipated future availability of novel technologies, GHG emissions can be estimated for key technological steps. Even with minor retrofits in cooling and freezing systems—such as installing efficient condensers, improved fans, and better maintenance—and using existing off-the-shelf technologies at TRL 8–9 by 2035, a realistic GHG reduction from 177.7 kg CO₂e to 130.8 kg CO₂e per ton of finished product (a 26.4% saving) can be achieved. By 2040 and 2050, through the development and adoption of emerging technologies currently at TRL 6–8, emissions could be further reduced to 104.9 kg CO₂e and 91.0 kg CO₂e per ton, representing total savings of 41% and 48.8%, respectively (

²¹⁹ Josephson, P. R. (2007). The ocean's hot dog: The development of the fish stick. *Technology and Culture*, 49(1), 41-61. doi:10.1353/tech.2008.0023.

²²⁰ Life cycle assessment of fish fingers and plant-based alternatives for WWF Switzerland (2022) Available at: carbotech.ch/en/projekte/oekobilanz-von-fischstaebchen/.

²²¹ Parameters that Affect Electricity Consumption in Fish Freezing. Case Study (2018) *Environmental and Climate Technologies* 2019, vol. 23, no. 3, pp. 15–25. doi: 10.2478/rtuect-2019-0076.

Table 20).

These reductions primarily result from eliminating separate energy sources for heating and cooling by integrating them into a heat recovery loop. This integration is enabled by local heat recovery (e.g., flue gas exhaust) or the use of high-temperature heat pumps (HTHPs) operating throughout the plant.

Table 20. Estimated carbon savings achievable for fish fingers.

Technological step	2020	2035		2040		2050	
	GHG emission KPI base	TRL	Estimated saving %	TRL	Estimated saving %	TRL	Estimated saving %
Chilled storage of ingredients (1000 m ³ volume per ton of stored product)	0.4 tCO ₂ e/y						
Minor retrofit by 2035 (efficient condenser and fans, maintenance)		8	-45%				
Major retrofit by 2040 (high efficient compressor, refrigerant change)				7	-68%		
New store by 2050 (new insulated store + all current technologies)						6	-84%
Frozen storage of ingredients (1000 m ³ volume per ton of stored product)	0.5 tCO ₂ e/y						
Minor retrofit by 2035 (efficient condenser and fans, maintenance)		8	-41%				
Major retrofit by 2040 (high efficient compressor, control change)				7	-62%		
New store by 2050 (new insulated store + all current technology)						6	-81%
Thawing (electrically heated continuous brine bath, fish with 70% water, -18°C to +1°C)	17.3 kgCO ₂ e/t						
Use of waste heat from 2035 (retrofit for hot water heating permitted by improved controls, circulation pump only)		9	-90%	9	-90%	9	-90%
Steam cooking (gas fired steam supply, cooking at +70°C)	10.2 kgCO ₂ e/t						
Use of HTHPs from 2035 (combined with the freezing compressors)		8	-60%	8	-70%	8	-80%
Pre-frying of battered fingers (gas fired, oil deep frying at 185°C, 12% water loss, 70% efficiency incl. radiation loss of the fryer)	36.2 kgCO ₂ e/t						
Exhaust heat recovery by 2035		8	-6%				
Conversion to electrical heating (saving coming from the use of renewable energy and lower carbon conversion factors)				9	-23%	9	-35%
Freezing (assumes 9% moisture loss in a spiral freezer)	54.0 kgCO ₂ e/t						
Minor retrofit by 2035 (efficient condenser and fans, maintenance)		8	-11%				
Major retrofit by 2040 (high efficient compressor, controller change)				7	-22%	7	-22%
OVERALL (note - selected processing steps only, per ton of product considering moisture loss during processing, 1 month frozen storage period)							
kgCO ₂ e/t	177.7		130.8		104.9		91.0
weighed % saving vs. 2020			-26.4%		-41.0%		-48.8%

10.4.2 Beef casserole

Beef casserole consists of cubed beef chunks, slow roasted and simmered with potatoes, carrots, onions, and stewed tomatoes or tomato paste. Chili powder, a blend of spices, enhances the flavour. High quality fresh vegetables may be used instead of frozen ones, resulting in a shorter cooking time. The casserole is typically produced by a batch process where the browned beef and sautéed vegetables are combined with spices in batches and cooked in a kettle.

The production of ready meals such as beef casserole involves multiple energy-intensive steps that contribute significantly to overall manufacturing costs and environmental impact. Understanding the key challenges associated with energy use is essential for identifying opportunities to improve efficiency and reduce GHG emissions.

One of the primary areas of concern is the high energy demand associated with cooking and heating processes. Cooking processes are among the most energy-intensive stages in food manufacturing²²². Batch cooking in large industrial kettles requires sustained thermal input to ensure the meat and vegetables are properly cooked. Energy requirement for cooking can be prodigious, and energy varies with different cooking methods. There are very limited studies in literature focused on the energy consumption for meat cooking. Traditional systems often rely on radiative gas burners or steam jackets, which can suffer from inefficiencies due to poor insulation, outdated technology, or lack of precision control. In many facilities, significant heat losses occur through uninsulated surfaces or during long heating cycles, resulting in unnecessary energy consumption. Whereas alternative methods offer significant savings in energy use, other quality factors like their impact on cooking loss, meat textural properties, colour, shrinkage and juiciness shall also be considered. For instance, traditional cooking methods for beef dishes can consume approximately 6.52 kWh per batch versus microwave cooking (4.67 kWh), also cooking time has been reduced by 56 % compared to traditional cooking²²³. When, in meat cooking and sautéing of vegetables, alternative cooking methods cannot be used it is important to increase the use of energy from renewable sources, together with energy efficient cooking equipment to reduce GHG emissions. Cooking energy demand should be optimised by improving real-time cooking data (e.g. based on texture), and benchmarking can identify the opportunities to reduce demand. Additionally, the batch nature of production introduces periods of idle time between processing cycles, during which equipment may continue to consume energy even when not actively producing. This stop-and-go operation limits the potential for steady-state efficiency and increases baseline energy use.

Another major contributor to energy use is the chilling and freezing stage, where cooked meals must be rapidly cooled to safe temperatures to prevent microbial growth and preserve shelf life. Equipment such as blast chillers and spiral freezers consume considerable amounts of electricity, particularly when operated at less than optimal capacity or without integrated energy management systems.

The lack of process integration across production stages further exacerbates energy inefficiency. In many operations, systems for cooking, chilling, and packaging function independently, making it difficult to recover waste heat or coordinate energy use across the entire process. For instance, excess heat generated during cooking is often released rather than reused elsewhere in the facility. This represents a missed opportunity for energy recovery, as HTHPs (Chapter 12.2.5) can be effectively used to capture waste heat from processes like cooking and redirect it for use in hot water or space heating,

²²² Pathare, P.B. and Roskilly, A.P., (2016) Quality and energy evaluation in meat cooking. *Food Engineering Reviews*, 8(4), pp.435–447. doi: 10.1007/s12393-016-9143-5.

²²³ Jouquand C et al. (2015) Optimization of microwave cooking of beef burgundy in terms of nutritional and organoleptic properties. *LWT Food Sci Technol* 60(1):271–276

significantly reducing overall energy consumption. HTHPs are increasingly recognised in the food industry for their efficiency and potential to decarbonise thermal processes above 100 °C

Lastly, the presence of aging equipment and insufficient maintenance practices can significantly impair energy performance. Older cooking vessels, burners, and refrigeration systems may operate below optimal efficiency due to wear, outdated controls, or poor calibration. These issues often go unnoticed without regular audits and preventive maintenance.

Scenarios have been modelled for technologies at TRL 8-9 in 2035 using a mix of electricity and natural gas, transitioning to 100% electricity from 2040 onwards. The model shows that minor upgrades to the plant's cooling system combined with the use of waste heat have achieved a 54% reduction in GHG emissions – lowering emissions from 40.4 kg CO₂e per ton of finished product to 18.5 kg CO₂e/ton. However, the complete elimination of natural gas has largely offset these savings, mainly due to the relatively low 60% conversion efficiency when using electrical energy for microwave heating. It is worth noting that microwave processes (e.g., microwave thawing and microwave pasteurisation) offer flexibility and faster processing compared to traditional methods. Nonetheless, this suggests that full electrification may not yield significant GHG reductions in all countries unless the electricity supply is predominantly renewable (Table 21).

Table 21. Estimated carbon savings achievable for beef casserole.

Technological step	2020	2035		2040		2050	
	GHG emission KPI base	TRL	Estimated saving %	TRL	Estimated saving %	TRL	Estimated saving %
Chilled storage of ingredients (1000 m ³ volume per ton of stored product)	0.4 tCO ₂ e/y						
Minor retrofit by 2035 (efficient condenser and fans, maintenance)		8	-45%				
Major retrofit by 2040 (high efficient compressor, refrigerant change)				7	-68%		
New store by 2050 (new insulated store + all current technology)						6	-84%
Frozen storage of ingredients (1000 m ³ volume per ton of stored product)	0.5 tCO ₂ e/y						
Minor retrofit by 2035 (efficient condenser and fans, maintenance)		8	-41%				
Major retrofit by 2040 (high efficient compressor, control change)				7	-62%		
New store by 2050 (new insulated store + all current technologies)						6	-81%
Thawing (electrically heated room or cabinet, beef with 65% water, -18°C to +4°C)	13.6 kgCO ₂ e/t						
Use of waste heat from 2035 (retrofit for hot water heating permitted by improved controls, circulation pump only)		9	-80%				
Microwave thawing from 2040				9	+80%	9	+70%

	2020	2035		2040		2050	
Technological step	GHG emission KPI base	TRL	Estimated saving %	TRL	Estimated saving %	TRL	Estimated saving %
(large scale microwave oven efficiency 60%; higher energy use but more flexible process)							
Meat browning and stewing (direct gas heated vessels, warming up and cooking at +95°C, incl. stove radiation losses)	9.3 kgCO ₂ e/t						
Use of HTHPs from 2035 (combined with the cooling compressors)		8	-60%	8	-70%	8	-80%
In-pack pasteurisation (gas fired, direct steam injection heated immersion bath at 80°C for 15 minutes, with steam losses)	3.7 kgCO ₂ e/t						
Electrically heated bath from 2035 (use of renewable energy and lower carbon conversion factors, with evaporation losses)		9	-14%				
Microwave heating from 2040 (large scale microwave oven efficiency 60%; dry heating process with no losses)				9	+60%	9	+50%
Chilling (cooling from 78°C to +3°C in a spiral freezer, no moisture loss in sealed packaging, COP=6.0)	3.0 kgCO ₂ e/t						
Minor retrofit by 2035 (efficient condenser and fans, maintenance)		8	-15%				
Major retrofit by 2040 (high efficient compressor, controller change)				7	-30%	7	-30%
OVERALL (note - selected processing steps only, per ton of product considering 10% moisture loss during processing, and 1 week chilled storage)							
kgCO ₂ e/t	40.4		18.5		39.5		35.4
weighed % saving vs. 2020			-54.1%		-2.2%		-12.3%

11 RECOMMENDATIONS

11.1 Meat processing

There is considerable potential to decarbonise meat processing through:

1. More efficient cooling processes: This can be though replacing inefficient components, better maintenance and controls or through changing the actual cooling process. Opportunities exist to reduce energy and carbon emissions through 2 stage chilling, rapid chilling or hot boning.
 → **Recommendation: audit the chilling process, compare performance to metrics available (see metrics section), assess performance against design conditions to identify gradual fall off in performance. Assess whether an alternative cooling process would save energy and carbon.**

2. Using HTHPs to replace fossil fuel boilers: Heat pumps are already being used for space heating and domestic water heating. HTHPs that can achieve temperatures of up to 160°C are due to be available on the market from around 2030 onwards. These will be able to provide high and low pressure steam.
 → **Recommendation: Use heat pumps for hot water and space heating wherever possible.**
3. Heat reclaim: Considerable potential exists to reclaim heat from high temperature processes in abattoirs. This can be used as a first stage to heat water or raise steam considerably increasing the COP of heat pumps.
 → **Recommendation: carry out an audit of where heat is wasted and the potential for heat reclaim. This could be from refrigeration plant, high temperature processes such as scalding and singeing or from other processes carried out in the facility. Consider whether the facility is close to a district heating system where heat could be shared (imports and exports to the facility).**
4. Air compressors: The optimisation, maintenance and efficiency of air compressors has considerable potential for improvements.
 → **Recommendation: assess current operation of equipment against industry benchmarks. Consider whether alternative compression technologies have benefits.**
5. Lower carbon gas grid: Higher temperature processes tend to be used in pork and poultry processing and less so in beef processing. Potentially abattoirs can generate biogas for use through Anaerobic Digestion (AD) plants that use waste from the processing.
 → **Consider the benefits of an AD plant on site to produce biogas for use on site or electrical power generation and to better manage waste emissions.**
6. Solar PV: Solar panels placed on the roof of facilities provide electricity, often at times of day when the abattoir is most utilised (morning to late afternoon). The carbon benefits of on site solar PV to replace grid electricity reduces as the grid carbon intensity decreased over time (all electrical grids should decarbonise). However, on site solar PV will reduce electrical requirements to the site which can be very costly and take time to upgrade. As facilities decarbonise and thus use more electricity, solar PV will help in maintain electrical demand from these extra processes.
 → **Recommendation: consider benefit of adding solar panels to roofs and how solar power output could match electrical demand.**

11.2 Fish processing

There is considerable potential to reduce greenhouse gas emissions in pelagic fish processing through a combination of targeted energy efficiency measures, including:

1. Improving refrigeration systems: refrigeration is the dominant energy consumer in pelagic fish processing, accounting for more than 75% of total energy use in typical facilities. Targeted improvements to system components, controls and operation can significantly reduce overall emissions.
 → **Recommendation: conduct a detailed refrigeration system audit to map internal energy flows, identify inefficiencies and assess potential for optimisation or technology upgrades. Prioritise systems with highest energy use**
2. Enhancing freezing operations: the freezing of round fish (and to a lesser extent fillets) is the main driver of energy consumption in pelagic plants. Process improvements can offer substantial efficiency gains.
 → **Recommendation: audit the freezing process with emphasis on load profiles and process requirements. Compare against best available techniques and identify energy-saving opportunities through improved procedures**

3. Adopting alternative freezing technologies: emerging freezer technologies can offer high efficiency and lower GHG emissions. This could include brine freezing or plate freezing with CO₂.
→ **Recommendation: assess technical and economic feasibility of adopting alternative freezing technologies (retrofits or in new installations)**
4. Adopting HTHPs for steam generation in fishmeal processing: fishmeal plants typically require low-pressure steam, often supplied by fossil fuel boilers. HTHP technology can now replace these systems and offer substantial emission reductions.
→ **Recommendation: for brownfield sites, evaluate the potential for replacing fossil-fuelled steam boilers with HTHPs. For greenfield installations, HTHP should be preferred technology choice: from 2030, systems with 10 MW capacity and up to 160°C steam output are expected to be commercially available**

11.3 Dairy processing to produce cheese

There is significant potential to decarbonise dairy processing through:

1. More efficient cooling processes: dairy processing relies heavily on cooling for pasteurisation, storage, and product quality. Inefficient cooling systems considerably contribute to energy consumption and carbon emissions.
→ **Recommendation: audit the entire cooling process, from raw milk reception to finished product storage. Compare the performance of existing systems against industry benchmarks and design specifications to identify areas of inefficiency or performance degradation over time. Evaluate the potential of alternative cooling technologies, such as new refrigerants such as R744 (CO₂) or more efficient refrigeration cycles, to reduce energy use and associated carbon emissions.**
2. Applying HTHPs to replace fossil fuel boilers: many dairy processes require substantial quantities of heat for pasteurisation, CIP, and evaporation. Traditional fossil fuel boilers can be replaced with HTHPs.
→ **Recommendation: Implement HTHPs for generating the hot water and steam needed for various processes wherever feasible. Investigate the potential of emerging HTHP technologies capable of reaching elevated temperatures relevant to dairy processing.**
3. Heat recovery and heat reclaim: dairy processing generates substantial waste heat from processes such as pasteurisation, sterilisation, and refrigeration. Recovering and reusing this heat can significantly reduce the demand for externally generated energy.
→ **Recommendation: conduct a thorough audit to identify sources of waste heat within the facility and assess the potential for heat recovery. This could include heat from refrigeration systems, pasteurisers, evaporators, and other thermal processes. Explore opportunities to utilise this reclaimed heat for pre-heating water, space heating, or other lower-temperature applications, thereby increasing the efficiency of heat pump systems. Investigate the feasibility of connecting with local district heating networks for potential heat exchange (both import and export).**
4. Air compressors: compressed air is used in various aspects of dairy processing. Improving the efficiency of air compression can result in significant energy savings.
→ **Recommendation: assess the current efficiency of air compressors against industry best practices and benchmarks. Implement measures to optimise their performance, such as leak detection and repair, using appropriately sized compressors, and potentially investing in more energy-efficient models.**
5. Lower carbon energy sources: reliance on fossil fuels for heating and electricity contributes to carbon emissions. Transitioning to lower-carbon alternatives is crucial.

- **Recommendation: as the electricity grids decarbonises, the carbon footprint associated with electricity use in dairy processing will naturally decrease.**
- 6. Explore the potential for on-site AD of dairy processing waste (e.g., whey, sludge) to produce biogas. This biogas can be used for on-site heat and power generation, reducing reliance on fossil fuels and improving waste management.
 - **Recommendation: investigate the feasibility of using other renewable energy sources for heating, such as biomass boilers (where sustainable sourcing is ensured).**
- 7. Use solar PV: dairy processing facilities often have large roof spaces that are suitable for PV installations.
 - **Recommendation: evaluate the benefits of installing PV panels on available roof areas. On-site PV can directly offset electricity consumption from the grid, particularly during peak daytime hours when processing demands are often high. While the carbon savings from solar PV might evolve with grid decarbonisation, the energy cost savings and increased energy independence remain significant. As facilities electrify more processes for decarbonisation, on-site solar can help manage increased electricity demand. Consider how the output of solar power can best integrate with the facility's energy usage patterns and potential battery storage solutions.**

11.4 Secondary processing to produce composite products

While specific studies on the process optimisation of beef casserole production are limited, several technologies identified in this report as well as general strategies from meat processing and food manufacturing can be applied to enhance efficiency and sustainability in beef casserole production.

1. Energy efficiency in cooking operations: cooking stages, particularly those involving large batch kettles, are significant energy consumers.
 - **Recommendation: implement advanced control systems and optimise heating methods to reduce energy consumption and improve process efficiency. This also offers an opportunity in batch processing and production scheduling by implementing batch processing techniques to streamline production and scheduling production runs to minimise downtime and maximise equipment utilisation²²⁴.**
2. Chilling and freezing efficiency: post-cooking cooling is critical for food safety and shelf-life but is also energy-intensive²²⁵
 - **Recommendation: vacuum cooling rapidly reduces the temperature of cooked products, minimizing energy use and preserving quality. However, it requires careful control to prevent product loss due to foaming or splattering²²⁶.**
3. Waste heat recovery: significant amounts of energy are lost as waste heat during cooking and other thermal processes.
 - **Recommendation: recover waste heat energy in order to improve overall efficiency. Heat-to-Heat Recovery Systems allow to directly transfer waste heat to preheat incoming water or air which in turn reduces the need for additional energy input. Install**

²²⁴ Evers, J. (2019). "The Role of Batch Processing in Food Production." Food Engineering Journal, 45(2), 100-110.

²²⁵ Clodoveo, M. L., Muraglia, M., Fino, V., Curci, F., Fracchiolla, G., and Corbo, F. F. R. (2021). Overview on Innovative Packaging Methods Aimed to Increase the Shelf-Life of Cook-Chill Foods. Foods, 10(9), 2086. doi: 10.3390/foods10092086.

²²⁶ Knipe, C. L and Rust R. E. (2010) Thermal Processing of Ready-to-Eat Meat Products. Wiley, Print ISBN:9780813801483. doi: 10.1002/9780813808611.

economisers or air pre-heaters to capture waste heat from flue gases, providing energy savings between 3% and 20%²²⁷.

4. Cold chain optimisation: maintaining the cold chain is essential for product safety but can be energy-intensive if not properly managed.
 - **Recommendation: adjust set points and improve insulation in cold storage facilities for energy saving, on average 8% for large stores and 14% for small stores²²⁸. Implement advanced refrigeration technologies (section 12.1) to further reduce energy consumption.**

By adopting these strategies, composite cook-chill products like beef casserole production can achieve improved efficiency, reduced GHG emission, and enhanced product quality.

²²⁷ Faraldo, F., and Byrne, P. (2024). A Review of Energy-Efficient Technologies and Decarbonating Solutions for Process Heat in the Food Industry. *Energies*, 17(12), 3051. doi: 10.3390/en17123051

²²⁸ ENOUGH WP2, D2.4: Cold storage road map. Evans, J.A., Hammond, E.C., Gigiel, A.J., Foster, A.M., Reinholdt, L., Fikiin, K. and Zilio, C. (2014). Assessment of methods to reduce the energy consumption of food cold stores. *Applied Thermal Engineering*, 62(2), pp.697–705. doi: 10.1016/j.applthermaleng.2013.10.023.

12 APPENDIX: DETAILED TECHNOLOGY/STRATEGY OPTIONS

12.1 Refrigeration

12.1.1 Air cycle (reverse Brayton cycle) refrigeration

Air cycle refrigeration uses air as the working fluid. Unlike vapour compression systems, air cycle works by compressing and expanding air in the gaseous phase, with no phase change. Air cycle refrigeration systems are far less efficient than vapour compression systems at typical chilling and freezing temperatures, but they can be competitive at very low temperatures for applications such as rapid freezing, particularly in comparison with cryogenic systems such as liquid nitrogen freezers. In addition, due to their in-efficiency, they produce considerable quantities of heat at high temperatures in the compression process. If this can be used as well as the low temperatures, combined heating/cooking and cooling can be achieved. According to Shuailing et al (2023) "At present, reverse Brayton air cycle machines have been applied in various fields such as food freezing, transportation, heat pump, refrigerator, and dryer, etc. With the increasingly stringent environmental laws and regulations, the air cycle system will have a wide perspective application in the future."

The use of air cycle systems in food processing has been reported for various products and with a range of system configurations. Shaw et al. (1995) presented the design and performance of an open cycle food freezing system known as ColdBlast™ (developed by Air Products in the USA) in which air at -157°C was blown over food in various configurations of in-line freezing tunnels. The air was then passed through a recuperator to cool the air entering the system's expander, after which it was exhausted at around -73°C to ambient. Freezing rates for a range of products including hamburgers, raw chicken and cooked chicken were said to be two four times faster than conventional vapour compression based freezing at -40°C and almost as fast a liquid nitrogen freezing. However, the nominal power consumption presented for a 300 kW system suggested a COP of only 0.25.

The same company went on to produce a closed cycle version known as Closed cycle air refrigeration (CCAR) (Pelsoci and Bond, 2001) which passed the cold air through a heat exchanger and then recirculated it rather than exhaust it to ambient. Also using more advanced turbo-machinery, a demonstration unit achieved a 211 kW capacity at -73°C, at which temperature its COP was found to be 0.66. At the higher temperature of -57°C, the COP improved to 0.75. The unit also demonstrated one of the advantages of air cycle systems in that its COP only dropped by about 3% when operating at 60% of full capacity.

Commercial semi-open/closed systems have also been developed. Semi-open/closed means that the cold air is introduced into the cooling chamber and then recirculated by extraction from the open chamber. Originally developed by Kajima in Japan and then produced by the Earthship Company, the AIRSTM50 systems were smaller than those previously mentioned, with a capacity of 17.6 kW and two different operating temperatures, -30°C (supply air -54°C) and -60°C (supply air -84°C). Despite the considerable difference in temperatures, COPs of 0.69 were claimed for both. Applications such as rapid freezing of expensive tuna were targeted. One of these systems was installed at a seafood processing plant in Italy, with freezing been carried out in a rotating tumble drum with air at -75°C (Gigiel et al, 2004). Weight loss from the seafood was reduced, as were freezing times.

Another machine developed in Japan by Mitsubishi Heavy Industries (described by Kikuchi et al 2005) was used as the basis for a theoretical study of a spiral freezer presented by Pearson 2006. Based on performance figures published by Andou and Okuda 2004, this study compared conventional freezing at -28°C of 450 kg per hour of uncooked burgers with air cycle at -67°C and found that freezing time reduced from 15 to 7 minutes. This would allow a far smaller spiral with lower capital cost. However,

the energy used by the air cycle system was around 25% higher than the conventional version, which was reflected in the running costs. By comparison the running costs for a similar liquid nitrogen system were calculated to be approximately 8 times greater than the air cycle running costs.

Smaller scale experimental studies have indicated other possible food processing uses. For example, Russell et al. (2000) used an air cycle system to supply cold air to a fluidised bed freezer for small Individually Quick Frozen (IQF) food products such as prawns and peas. Foster et al 2011 used both the cooling and heating in a combined system for cooking burgers and then rapidly freezing them.

Interest in air cycle has continued (for example Shuo et al. (2012) described an experimental study of an air cycle quick-freezing system but uptake and application has not been widespread. As well as comparative efficiencies only being favourable at low temperatures or in comparison with liquid nitrogen, the capital cost of very low volume production machines is typically prohibitive.

Scope 1 emissions savings (% or another quantifiable metric)	Scope 1 emission reduction possible if the waste heat replaces fossil fuel cooking.
Quality of scope 1 emissions information	NA
Scope 2 emissions savings (% or another quantifiable metric)	For low temperature freezing energy savings are possible but very variable and dependant on the technology being replaced.
Quality of scope 2 emissions information	Low.
Availability barriers	Cost, availability, suitability of limited applications.
TRL level	7
Maintainability issues	Turbo-machinery is generally very reliable and maintenance costs are less than conventional refrigeration systems.
Legislative concerns	None.
Payback time (years)	No direct information, but Shaw et al 1995 estimated a 300 kW ColdBlast system with freezing tunnel would cost 1.8 million USD.

Andou K. and Okuda S., 2004. Development of air refrigerating system, In 6th IIR Gustav Lorentzen Conference on Natural Working Fluids, Glasgow.

Foster, A.M., Brown, T., Gigiel, A.J., Alford, A. and Evans, J.A., 2011. Air cycle combined heating and cooling for the food industry. *International Journal of Refrigeration*, 34(5), pp.1296-1304.

Gigiel A., Polonara F. and Di Nicola G., 2004. Rapid freezing of food in an open cycle freezer, Proc. 6th IIR Gustav Lorentzen Conference on Natural Working Fluids, Glasgow.

Kikuchi, S., Okuda, S., Igawa, H., Morii, S., Mitsuhashi, M. and Higashimori, H.I.R.O.T.A.K.A., 2005. Development of air cycle system for refrigeration. *MITSUBISHI JUKO GIHO*, 42(4), p.194.

Shuailing, L., Guoyuan, M., Shuxue, X., Yuexuan, G., Xiaoya, J. and Guoqiang, W., 2023. A review of reverse Brayton air cycle refrigerators. *International Journal of Refrigeration*, 150, pp.200-214.

Pearson S.F., 2006. Air cycle refrigerating system for continuous freezer, IIR Conference, Palmerston North, New Zealand.

Pelsoci, T. and Bond, P.J., 2001. Closed-Cycle Air Refrigeration Technology. In Economic Case Study of an ATP-funded Project.

Russell S.L., Gigiel A.J., James S.J., 2000. Development of a fluidised bed food freezing system that can use air cycle technology, IChemE Food and Drink 2000, Birmingham, 78-81.

Shaw, R.J. Kiczek E.F. and Rossman J.C., 1995. Coldbast™ air cycle freezing system, Vol IIIa, Proc. 19th International Congress of Refrigeration, The Hague, Netherlands, 684-691.

Shuo, Z., Xianmin, G. and Liang, Z., 2012, November. Experimental study of air cycle refrigeration system for quick-freezing. In International Conference on Cooling and Heating Technologies (pp. 1-9).

12.1.2 Ambient cooling

Removal of high temperature heat loads from foods which have just been cooked or baked can be achieved using ambient air drawn from outside the production facility. Considerable amounts of the initial peak heat loads from such products can be transferred to the ambient air, which in the UK for example is typically below 20°C for around 95% of the year and below 10°C for approximately 45% of the year. This reduces the proportion of the heat load which needs to be removed using vapour compression refrigeration or other cooling systems. At the same time, it can remove a considerable amount of the moisture leaving the products during the cooling process, avoiding excessive icing up and defrosting of the refrigeration evaporators. Combining these factors allows ambient cooling to assist in removing the heat loads using less energy and maintaining throughputs at higher efficiencies in the active cooling systems.

The potential for reducing energy consumption using ambient cooling has not been widely reported, but some studies provide examples. A theoretical study carried out by Evans (2009), and subsequently reported by James et al. (2010), used mathematical modelling to estimate the chilling times for a Bolognese sauce ready meal with varied ambient cooling periods, using ambient air at 20°C. Examples of the reduction in heat load are shown in Figure 62 and Figure 63. Reduction in active (refrigerated) cooling times are shown in Figure 64.

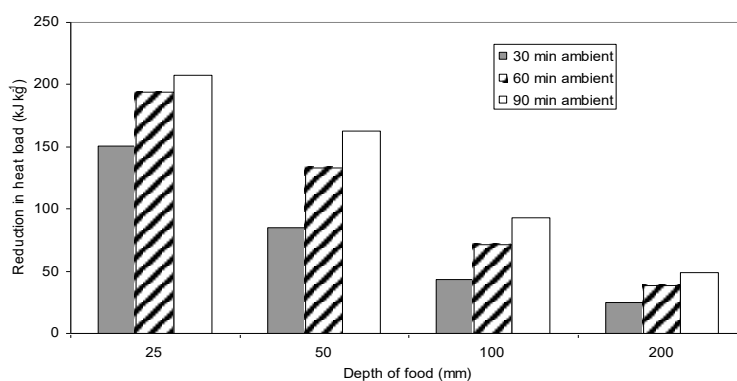


Figure 62. Reduction in heat load during active (refrigerated) cooling for Bolognese sauce cooled to a mean temperature of 5°C in air with a heat transfer coefficient of 40 W m⁻².K.

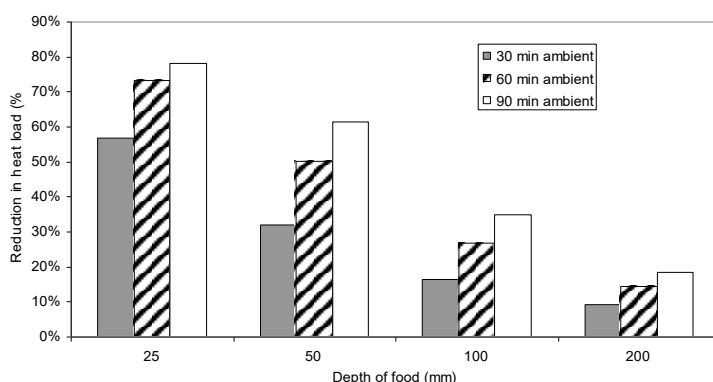


Figure 63. Percentage reduction in heat load during active (refrigerated) cooling for Bolognese sauce cooled to a mean temperature of 5°C in air with a heat transfer coefficient of 40 W m⁻².K.

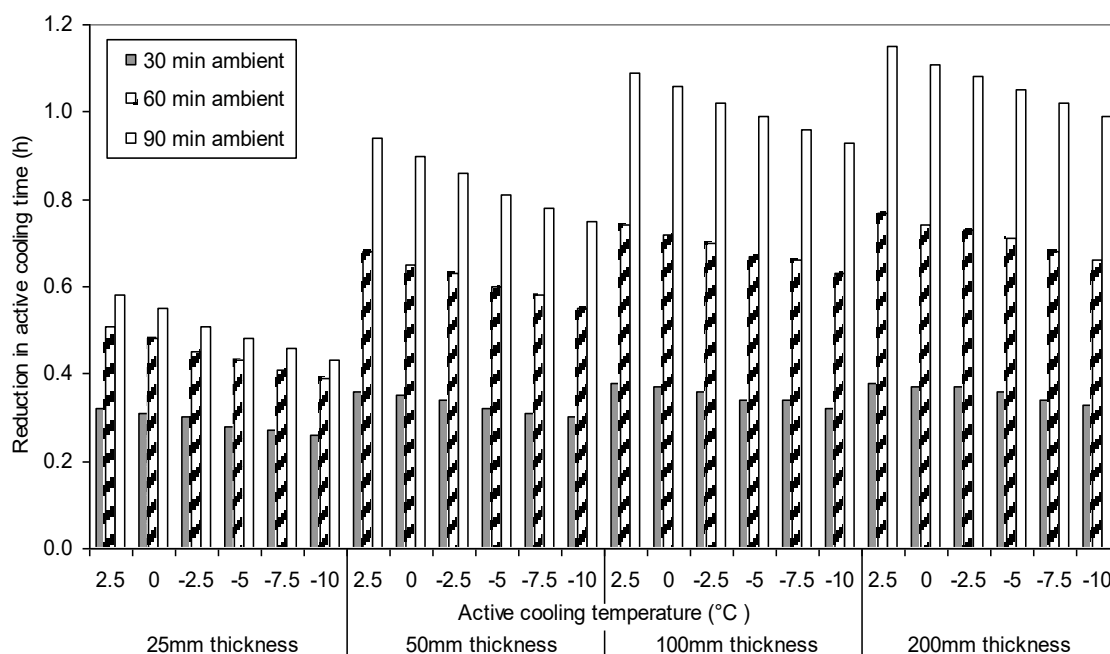


Figure 64. Reduction in active (refrigerated) cooling time (excluding ambient cooling period) for Bolognese sauce cooled to a mean temperature of 5°C in air with a heat transfer coefficient of 40 W m⁻².K.

Evans (2009) reported that the heat removed during a 1-hour ambient cooling period was 134 kJ/kg, equivalent to 49% of the total heat load needing to be removed. Evans (2009) also showed that for small and thin potato hash browns at 80°C following frying, a 5-minute, 22°C ambient cooling stage, removed 31% of the total heat load, while a longer 10-minute ambient cooling stage removed 44% of the load. In addition, large quantities of water from the hash browns were extracted during the ambient stage instead of freezing on the spiral freezer's evaporators.

As well as the above products, James et al. (2010) also presented results from two-stage cooling of cooked pies, claiming significant reductions in the heat loads due to the use of ambient first stages. As an example, a 0.5-hour ambient cooling stage at 10°C (which would not always be possible) was reported to have removed 50% of the total heat load.

Requirements for using ambient cooling are additional space, (e.g. cooling tunnel or spiral cooler), a supply of hygienic air (filtered if required) and power to drive circulation fans. The fan power is

however a fraction of the power used by active cooling systems, which may include similar circulation fans or pumps as well as vapour compression refrigeration or other plant.

Scope 1 emissions savings (% or another quantifiable metric)	No information, but potentially smaller charge refrigeration systems may be possible.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Between 31 and 50% of the total product loads of several different products removed by various types of ambient cooling stage. (James et al, 2010 and Evans 2009).
Quality of scope 2 emissions information	Basis limited to a small number of experiments and mathematical modelling, with no measurement of actual energy consumption.
Availability barriers	None
TRL level	9
Maintainability issues	Hygiene requirements would necessitate filtration of air, but this is commonplace for applications such as bread bakeries.
Legislative concerns	None
Payback time (years)	No information available.

Evans, J.A. (2009). The use of ambient cooling to reduce energy consumption in the food industry. FRPERC Defra project report, 11pp. <https://www.grimsby.ac.uk/documents/defra/manf-ambientcooling.pdf>.

James, S. J., Senso, Y., and James, C. (2010). The energy saving potential of ambient cooling systems. Sustainability and the cold chain, meeting of IIR commissions B1, B2, C2, D1 and D2, Cambridge, UK.

12.1.3 Antifreeze proteins

Antifreeze proteins lower the freezing point of water in biological materials and also prevent the growth of ice crystals and recrystallisation during frozen storage. They are naturally present in many fish and invertebrates as well as plants to prevent them freezing in cold weather or cold water and have been synthesised on a limited industrial scale.

Their ability to impact the formation and growth of ice crystals has led to suggested application in products such as ice cream, where quality can be adversely affected by slow (and hence larger) ice crystal formation and by growth and recrystallisation of ice crystals at warmer and fluctuating frozen temperatures. Use of antifreeze proteins in meat has also been studied for quality reasons, with the aim of reducing drip loss (Payne et al 1994; Payne and Young, 1995). Ustun and Turhan 2015, and Venketesh and Dayananda 2008 reviewed the functions, sources and potential uses of antifreeze proteins in the food industry.

The proteins could also have an impact on energy consumption in freezing processes by reducing the proportion of water in a food which is frozen at a particular temperature. This would reduce the amount of latent heat which needs to be removed to get to frozen storage temperatures. The energy saving is potentially significant as most of the heat extracted from products in freezing is latent heat. However, with the focus being on quality aspects of their application, the impact on energy consumption has not been reported.

The addition of the proteins in food has been identified as a possible risk to people susceptible to allergic reactions, and this would require extensive research before commercial exploitation (Ustun

and Turhan 2015, and Venketesh and Dayananda 2008). With low yields of proteins from natural sources, cost may be another barrier unless synthesisation can be exploited.

Scope 1 emissions savings (% or another quantifiable metric)	No information, but potentially smaller charge refrigeration systems may be possible.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	No data reported.
Quality of scope 2 emissions information	No data.
Availability barriers	Low yields of natural proteins, high costs.
TRL level	Low, function has been proven but use in the food industry has not been widely studied. TRL4-5
Maintainability issues	Unknown
Legislative concerns	Possible allergenic risk.
Payback time (years)	Unknown

Payne, S. R., and Young, O. A. (1995). Effect of pre-slaughter administration of antifreeze proteins on frozen meat quality. *Meat Science*, 41, 147–155.

Payne, S. R., Sandford, D., Harris, A., and Young, O. A. (1994). The effects of antifreeze proteins on chilled and frozen meat. *Meat Science*, 37, 429–438.

Ustun, N.S. and Turhan, S., 2015. Antifreeze proteins: Characteristics, function, mechanism of action, sources and application to foods. *Journal of food processing and preservation*, 39(6), pp.3189-3197.

Venketesh S. and Dayananda C. (2008) Properties, Potentials, and Prospects of Antifreeze Proteins, *Critical Reviews in Biotechnology*, 28:1, 57-82, DOI: 10.1080/07388550801891152.

12.1.4 Cold recovery on LNG driven fishing vessels (fish)

Fishing vessels are significant energy consumers, and also in many cases the first step in which processing (e.g, chilling, freezing, filleting) of several wild caught fish products begin. Transitioning from conventional fossil fuels to liquefied natural gas (LNG) for fishing vessels can reduce GHG emissions by up to 20%, as discussed in a separate review (Alternative fuels for fishing vessels). This review examines the potential added benefit of utilizing the 'waste cold' produced during the onboard LNG re-gasification process.

To use LNG as a fuel, it needs to be converted into gas through regasification process, which typically involves warming the cold LNG (-162°C) by e.g. heat exchange with seawater. The key idea is to capture and utilise the cooling energy ('coolth') from the LNG stream, which is usually discarded. This concept has been studied in various contexts, including onshore LNG facilities (Astolfi et al., 2017), refrigerated vehicles (Tan et al., 2010) and marine vessels (Baldasso et al., 2020; Xiao et al., 2023; Yao et al., 2021). Baldasso et al. (2020) proposed several applications for utilizing recovered cold from LNG, including supporting onboard HVAC systems (fuel savings of 0.43 - 0.84%), serving as a cold sink for Organic Rankine Cycle (ORC) systems (fuel savings of 0.87 - 2.34%) and enhancing engine performance by cooling intake air (fuel savings of 0.41 - 0.44%). Both Xiao et al. (2023) and Yao et al. (2021) examined the design of multi-stage cascade systems to maximise coolth recovery at several temperature levels, achieving exergy efficiency levels of 53.13 - 58.63% for large chemical tankers.

Saeed et al. (2020) investigated the recovery of coolth from LNG regasification on a fishing vessel with a refrigerated seawater (RSW) system. They explored several approaches, such as enhancing the refrigeration system's efficiency by sub-cooling the refrigerant (increasing COP by 4.5 - 8%), directly exchanging heat with the RSW to maintain low fish-tank temperatures, and storing the coolth in a PCM-based thermal energy storage (TES) system. For a 760 kW coastal demersal trawler, the coolth recovery potential varied during different fishing stages, reaching a maximum of 13.63 kW. Currently, only one fishing vessel is known to use LNG coolth recovery for its RSW system, but performance data is unavailable ('Grensesprengerne', 2023).

Scope 1 emissions savings (% or another quantifiable metric)	Transitioning from marine gas oil (MGO) to LNG: up to 20% For fishing vessels: COP increase of 4.5-8% of onboard refrigeration system, translating to less fuel use.
Quality of scope 1 emissions information	Several studies on LNG coolth recovery for large ships, not necessarily relevant for fishing vessels. Utilizing recovered coolth: n/a
Scope 2 emissions savings (% or another quantifiable metric)	None
Quality of scope 2 emissions information	n/a
Availability barriers	Only one source
TRL level	8-9
Maintainability issues	One system is in use, no performance data available
Legislative concerns	n/a
Payback time (years)	n/a

Astolfi, M., Fantolini, A.M., Valenti, G., De Rinaldis, S., Inglese, L.D., Macchi, E., 2017. Cryogenic ORC To Enhance The Efficiency Of LNG Regasification Terminals. Energy Procedia, 4th International Seminar on ORC Power Systems September 13-15th 2017 POLITECNICO DI MILANO BOVISA CAMPUS MILANO, ITALY 129, 42–49. <https://doi.org/10.1016/j.egypro.2017.09.177>.

Baldasso, E., Mondejar, M.E., Mazzoni, S., Romagnoli, A., Haglind, F., 2020. Potential of liquefied natural gas cold energy recovery on board ships. J. Clean. Prod. 271, 122519–122519. <https://doi.org/10.1016/j.jclepro.2020.122519>.

Grensesprengerne [WWW Document], 2023. URL <https://www.innovasjon Norge.no/artikkel/grensesprengerne> (accessed 9.27.24).

Saeed, M.Z., Widell, K.N., Hafner, A., Nordtvedt, T.S., Svendsen, E.S., 2020. Cryogenic cold utilization and system integration possibilities for LNG-driven fishing vessels, in: Refrigeration Science and Technology. International Institute of Refrigeration, pp. 457–464. <https://doi.org/10.18462/iir.iccc.2020.292842>.

Tan, H., Li, Y., Tuo, H., Zhou, M., Tian, B., 2010. Experimental study on liquid/solid phase change for cold energy storage of Liquefied Natural Gas (LNG) refrigerated vehicle. Energy 35, 1927–1935. <https://doi.org/10.1016/j.energy.2010.01.006>.

Xiao, X., Xu, X., Wang, Z., Liu, C., He, Y., 2023. Research on a Novel Combined Cooling and Power Scheme for LNG-Powered Ship. J. Mar. Sci. Eng. 11, 592. <https://doi.org/10.3390/jmse11030592>.

Yao, S., Wang, M., Zhao, R., 2021. Cold exergy recovery in LNG powered ships with a new integral intermediate fluid vaporiser. AIP Adv. 11, 035022. <https://doi.org/10.1063/5.0034865>.

12.1.5 Dehydrofreezing

Dehydrofreezing involves the partial dehydration of foodstuffs, using either air or more commonly osmotic solutions such as sucrose, glucose, fructose, sorbitol, corn syrup, and salts. The partially dehydrated products are then frozen. With lower water content, freezing is faster and typically less damage is caused by ice crystal formation, offering claimed advantages of better texture, quality and reduced subsequent drip loss on thawing.

The process has mainly been studied for use with high water content fruits and vegetables. James et al 2014 presented comprehensive lists of products and conditions reported in the scientific literature. It was noted that research efforts have focussed almost exclusively on quality aspects.

However, one of the benefits offered by dehydrofreezing is that by reducing the proportion of water in the food by dehydration, less latent heat will have to be removed to freeze it. This translates into lower energy consumption (as claimed by Huxsoll 1982 and by Mascheroni, 2007). Crivelli et al. (1987) estimated energy savings of 27% when dehydrofreezing compared with conventional freezing.

A further factor in energy reduction is that shorter freezing processes are possible after dehydration, meaning that refrigeration systems can be used more efficiently. An example of this was given by Mascheroni, 2007, who presented freezing curves for products which had been dehydrated to various different extents (see Figure 4).

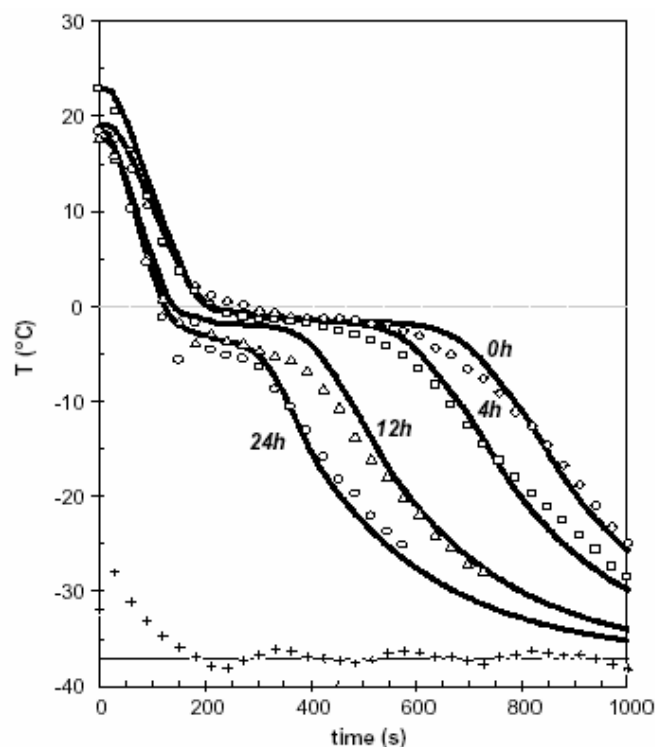


Figure 65. Product being frozen after dehydration for various times (from Mascheroni, 2007).

Despite the potential advantages, use of dehydrofreezing has not become widespread, possibly due to complication of processing and capital cost. James et al. (2015) postulated that the majority of any such commercial uses are likely to use simple air drying in preference to osmotic dehydration.

Scope 1 emissions savings (% or another quantifiable metric)	No information, but potentially smaller charge refrigeration systems may be possible.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	27% energy savings compared with conventional freezing Crivelli et al. (1987)
Quality of scope 2 emissions information	Poor, very limited information.
Availability barriers	Dedicated equipment is mainly available in the American market and is not widespread (James et al., 2015).
TRL level	9
Maintainability issues	Air drying simpler to use and maintain than osmotic, but each requires an additional process compared with conventional freezing.
Legislative concerns	Uptake of various osmotic solutions has been considered and studied, and they would need to be food grade for commercial use.
Payback time (years)	Unknown

Crivelli, G., Torregiani, D., Bertolo, G., Forni, E., and Maestrelli, A. (1987). Research on dehydrofreezing of fruit. Part 1: utilization for the preparation of fruit salad. *Annales Istituto Sperimentale Valorizzazione Tecnologica dei Prodotti Agricoli*, 18, 63–67.

Huxsoll, C. C. (1982). Reducing the refrigeration load by partial concentration of foods prior to freezing. *Food Technology*, 36(5), 98–102.

James, C., Purnell, G. and James, S.J., (2014). A critical review of dehydrofreezing of fruits and vegetables. *Food and bioprocess technology*, 7, pp.1219-1234.

Mascheroni R.H. (2007). Overview on new freezing technologies. Refrigeration, energy and environment: challenges and perspectives 5th Alcuefood Seminar (São Paulo) - 27-29 March, 2007.

12.1.6 Electrostatic field freezing

Electrostatic field (EF) or pulsed electric field (PEF) freezing has similarities in operation and intent with magnetic field freezing. The application of electric fields during freezing at various voltage intensities aims to control ice nucleation by aligning the water molecules in the food, offering shorter freezing times and smaller ice crystals (Orlowska et al., 2009). Fallah-Joshagani et al. (2019) found that it raised ice nucleation temperatures in distilled water, salt solutions, mushroom extract and mushrooms. The smaller ice crystals may lead to less damage to cell walls and in turn less drip loss from meat and improved quality of other foods during and after subsequent thawing.

Several types of food have been reported on, with varying intensities and freezing process conditions. Babakin et al 2019 applied EF (in this case termed electroconvection) to meat samples and found reduced freezing times and weight loss, Xanthakis et al. (2013) reported reductions in ice crystal size and freezing time of pork at high (microwave) frequencies, while Dalvi-Isfahan et al. (2016) achieved only weak effects on the kinetics of the freezing process for lamb, but nevertheless found much smaller and more spherical ice crystals, reducing subsequent drip loss. For salmon, electroconvection reduced ice crystal size, thawing time and weight loss (Li et al., 2020). Jha et al. (2017) combined EF with magnetic fields during freezing of apple and potato and found a more even distribution of ice crystals and reduction of loss during thawing.

With further similarity to magnetic field freezing, the literature on EF is focused not on energy consumption but on quality and weight loss. Potentially faster processing could lead to reduced energy consumption through shorter operation of the refrigeration systems.

Scope 1 emissions savings (% or another quantifiable metric)	Unknown.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Faster freezing could allow shorter run times for refrigeration systems, but no data have been presented.
Quality of scope 2 emissions information	n/a
Availability barriers	Commercial, full-scale systems are not available at this time.
TRL level	5 - 6
Maintainability issues	Unknown.
Legislative concerns	Effects are better at higher voltage intensities, but these may be problematic from a safety viewpoint.
Payback time (years)	Unknown.

Babakin, B.S., Voronin, M.I., Belozerov, G.A., Babakin, S.B. (2019). Study of freezing process and short term storage of meat using electroconvection. 25th IIR international congress of refrigeration “Refrigeration science and technology proceedings”. Montreal, Quebec, Canada.

Dalvi-Isfahan, M., Hamdami, N., Le-Bail, A. (2016). Effect of freezing under electrostatic field on the quality of lamb meat. *Innovative Food Science and Emerging Technologies*, 37(Part A), 68–73.

Fallah-Joshaqani, S., Hamdami, N., Keshavarzi, E., Keramat, J., Dalvi-Isfahan, M. (2019). Evaluation of the static electric field effects on freezing parameters of some food systems. *International Journal of Refrigeration*, 99, 30–36.

Jha, P.K., Xanthakis, E., Jury, V., Le-Bail, A. (2017). An overview on magnetic field and electric field interactions with ice crystallisation; application in the case of frozen food. *Crystals*, 7(10), Article 299.

Li, J., Shi, J., Huang, X., Zou, X., Li, Z., Zhang, D. et al. (2020). Effects of pulsed electric field on freeze-thaw quality of Atlantic salmon. *Innovative Food Science and Emerging Technologies*, 65, Article 102454.

Orlowska, M., Havet, M., Le-Bail, A. (2009). Controlled ice nucleation under high voltage DC electrostatic field conditions. *Food Research International*, 42(7), 879–884.

Roujia, Z., Shiyi L., Jiyong, S., Xiaobo, Z. (2022). Quick-freezing device with cooperating high-voltage pulse electric field and low-frequency alternating magnetic field and method for quick-freezing of instant rice through quick-freezing device. Patent CN, no. 114009660.

Xanthakis, E., Havet, M., Chevallier, S., Abadie, J., and Le-Bail, A. (2013). Effect of static electric field on ice crystal size reduction during freezing of pork meat. *Innovative Food, Science and Emerging Technologies*, 20(0), 115–120.

Zhang, R., Ding, F., Zhang, Y., Zhou, C., Zhang, W., Shi, J. et al. (2022). Freezing characteristics and relative permittivity of rice flour gel in pulsed electric field assisted freezing. *Food Chemistry*, 373(Part A), Article 131449.

12.1.7 Heat pipes

The rate at which heat can be conducted through many large food items such as joints of meat and trays of sauces is the governing factor in their chilling, freezing or thawing times. If reducing their thickness is not an option, another approach to improve heat transfer is to insert high conductivity rods or heat pipes. Heat pipes contain refrigerant fluids which evaporate at one end of the pipe and condense at the other, with high rates of heat transfer between them.

Investigations carried out by Ketteringham and James, (2000) showed the benefit of using such devices, including heat pipes, thermosyphons and solid metal rods to increase the cooling rate of hot foods. In experiments with mashed potato the various inserts reduced times to cool from 70°C to 10°C and 3°C by between 6% and 29%, with heat pipes providing the greatest benefit (

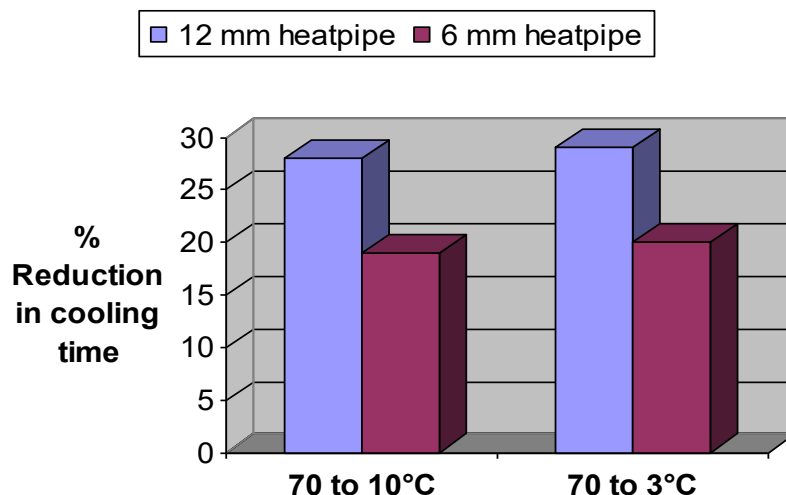


Figure 66). Such time savings could translate into significant energy savings, although these were not estimated. It was noted that while faster cooling could offer improvements in food quality and safety, the materials used for the inserts (or their coatings) would need to be food safe and robust.

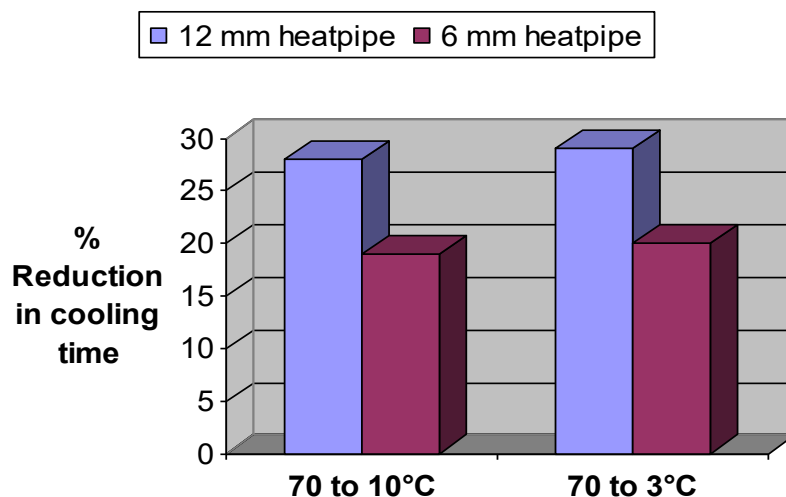


Figure 66. Reduction in cooling time of mashed potato when using high thermal conductivity inserts (Ketteringham and James 2000).

Use of heat pipes inserted into joints of meat for cooking and subsequent cooling was studied by James et al 2005. Heat pipes were found to be able to reduce the cooking time by 50% and reduce the cooling time of bacon joints by over 25%.

James and James (1999) applied heat pipes to the lower temperature processes of freezing and thawing of meat joints. Depending on the size of joint and the diameter of the heat pipes inserted, reductions of up to 42% in freezing time and up to 54.5% in thawing time were achieved. It was however noted that such insertion leads to damage to the product and is complicated by the need to leave the inserts in place after freezing, until they are able to be removed following thawing.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Reduced times for chilling, freezing, thawing and cooking processes have been reported. These should translate into energy savings for shorter processing, but the studies were focused on duration of processing not energy consumption.
Quality of scope 2 emissions information	No energy consumption measured.
Availability barriers	Cost, practicality of insertion and likely damage, food safety of materials used.
TRL level	High for heat pipes in genera (TRL 9), not as high for food processing applications (TRL 4).
Maintainability issues	Robust heat pipes should present few problems, cleaning would be required between uses.
Legislative concerns	No obvious concerns other than hygiene and food safety aspects.
Payback time (years)	Not known.

James C., Araujo M., Carvalho A. and James S.J. (2005). The heat pipe and its potential for enhancing the cooking and cooling of meat joints, *International Journal of Food Science and Technology*, 40, pp 419–423.

James C. and James S.J. (1999). The heat pipe and its potential for enhancing the freezing and thawing of meat in the catering industry, *International Journal of Refrigeration*, 22, pp 414–424.

Ketteringham L, James S (2000), Use of high thermal conductivity inserts to improve the cooling of cooked foods, *Journal of Food Engineering* 45 (1), pp. 49-53.

12.1.8 Hydrofluidisation

Hydrofluidisation utilises a pump that circulates a liquid cooling media through orifices or nozzles to create agitating jets in a refrigeration vessel. This forms a fluidised bed of highly turbulent liquid that agitates product and generates extremely high heat transfer coefficients at the surface of the products (Fikiin 1985, Fikiin 1992, Fikiin and Pham 2003). Suitable refrigerant media include brines, soluble carbohydrates (such as sucrose, invert sugar, glucose (dextrose), fructose and other mono- and disaccharides) with additions of ethanol, salts and glycerol. Freezing rates for fish and vegetables have been shown to exceed those for Individually Quick Frozen (IQF) products, with heat transfer coefficients exceeding $900 \text{ W m}^{-2} \text{ K}^{-1}$ (Fikiin, 1992, Fikiin and Pham, 1985). This leads to low weight loss as the surface of the product is frozen extremely rapidly.

Considerable experimental research and mathematical modelling has been reported on the heat transfer coefficients and freezing times which can be achieved with different sizes, shapes and types of foods, and with different media and equipment (for example Palacz et al 2021, Peralta 2012, Stebel et al 2021, Stebel 2022 and others). Information on energy consumption is however not available, but for small products that are frozen fast, the energy use may be low. For some products, the heat transfer rates may be limited by conduction through the product rather than that between the cooling fluid and the product, and in such cases the increased pump energy required for hydrofluidisation may outweigh the benefits in some circumstances.

Scope 1 emissions savings (% or another quantifiable metric)	No information.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Rapid processing could reduce energy consumption, but no data has been presented.
Quality of scope 2 emissions information	n/a
Availability barriers	None.
TRL level	9
Maintainability issues	As with other immersion processes, hygiene and disposal of the liquid coolant presents additional challenges compared with use of air to cool.
Legislative concerns	None.
Payback time (years)	Unknown.

Fikiin, A.G., 1992. New method and fluidized water system for intensive chilling and freezing of fish. Food Control 3 (3), 153–160.

Fikiin, K., 2003. Novelties of Food Freezing Research in Europe and Beyond. Flair-Flow Europe Synthetic Brochure, INRA: Institut National de la Recherche Agronomique, Paris, France.

Fikiin, K., 2008. Emerging and novel freezing processes chapter 5. Frozen Food Science and Technology. Wiley Blackwell, Oxford, pp. 101–123.

Fikiin, K., Fikiin, A.G., 1998. Individual quick freezing of foods by hydrofluidisation and pumpable ice slurries. Refrigeration Science and Technology, International Institute of Refrigeration 319–326.

Palacz, M., Piechnik, E., Halski, M., Stebel, M., Adamczyk, W., Eikevik, T.M. and Smolka, J., 2021. Experimental analysis of freezing process of stationary food samples inside a hydrofluidisation freezing chamber. International Journal of Refrigeration, 131, pp.68-77.

Peralta, J.M., Rubiolo, A.C. and Zorrilla, S.E., 2012. Mathematical modeling of the heat and mass transfer in a stationary potato sphere impinged by a single round liquid jet in a hydrofluidization system. Journal of food engineering, 109(3), pp.501-512.

Stebel, M., Smolka, J., Palacz, M., Piechnik, E., Halski, M., Knap, M., Felis, E., Eikevik, T.M., Tolstorebrov, I., Peralta, J.M. and Zorrilla, S.E., 2021. Numerical modelling of the food freezing process in a quasi-hydrofluidisation system. Innovative Food Science and Emerging Technologies, 74, p.102834.

Stebel, M., Smolka, J., Palacz, M., Eikevik, T.M. and Tolstorebrov, I., 2022. Numerical modelling of conjugate heat and mass transfer during hydrofluidisation food freezing in different water solutions. Innovative Food Science and Emerging Technologies, 75, p.102898.

12.1.9 Ice bank chilling

Chilling of food products such as unwrapped vegetables and meat in air-based chillers results in weight loss as water from the product evaporates into the dry air. Raising the humidity of the air during the process can reduce this weight loss. This can be achieved using an ice bank system. Such systems build up a bank of ice in a tank of water, and heat is exchanged between the water and air from the cooling chamber, resulting in high humidity air at temperatures close to 0°C. In addition to saving weight loss, additional advantages are that the bank of ice can be built up over long periods of time (possibly using off peak electricity) with smaller refrigeration systems than those used in blast chillers. By using the compressors at full power, they will operate at peak efficiency and the ice bank can be used to overcome the peak heat loads in the initial stages of chilling.

Ice banks have seen application in chilling and storage of fruit and vegetables (see for example Farrimond et al 1979) and for milk (e.g. Jordan et al 2018). These authors and others highlighted the above advantages but did not measure or estimate actual energy usage. Their use in pig carcass chilling has been investigated by Gigiel and Badran (1988), who compared the value of the weight saved with the cost of energy required by a conventional air blast system to achieve the same cooling process. Actual energy consumption for the ice bank was not measured.

Scope 1 emissions savings (% or another quantifiable metric)	Smaller refrigeration systems with smaller refrigerant charges may have lower direct emissions.
Quality of scope 1 emissions information	No data.
Scope 2 emissions savings (% or another quantifiable metric)	Smaller refrigeration systems running at peak efficiency will use less energy than conventional systems designed to meet peak heat loads. However quantitative data on such savings are not available.
Quality of scope 2 emissions information	No data.
Availability barriers	None.
TRL level	9
Maintainability issues	Consideration of hygiene related to the water in the systems is required. In addition, maintaining high surface water contents is potentially favourable for bacterial growth (although the studies reviewed did not present any data to this effect).
Legislative concerns	None.
Payback time (years)	Unknown.

Farrimond, A., Lindsay, R.T. and Neale, M.A., 1979. The ice bank cooling system with positive ventilation. *International Journal of Refrigeration*, 2(4), pp.199-205.

Gigiel, A. and Badran, R., 1988. Chilling and storage of pig carcasses using high humidity air as produced by an ice bank cooler. *International Journal of Refrigeration*, 11(2), pp.100-104.

Jordan, R.A., Cortez, L.A., Silveira Jr, V., Cavalcanti-Mata, M.E. and Oliveira, F.D.D., 2018. Modeling and testing of an ice bank for milk cooling after milking. *Engenharia Agrícola*, 38, pp.510-517.

12.1.10 Ice nucleation proteins (INPs)

In the air, ice crystals of pure water grow at -38°C ([Hoose and Möhler, 2012](#)). In nature, ice crystals grow at much warmer temperatures because various surfaces allow ice nucleation. INPs reduce the

ability of water-rich materials (such as many foodstuffs) to supercool below their initial freezing point without formation of ice. According to Petzold, G., and Aguilera, J. M. (2009) these substances are present in several biological organisms such as bacteria, fungi, insects, and even frogs.

Li and Lee, 1995 described their use in fish muscle with an initial freezing point of -1°C . Without the nucleation protein the fish muscle supercooled to -4.9°C before nucleation occurred, whereas with the protein nucleation occurred at -1.5°C . This was said to reduce freezing time by between 12 and 33%, reducing the energy consumption for freezing. In addition, it was suggested that higher storage temperatures could be used as the protein ensured that the food was properly frozen at the warmer temperature. The authors gave an example of raising the storage temperature from -40°C to -30°C , saving 6.3% of the refrigeration plant energy (although it should be noted that -40°C is a very low storage temperature). The use of the proteins is also claimed to improve frozen food quality (e.g. Soviezi et al, 2023).

As the ice nucleation proteins are commonly derived from bacterial sources (usually of genera *Pseudomonas*, *Erwinia* and *Xanthomonas*) care needs to be taken in their application to ensure that they are safe, non-toxic and non-pathogenic (Li and Lee, 1995 and Li and Lee, 1998).

According to James et al. (2015) most studies have been on model solutions or liquid foods and at a laboratory scale and they have found no evidence of them being used for any commercial products.

Scope 1 emissions savings (% or another quantifiable metric)	Quicker freezing and warmer frozen storage temperatures could allow use of smaller refrigeration systems with lower charge.
Quality of scope 1 emissions information	Low.
Scope 2 emissions savings (% or another quantifiable metric)	6.3% of storage refrigeration plant.
Quality of scope 2 emissions information	Limited.
Availability barriers	Large scale adoption would require industrial production of the proteins and further research into safety aspects.
TRL level	7 to 8.
Maintainability issues	No obvious issues.
Legislative concerns	Food safety aspects may require further research.
Payback time (years)	Unknown.

Hoose C, Möhler O. Heterogeneous ice nucleation on atmospheric aerosols: a review of results from laboratory experiments. *Atmospheric Chemistry and Physics*. 2012;12:9817–9854. doi: 10.5194/acp-12-9817-2012.

James, C., Purnell, G. and James, S.J., 2015. A review of novel and innovative food freezing technologies. *Food and bioprocess technology*, 8, pp.1616-1634.

Li, J., and Lee, T. C. (1995). Bacterial ice nucleation and its potential application in the food industry. *Trends in Food Science and Technology*, 6, 259–265.

Li, J., and Lee, T. C. (1998). Bacterial extracellular ice nucleator effects on freezing of foods. *Journal of Food Science*, 63(3), 375–381.

Petzold, G., and Aguilera, J. M. (2009). Ice morphology: Fundamentals and technological applications in foods. *Food Biophysics*, 4(4), 378–396.

Soveizi, N., Latifi, A.M., Mehrabian, S. and Akhavan Sepahi, A., 2023. Bacterial Ice Nucleation Proteins: Features, Structure, and Applications. *Journal of Applied Biotechnology Reports*, 10(3), pp.1041-1054.

12.1.11 Impingement cooling/freezing

Air impingement technology directs high velocity (typically up to 50 m.s⁻¹) air jets via nozzles or slots onto the surface of the food being processed. Rates of surface heat transfer are greatly increased in comparison with conventional forced air equipment. This can offer quicker processing or adjustments to processing temperature, particularly for thinner products where convection from the surface is the predominant mode of heat transfer.

A variety of processes can benefit from impingement, include cooking (e.g. Altay et al., 2023) and baking (reviewed by Chhanwal et al., 2018), chilling and freezing (Dirita et al 2007, Marazani et al., 2017, Yang et al., 2019), thawing (Anderson and Singh, 2006, and Bozatto et al., 2021) and drying (Modeira, 2001). In addition to application-specific studies, many fundamental and theoretical studies have been published aimed at aspects such as optimisation of flow (Sakhar and Singh, 2004 and Sarkar et al., 2004).

In terms of performance and efficiency, Chhanwal et al. (2018) reported that the rates of heat transfer for an example baking process were increased by a factor of 4, reducing baking times by a half. Such improvements allowed the oven temperature to be reduced by 25°C to achieve the same baking time.

For freezing of thin products like hamburgers and other meat patties, Salvadori and Mascheroni (2022) (partly based on the results of Sundsten et al., 2001) found that use of impingement compared with air blast freezing reduced freezing times by between 62% and 79% depending on thickness. This made possible freezing durations similar to those in liquid nitrogen freezer at considerably lower cost. Yang et al 2017 reported impingement freezing times for shrimp which were 9.5 times shorter than natural convection.

Bozatto et al. (2021) used impingement for thawing of a thin chicken product and found reductions of up to 85% in thawing time compared to air thawing.

Scope 1 emissions savings (% or another quantifiable metric)	While impingement increases heat transfer and reduces processing times, the impact of this on reducing size and charge of refrigeration systems is less clear.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Faster processing times should lead to energy reductions as long as the increased fan energy required by impingement is not greater than the reduced energy due to the shorter times. Alternatively, savings are possible from raising freezing temperatures or reducing oven temperatures while maintaining similar processing times to conventional air blast or oven systems. It is difficult to enumerate emission savings based on the available information.
Quality of scope 2 emissions information	Low - energy consumption is often mentioned as being lower but without data to back up the statements.
Availability barriers	None.
TRL level	9
Maintainability issues	More powerful fans may require additional maintenance, impingement nozzles or plates may require more cleaning.

Legislative concerns	None.
Payback time (years)	Unknown.

Altay, Ö., Selçuk, E., Abacı, Ö., Erdem, F., Dirim, S.N., Şentürk, U. and Kaymak-Ertekin, F., 2023. Recent progress in food processing applications of air impingement technology: A review. *Comprehensive Reviews in Food Science and Food Safety*.

Anderson, B.A. and Singh, R.P., 2006. Modeling the thawing of frozen foods using air impingement technology. *International Journal of Refrigeration*, 29(2), pp.294-304.

Bozzato, A., Pippia, E., Tiberi, E. and Manzocco, L., 2021. Air impingement to reduce thawing time of chicken fingers for food service. *Journal of Food Processing and Preservation*, 45(11), p.e15962.

Chhanwal, N., Bhushette, P.R. and Anandharamakrishnan, C. Current Perspectives on Non-conventional Heating Ovens for Baking Process—a Review. *Food Bioprocess Technol* 12, 1–15 (2019).

Dirita, C., De Bonis, M.V. and Ruocco, G., 2007. Analysis of food cooling by jet impingement, including inherent conduction. *Journal of Food Engineering*, 81(1), pp.12-20.

Marazani, T., Madyira, D.M. and Akinlabi, E.T., 2017. Investigation of the parameters governing the performance of jet impingement quick food freezing and cooling systems—a review. *Procedia Manufacturing*, 8, pp.754-760.

Moreira, R.G., 2001. Impingement drying of foods using hot air and superheated steam. *Journal of Food Engineering*, 49(4), pp.291-295.

Sarkar, A., Nitin, N., Karwe, M.V. and Singh, R.P., 2004. Fluid flow and heat transfer in air jet impingement in food processing. *Journal of food science*, 69(4), pp.113-122.

Sarkar, A. and Singh, R.P., 2004. Air impingement technology for food processing: visualization studies. *LWT-Food Science and Technology*, 37(8), pp.873-879.

Salvadori, V.O. and Mascheroni, R.H., 2002. Analysis of impingement freezers performance. *Journal of Food Engineering*, 54(2), pp.133-140.

Sundsten S, Andersson A and Tornberg E. 2001. The effect of the freezing rate on the quality of hamburger. In: *Rapid cooling of food, meeting of IIR Commission C2, Section 2, Bristol, UK, 28–30 March 2001*, pp.181–186.

Yang, D., Xie, J., Tang, W., Wang, J. and Shu, Z., 2019. Air-impingement freezing of peeled shrimp: Analysis of flow field, heat transfer, and freezing time. *Advances in Mechanical Engineering*, 11(3), p.1687814019835040.

12.1.12 Localised cooling

The use of localised air delivery systems to maintain the temperature of food directly was considered by Burfoot et al. (2004) as an alternative to controlling the temperature of entire food production areas. The system utilised localised air delivery systems consisting of air supply ducts located on each side of a conveyor handling the food. By using localised delivery systems savings of up to 26% were obtained when compared to operating the production area at 5°C. Savings of up to 32% were achieved compared to operating at 10°C. In addition, the system was claimed to improve food safety and the conditions for workers.

Wagner et al. (2014) modelled similar approaches used to control temperatures in smaller localised refrigeration housings rather than entire production areas. They suggested that this could reduce total energy demand by up to 65%, although this would be dependent on specific circumstances.

Scope 1 emissions savings (% or another quantifiable metric)	Controlling the temperature of a number of small stations or enclosures instead of entire production areas would seem to offer the chance to reduce the size and charge of refrigeration systems but no data is available.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Although very dependent on specific circumstances, the limited examples found in the literature suggest energy savings up to 65% compared with conditioning entire production areas.
Quality of scope 2 emissions information	Limited.
Availability barriers	None, but requires space for enclosures and ducting, which may impact on production area design and use.
TRL level	9
Maintainability issues	Possibly additional cleaning of enclosures.
Legislative concerns	None.
Payback time (years)	Unknown.

Burfoot D, Reavell S, Wilkinson D and Duke N (2004), Localised air delivery to reduce energy use in the food industry, *Journal of Food Engineering* 62, 23–28.

Wagner, J., Schäfer, M., Schlüter, A., Harsch, L., Hesselbach, J., Rosano, M. and Lin, C.X., (2014). Reducing energy demand in production environment requiring refrigeration—A localised climatization approach. *HVAC&R Research*, 20(6), pp.628-642.

12.1.13 Magnetic field freezing/ Cell Alive System (CAS)

Use of magnetic fields during freezing has received considerable attention in recent years. Various types and classifications have been studied, including magnetic resonance freezing (MRF), oscillating or alternating magnetic field (OMF/AMF), static magnetic field (SMF) and commercial versions such as Cells Alive System (CAS) (described in patents Owada and Kurita, 2001 and Owada, 2007) are available but not widely used. Typically, the various types rely on continuous or pulsed magnetic wave vibrations which impede ice crystallisation, allowing greater supercooling of the foods below their initial freezing points. When the magnetic field is removed the product can freeze rapidly.

Benefits claimed (for example by the commercial manufacturers of CAS) include the ability to freeze and subsequently thaw with no detriment to quality compared with the fresh product. Of greater relevance to the current review, it is claimed that the technology allows more rapid freezing. However, academic studies on a range of food products have found mixed results, with many showing no impact at the low magnetic intensities typically used. This was clearly shown by Belozarov et al. (2023), who included a review of publications on a range of products, including apple and potato (Purnell et al., 2017), pork (Rodriguez et al., 2019 and Tang et al., 2019), cod (Erikson et al., 2020), fish and potato (Suzuki et al., 2007), crab sticks (Otero et al., 2017), garlic (James et al., 2015) and other food types.

Reviews by Kaur and Kumar (2020) on application to fruits and vegetables and by Otero et al. (2016) on application to a range of biological products found similar results, with many researchers reporting no clear benefits, some showing an impact on quality but limited or no impact on freezing time, and a smaller number which did find an impact on freezing time. It was noted by Belozarov et al. (2023) however that many of the studies did not fully describe the conditions and experimental methods

used, and in addition many did not have comparable controls using exactly the same process conditions but without magnetic fields.

In summary it is unclear whether magnetic freezing is likely to offer any reliable benefit in faster freezing. Furthermore, no measurements or estimation of energy consumption were included in the literature, with product quality instead being the main focus.

Scope 1 emissions savings (% or another quantifiable metric)	Unknown.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Faster freezing could offer shorter operation times for freezing systems, but the published studies do not offer and consensus on impact.
Quality of scope 2 emissions information	n/a
Availability barriers	Systems such as CAS are available but have not seen widespread use. The equipment used in most if not all of the studies appear to have been small scale laboratory apparatus.
TRL level	5 - 6.
Maintainability issues	Unknown.
Legislative concerns	Possible concerns if high magnetic intensities are used.
Payback time (years)	Unknown.

Belozarov, G.A., Belozarov, A.G. and Konnov, A.V., 2023. The effect of magnetic and electric fields on the processes of food freezing. Theory and practice of meat processing, 8(3), pp.227-236.

Erikson, U., Kjørsvik, E., Bardal, T., Digre, H., Schei, M., Søreide, T.S. and Aursand, I.G., 2016. Quality of Atlantic cod frozen in cell alive system, air-blast, and cold storage freezers. Journal of aquatic food product technology, 25(7), pp.1001-1020.

James, C., Reitz, B. and James, S.J., 2015. The freezing characteristics of garlic bulbs (*Allium sativum* L.) frozen conventionally or with the assistance of an oscillating weak magnetic field. Food and bioprocess technology, 8, pp.702-708.

Kaur, M. and Kumar, M., 2020. An innovation in magnetic field assisted freezing of perishable fruits and vegetables: A review. Food Reviews International, 36(8), pp.761-780.

Otero, L., Pérez-Mateos, M., Rodríguez, A.C. and Sanz, P.D., 2017. Electromagnetic freezing: Effects of weak oscillating magnetic fields on crab sticks. Journal of Food Engineering, 200, pp.87-94.

Otero, L., Rodríguez, A.C., Pérez-Mateos, M. and Sanz, P.D., 2016. Effects of magnetic fields on freezing: Application to biological products. Comprehensive Reviews in Food Science and Food Safety, 15(3), pp.646-667.

Owada N. Kurita S. 2001. Super-quick freezing method and apparatus therefor. Patent US, no. 6250087B1.

Owada N. 2007. Highly-efficient freezing apparatus and highly-efficient freezing method. Patent US, no. 7237400B2.

Purnell, G., James, C. and James, S.J., 2017. The effects of applying oscillating magnetic fields during the freezing of apple and potato. Food and Bioprocess Technology, 10, pp.2113-2122.

Rodríguez, A.C., James, C. and James, S.J., (2017). Effects of weak oscillating magnetic fields on the freezing of pork loin. *Food and Bioprocess Technology*, 10, pp.1615-1621.

Suzuki, T.; Takeuchi, Y.; Masuda, K.; Watanabe, M.; Shirakashi, R.; Fukuda, Y.; Tsuruta, T.; Yamamoto, K.; Koga, N.; Hiruma, N.; Ichioka, J. and Taki, K. (2007). Test report on effectiveness of magnetic field for food freezing process. JSRAE (Japanese Society for Refrigeration and Air Conditioning Engineering). 2007.10.22-24.

Tang, J., Shao, S. and Tian, C., (2019). Effects of the magnetic field on the freezing parameters of the pork. *International Journal of Refrigeration*, 107, pp.31-38.

12.1.14 Superchilling

Superchilling is a process where the product is reduced to just below (1-2°C) the initial freezing point and is one of several terms used to describe the partial freezing of food products, i.e., 5-30% of the freezable water is frozen, although there is no commonly agreed definition (Bantle et al., 2016). Note that supercooling refers to lowering of food temperature without any ice formation and is listed as a separate review in this roadmap, even though the terms might be used interchangeably in literature. Superchilling has the following advantages according to Kaale and Eikevik (2014): 1) maintains fresh quality; 2) extended shelf life reduces food loss and thereby lower total energy use, 3) For fresh fish, no additional ice necessary during transportation reduce labour and transport costs and lower the environmental impact. no need for ice inside the transport boxes, which means that much more fish can be transported per truck unit which reduces the overall direct emissions. According to Bantle et al. (2016), ice makes up for about 25% of the total payload meaning that 4 trucks can be reduced to 3 and still deliver the same quantity of fish. If transported superchilled

ENOUGH DEMONSTRATOR: SUPERCHILLING

Specialised equipment was developed to enable meat to be maintained at superchilled temperatures. The work focused on a domestic refrigerator but could be further developed for industrial use.

A specialised compartment within a cooling system was designed and developed to facilitate the superchilling process. This compartment was engineered to maintain stable and customisable temperature settings, ensuring that the desired target conditions could be accurately achieved. An autonomous control mechanism enabled the compartment to independently regulate its internal temperature and other environmental conditions, separate from the main cooling unit.

RESULTS

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.

Temperature stability: average product temperature was maintained at approximately -1.5°C (ice fraction was 42%). Temperature fluctuations in the meat remained below ±0.1°C.

Microbial load reduction: delay of at least 10 days in reaching critical microbial thresholds under superchilling compared to chilling.

Oxidative stability: slower progression of lipid oxidation markers, suggesting improved retention of freshness and nutritional value.

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 compartment insulation efficiency.

Sensory acceptability: products retained acceptable sensory properties (appearance, odour, texture) for over 16 days, validated via panel evaluations. Potentially this reduces food waste.

fish enters the market and further stored at traditional refrigeration temperatures, the benefit of increased shelf life is lost.

They however also note that more research is needed to study the undesired effects that have been observed, like formation and growth of ice crystals, and that an important challenge is to control the process during processing and storage. A superchilled state is typically 1-2 K below the initial freezing point of a food, and thus, the process is very temperature sensitive to keep this state. With respect to increased shelf life, Bantle et al. (2016) lists the following results for different products, superchilled and stored: cod fillets (-2.2°C) +14 days shelf life, pork roast (-2.0 °C) +14 days, Atlantic salmon (farmed) (-1.4 and -3.6 °C) +17-21 days, chicken + 15 days and lamb-leg (-1.6°C) + 19 days (i.e., extended shelf life compared to conventional refrigeration). Sørensen et al. (2020) found that superchilling in combination with modified atmosphere packaging (MAP) limited microbial growth, and extended shelf life of Atlantic cod from 15 to 32 days.

The process of superchilling can be carried out using different equipment according to Kaale et al. Fast surface freezing (flowfreezers) of product followed by a period of temperature equalisation at superchilling temperature minimise quality reduction. Different freezer technologies will have different energy intensities and thus impact the indirect emissions savings due to Coefficient of performance and choice of refrigerant.

Iversen et al. (2022) investigated the impact on emissions by transportation of superchilled salmon from Norway to the European market by lorry, or the Asian market by plane. The study included effects from different stages: slaughtering, packing and transportation, and found that for the EU scenario, total emission savings could be upwards to 13% while to the Asian market could be 17%.

Scope 1 emissions savings (% or another quantifiable metric)	Transportation of superchilled salmon: 13-17% due to less transportation need, where no additional ice gives more weight of fish per volume.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	No quantifications found in literature, however, results on extended shelf life, reduced transportation volume etc. indicate emission savings.
Quality of scope 2 emissions information	n/a
Availability barriers	L
TRL level	7-9
Maintainability issues	Challenging to maintain the superchilled state throughout the cold chain
Legislative concerns	n/a – however, food regulations are concerned with ‘frozen’ or ‘chilled’ food, and the concept of superchilling might challenge current legislations.
Payback time (years)	n/a

Bantle, M., Nordtvedt, T.S., Claussen, I.C., Indergård, E., 2016. State of the Art: Superchilling in the Food Processing Industry, in: 4th IIR International Conference on Sustainability and the Cold Chain - Proceedings. International Institute of Refrigeration. <https://doi.org/10.18462/iir.iccc.2016.0001>

Iversen, A., Ziegler, F., Rotabakk, B.T., 2022. Økonomiske og miljømessige effekter av superkjøling av laks. Nofima AS.

Kaale, L.D., Eikevik, T.M., 2014. The development of ice crystals in food products during the superchilling process and following storage, a review. *Trends Food Sci. Technol.* 39, 91–103. <https://doi.org/10.1016/j.tifs.2014.07.004>.

Sørensen, J.S., Bøknæs, N., Mejlholm, O., Dalgaard, P., 2020. Superchilling in combination with modified atmosphere packaging resulted in long shelf-life and limited microbial growth in Atlantic cod (*Gadus morhua* L.) from capture-based-aquaculture in Greenland. *Food Microbiol.* 88, 103405. <https://doi.org/10.1016/j.fm.2019.103405>.

12.1.15 Supercooling

Supercooling of foods and other materials is achieved by lowering their temperature below the initial freezing point without formation of any ice crystals. For example, meat and fish might be cooled to -5°C without any ice formed. This has the potential to save energy as foods can be stored at relatively low temperature without having to remove the latent heat to freeze it. Some of the more novel types of freezing such as high pressure freezing can act as promoters of supercooling (see for example Kang et al., 2020).

In practice the volatile nature of supercooled food makes it difficult to maintain in that state, as ice nucleation can be triggered by events such as physical shock, vibration, and release of pressure (Lin et al., 2023). Once nucleation is triggered, the food will effectively change from supercooled to superchilled (below its initial freezing point but with only a small amount of ice present). The rapid formation of ice warms the product back up in the direction of its initial freezing point, and the benefit of avoiding latent heat removal is lost.

Application of supercooling to a range of food types has been studied, with examples being meat (Kim et al., 2022, Park et al., 2022, You et al., 2020), fish (Fukuma et al., 2012, Kang et al., 2020, Park et al., 2021 and 2022), fruit and vegetables (Cox and Moore, 1997, Diehl and Wright, 1924, Fuller and Wisniewski, 1998, James et al., 2009, 2011, Kobayashi et al., 2019, Koide et al., 2022, Lucas, 1954, Martins and Lopes, 2007, You et al., 2021) and various others, including a literature review with multiple food types (Stonehouse and Evans, 2015).

Despite the recent increase in literature on supercooling of foods, the potential for energy saving has not been studied, with the focus being the impact on storage life, ice crystal damage and other quality aspects.

Scope 1 emissions savings (% or another quantifiable metric)	No information.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	There is potential for energy saving compared with freezing, but no data are available.
Quality of scope 2 emissions information	n/a
Availability barriers	The unstable nature of supercooled food makes reliable maintenance of the supercooled state difficult. Requires careful temperature control, slow rates of cooling, and can be enhanced by other processes such as high pressure and magnetic assisted freezing.
TRL level	3-5
Maintainability issues	Nothing specific.

Legislative concerns	None.
Payback time (years)	Unknown.

Cox, D.R.G., Moore, S.R., 1997. A Process for Supercooling, Patent WO 97/18879.

Diehl, H.C., Wright, R.C., 1924. Freezing injury of apples. J. Agric. Res. 29, 0099–0127.

Fukuma, Y., Yamane, A., Itoh, T., Tsukamasa, Y. and Ando, M., 2012. Application of supercooling to long-term storage of fish meat. Fisheries science, 78, pp.451-461.

Fuller, M.P., Wisniewski, M., 1998. The use of infrared thermal imaging in the study of ice nucleation and freezing of plants. J. Therm. Biol. 23, 81–89.

James C.; Hanser P. and James S.J. (2011). Super-cooling phenomena in fruits, vegetables and seafoods. 11th International Congress on Engineering and Food (ICEF 2011), Athens, Greece, 22-26 May 2011.

James, C.; Seignemartin, V. and James, S.J. (2009). The freezing and supercooling of garlic (*Allium sativum* L.). International Journal of Refrigeration, 32, (2009), 253-260.

Kang, T., Shafel, T., Lee, D., Lee, C.J., Lee, S.H. and Jun, S., 2020. Quality retention of fresh tuna stored using supercooling technology. Foods, 9(10), p.1356.

Kang, T., You, Y. and Jun, S., 2020. Supercooling preservation technology in food and biological samples: A review focused on electric and magnetic field applications. Food science and biotechnology, 29, pp.303-321.

Kim, H. and Hong, G.P., 2022. Comparison of Superchilling and Supercooling on Extending the Fresh Quality of Beef Loin. Foods, 11(18), p.2729.

Kobayashi, R. and Suzuki, T., 2019. Effect of supercooling accompanying the freezing process on ice crystals and the quality of frozen strawberry tissue. International Journal of Refrigeration, 99, pp.94-100.

Koide, S., Ito, T., Osuga, R. and Orikasa, T., 2022. Assessment of cumulative freezing frequency of supercooled fresh-cut onion: Effects of sample size, supercooling temperature, and supercooled storage time. Journal of Agriculture and Food Research, 10, p.100440.

Lin, H., Xu, Y., Guan, W., Zhao, S., Li, X., Zhang, C., Blecker, C. and Liu, J., 2023. The importance of supercooled stability for food during supercooling preservation: a review of mechanisms, influencing factors, and control methods. Critical Reviews in Food Science and Nutrition, pp.1-15.

Lucas, J.W., 1954. Subcooling and ice nucleation in lemons. J. Plant Physiol. 29, 245–251.

Martins, R.C. and Lopes, V.V. (2007). Modelling supercooling in frozen strawberries: Experimental analysis, cellular automation and inverse problem methodology. Journal of Food Engineering. Volume 80, Issue 1, May 2007, Pages 126-141.

Park, D.H., Kim, E.J., Kim, H., Hong, G.P. and Choi, M.J., 2022. Conditions of the Stepwise Cooling Algorithm for Stable Supercooling Preservation and Freshness of Pork Loin. Foods, 11(24), p.4021.

Park, D.H., Lee, S., Lee, J., Kim, E.J., Jo, Y.J., Kim, H., Choi, M.J. and Hong, G.P., 2021. Stepwise cooling mediated feasible supercooling preservation to extend freshness of mackerel fillets. LWT, 152, p.112389.

Park, D.H., Lee, S., Byeon, Y.M., Kim, E.J. and Choi, M.J., 2022. Effect of supercooling storage applied with stepwise algorithm for fishes (salmon and olive flounder) and its freshness during extended storage. Food Bioscience, 49, p.101950.

Stonehouse, G.G. and Evans, J.A., 2015. The use of supercooling for fresh foods: A review. *Journal of Food Engineering*, 148, pp.74-79.

You, Y., Her, J.Y., Shafel, T., Kang, T. and Jun, S., 2020. Supercooling preservation on quality of beef steak. *Journal of Food Engineering*, 274, p.109840.

You, Y., Kang, T. and Jun, S., 2021. Control of ice nucleation for subzero food preservation. *Food Engineering Reviews*, 13, pp.15-35.

You, Y., Li, M., Kang, T., Ko, Y., Kim, S., Lee, S.H. and Jun, S., 2021. Application of supercooling for the enhanced shelf life of Asparagus (*Asparagus officinalis* L.). *Foods*, 10(10), p.2361.

12.1.16 Ultrasound assisted freezing

Ultrasound assisted freezing (also termed power ultrasound freezing and ultrasonic freezing) uses sound energy to accelerate freezing. Ultrasound can create cavitation in cells, which promotes ice nucleation and accelerates heat transfer, reducing freezing times. Ultrasound can also potentially fracture ice crystals leading to small crystal sizes and in some cases better product quality. The technology and its potential benefits have been reviewed by authors such as Delgado and Sun, 2010, Zheng and Sun, 2006, Zhang et al., 2018, and included in several reviews of novel freezing technologies (e.g. Cheng et al., 2017, James et al., 2015, Mascheroni, 2007). While the majority of studies assessed ultrasound applied to immersion freezing systems, some applied ultrasound by direct contact (e.g. Astráin-Redín et al., 2021, Islam et al., 2015).

Application to various food types has been reported, including amongst others chicken (Astráin-Redín et al., 2021, Zhang et al., 2022), pork (Zhang et al., 2018), fish (Bian et al., 2022, Sun et al., 2019), strawberries (Cheng et al., 2014), mushrooms (Islam et al., 2014, Islam et al., 2015), potatoes (Tian et al., 2020), radishes (Tian et al., 2020, Xu et al., 2015), broccoli (Xin et al., 2014), and fruits and vegetables more generally (Islam et al., 2017). Reduced freezing times compared with unassisted freezing have been reported for most of these materials, but these vary depending on the type of material and their sizes, plus which conventional freezing process they are being compared with. Examples of the percentage reductions in freezing time are Astráin-Redín et al. (2021) 11% reduction for chicken, Tian et al. (2020) up to 42% for potato cylinders, Bian et al. (2022) up to approximately 33% for strawberries depending on use of single or multiple frequency ultrasound and Islam et al. (2014) up to approximately 50% for mushrooms depending on type and ultrasound intensity.

The impact of the reduced freezing times on energy consumption compared with the additional energy required for the ultrasound generation does not seem to have been measured or assessed, with literature tending to focus mainly on ice nucleation and crystal size and the effects on various quality traits.

Scope 1 emissions savings (% or another quantifiable metric)	No information.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Shorter freezing times potentially reduce run times and / or refrigeration duty.
Quality of scope 2 emissions information	n/a
Availability barriers	No barriers but not suitable for some products, particularly larger items.
TRL level	6 - 7

Maintainability issues	Additional equipment compared to conventional processes.
Legislative concerns	None.
Payback time (years)	Unknown.

Astráin-Redín, L., Abad, J., Rieder, A., Kirkhus, B., Raso, J., Cebrián, G. and Álvarez, I., 2021. Direct contact ultrasound assisted freezing of chicken breast samples. *Ultrasonics sonochemistry*, 70, p.105319.

Bian, C., Yu, H., Yang, K., Mei, J. and Xie, J., 2022. Effects of single-, dual-, and multi-frequency ultrasound-assisted freezing on the muscle quality and myofibrillar protein structure in large yellow croaker (*Larimichthys crocea*). *Food Chemistry: X*, 15, p.100362.

Cheng, L., Sun, D.W., Zhu, Z. and Zhang, Z., 2017. Emerging techniques for assisting and accelerating food freezing processes: A review of recent research progresses. *Critical reviews in food science and nutrition*, 57(4), pp.769-781.

Cheng, X.F., Zhang, M., Adhikari, B., Islam, M.N. and Xu, B.G., 2014. Effect of ultrasound irradiation on some freezing parameters of ultrasound-assisted immersion freezing of strawberries. *International Journal of Refrigeration*, 44, pp.49-55.

Delgado, A.E. and Sun, D.W., 2010. Ultrasound-assisted freezing. In *Ultrasound technologies for food and bioprocessing* (pp. 495-509). New York, NY: Springer New York.

Islam, M.N., Zhang, M. and Adhikari, B., 2017. Ultrasound-assisted freezing of fruits and vegetables: design, development, and applications. *Global food security and wellness*, pp.457-487.

Islam, M.N., Zhang, M., Adhikari, B., Xinfeng, C. and Xu, B.G., 2014. The effect of ultrasound-assisted immersion freezing on selected physicochemical properties of mushrooms. *International Journal of Refrigeration*, 42, pp.121-133.

Islam, M.N., Zhang, M., Fang, Z. and Sun, J., 2015. Direct contact ultrasound assisted freezing of mushroom (*Agaricus bisporus*): Growth and size distribution of ice crystals. *International Journal of Refrigeration*, 57, pp.46-53.

James, C., Purnell, G. and James, S.J., 2015. A review of novel and innovative food freezing technologies. *Food and Bioprocess Technology*, 8, pp.1616-1634.

Mascheroni R.H. (2007). Overview on new freezing technologies. *Refrigeration, energy and environment: challenges and perspectives 5th Alcuefood Seminar (São Paulo) - 27-29 March, 2007*.

Sun, Q., Chen, Q., Xia, X., Kong, B. and Diao, X., 2019. Effects of ultrasound-assisted freezing at different power levels on the structure and thermal stability of common carp (*Cyprinus carpio*) proteins. *Ultrasonics Sonochemistry*, 54, pp.311-320.

Tian, Y., Zhang, P., Zhu, Z. and Sun, D.W., 2020. Development of a single/dual-frequency orthogonal ultrasound-assisted rapid freezing technique and its effects on quality attributes of frozen potatoes. *Journal of Food Engineering*, 286, p.110112.

Tian, Y., Chen, Z., Zhu, Z. and Sun, D.W., 2020. Effects of tissue pre-degassing followed by ultrasound-assisted freezing on freezing efficiency and quality attributes of radishes. *Ultrasonics Sonochemistry*, 67, p.105162.

Xin, Y., Zhang, M. and Adhikari, B., 2014. The effects of ultrasound-assisted freezing on the freezing time and quality of broccoli (*Brassica oleracea* L. var. botrytis L.) during immersion freezing. *International Journal of Refrigeration*, 41, pp.82-91.

Xu, B.G., Zhang, M., Bhandari, B., Cheng, X.F. and Islam, M.N., 2015. Effect of ultrasound-assisted freezing on the physico-chemical properties and volatile compounds of red radish. *Ultrasonics Sonochemistry*, 27, pp.316-324.

Zhang, C., Chen, Q., Sun, Q., Liu, H., Xia, X. and Kong, B., 2022. Ultrasound-assisted freezing retards the deterioration of functional properties of myofibrillar protein in chicken breast during long-term frozen storage. *LWT*, 170, p.114064.

Zhang, M., Haili, N., Chen, Q., Xia, X. and Kong, B., 2018. Influence of ultrasound-assisted immersion freezing on the freezing rate and quality of porcine longissimus muscles. *Meat Science*, 136, pp.1-8.

Zhang, P., Zhu, Z. and Sun, D.W., 2018. Using power ultrasound to accelerate food freezing processes: Effects on freezing efficiency and food microstructure. *Critical reviews in food science and nutrition*, 58(16), pp.2842-2853.

Zheng, L. And Sun, Da-Wen (2006). Innovative applications of power ultrasound during food freezing processes: a review. *Trends in food science and technology*. Vol. 17, no. 1, pp. 16-23.

12.1.17 Vascular perfusion / infusion

Meat carcasses must be chilled to below 7°C before leaving the slaughterhouse. Typically, this is done by circulating refrigerated air over the surfaces of the eviscerated and de-hided carcasses. As the cooling medium is only acting on the outer surfaces, it can take many hours for temperatures at the centre of the carcasses to drop below 7°C. To maintain relatively high rates of heat transfer, powerful fans are used to circulate the air at high velocities, but fan energy can be as much as 30% of the overall energy consumption of the process.

Vascular perfusion (VP), also referred to in some studies as vascular infusion (VI) is an alternative type of chilling process which aims to take heat directly from the deeper tissues. Cold fluids such as sodium chloride brine or ice slurries are circulated through the intact vascular system shortly after slaughter, offering reductions in cooling time and negating the need for powerful fans. Reducing the time required to chill carcasses can offer substantial benefits to the meat industry in terms of both quality and energy usage, although perfusion systems add additional complexity to processing and require disposal of considerable quantities of used cooling fluid.

Reported applications include commercial systems in use in the USA and Australia, which are aimed to provide partial chilling and at the same time remove blood from carcasses (so-called 'Rinse and Chill™'). Studies with this system and with other more laboratory scale systems have been reported for various meat animal species, including beef (Dikeman et al., 2003, Farouk et al., 1992, Moreira et al., 2018, Hite et al., 2019, Hunt et al., 2003, Kethavath et al., 2022, Wang et al., 1995), lamb (Farouk and Price, 1994, Fowler et al., 2017, Mickelson et al., 2018), bison (Mickelson and Claus, 2020) and pork (Brown et al., 2009, Kethavath et al., 2021).

The majority of these studies focus on meat quality traits and impact on weight loss, but some present data on improved chilling rates. However, as with the commercial systems mentioned above, typically perfusion / infusion is not aimed at extended application as a chilling method to replace conventional chilling, but rather as a short term, partial enhancement to conventional chilling. As such, the impact on chilling rates is generally somewhat limited. The associated potential to reduce refrigeration energy consumption due to shorter primary chilling times has not been evaluated.

Scope 1 emissions savings (% or another quantifiable metric)	None reported. The impact of liquid chilling and circulation versus air blast on refrigeration system size may be slight as conventional chilling is still required.
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Quality of scope 1 emissions information	n/a.
Scope 2 emissions savings (% or another quantifiable metric)	Quicker and more efficient chilling could potentially reduce energy consumption, but studies have not assessed this.
Quality of scope 2 emissions information	n/a.
Availability barriers	None, although additional complexity may be a barrier to adoption.
TRL level	7-8
Maintainability issues	Cleaning and maintenance of the liquid chilling system and heat exchangers is required in addition to the air blast system.
Legislative concerns	Uptake of water and any included ingredients (e.g. salt) can be excessive.
Payback time (years)	Unknown.

Brown, T., Richardson, R.I., Wilkin, C.A. and Evans, J.A., 2009. Vascular perfusion chilling of red meat carcasses—A feasibility study. *Meat science*, 83(4), pp.666-671.

Dikeman M E, Hunt M C, Addis P B, Schoenbeck H J, Pullen M, Katsanidis E and Yancey E J (2003), Effects of postexsanguination vascular infusion of cattle with a solution of saccharides, sodium chloride, and phosphates or with calcium chloride on quality and sensory traits of steaks and ground beef. *Journal of Animal Science*, 81, 156-166.

Erazo-Castrejón, S.V., Zhang, W., Mickelson, M.A., Claus, J.R., Yin, J. and Richards, M.P., 2019. Quantification of hemoglobin and myoglobin in pork muscle: effect of rinse and chill technology on blood removal. *Meat and Muscle Biology*, 1(3).

Farouk, M. M., Price, J. F., Salih, A. M., and Burnett, R. J. (1992). The effect of postexsanguination infusion of beef on composition, tenderness, and functional properties. *Journal of Animal Science*, 70, 2773–2778.

Farouk, M. M., Price, J. F., and Salih, A. M. (1992). Post-exsanguination infusion of ovine carcasses: Effect on tenderness indicators and muscle microstructure. *Journal of Food Science*, 57, 1311–1315.

Farouk, M. M., and Price, J. F. (1994). The effect of post-exsanguination infusion on the composition, exudation, colour and post-mortem metabolic changes in lamb. *Meat Science*, 38, 477–496.

Fowler, S.M., Claus, J.M. and Hopkins, D.L., 2017. The effect of applying a rinse and chill procedure to lamb carcasses immediately post-death on meat quality? *Meat science*, 134, pp.124-127.

Hite, L.M., Grubbs, J.K., Blair, A.D. and Underwood, K.R., 2020. Influence of post-harvest circulatory rinse on tenderness and objective color of cow striploin steaks.

Hunt, M. C., Schoenbeck, J. J., Yancey, E. J., Dikeman, M. E., Loughin, T. M., and Addis, P.B. (2003). Effects of postexsanguination vascular infusion of carcasses with calcium chloride or a solution of saccharides, sodium chloride, and phosphates on beef display- colour stability. *Journal of Animal Science*, 81, 669–675.

Hwang KE Campbell RE Claus JR (2020). Rinse and Chill® technology research: vascular rinsing and chilling carcasses improves meat quality and food safety: a review Paper presented at: 66th International Congress of Meat Science and Technology (ICoMST) and 73rd Reciprocal Meat Conference (RMC).

Kethavath, S.C., da Cunha Moreira, L., Hwang, K.E., Mickelson, M.A., Campbell, R.E., Chen, L. and Claus, J.R., 2022. Vascular rinsing and chilling effects on meat quality attributes from cull dairy cows associated with the two lowest-valued marketing classes. *Meat Science*, 184, p.108660.

Kethavath, S.C., Hwang, K.E., Mickelson, M.A., Campbell, R.E., Richards, M.P. and Claus, J.R., 2021. Vascular infusion with concurrent vascular rinsing on color, tenderness, and lipid oxidation of hog meat. *Meat Science*, 174, p.108409.

Mickelson, M.A. and Claus, J.R., 2020. Carcass chilling method effects on color and tenderness of bison meat. *Meat science*, 161, p.108002.

Moreira, L.C., Connolly, C. and Claus, J.R., 2018. Vascular rinse and chill effects on meat quality and shelf life of beef. In 64th International Congress of Meat Science and Technology, Melbourne, Australia www.iastatedigitalpress.com/mmb/article/id/8886.

Wang, Y., McGinnis, D. S., Segada, R. R., and Jones, S. D. M. (1995). Vascular infusion of beef carcasses effects on chilling efficiency and weight change. *Food Research International*, 28(4), 425–430.

Yancey, E.J., Dikeman, M.E., Addis, P.B., Katsanidis, E. and Pullen, M., 2002. Effects of vascular infusion with a solution of saccharides, sodium chloride, and phosphates with or without vitamin C on carcass traits, Warner–Bratzler shear force, flavor-profile, and descriptive-attribute characteristics of steaks and ground beef from Charolais cattle. *Meat science*, 60(4), pp.341-347.

12.2 Heating

12.2.1 Automatic shutdown

Stojceska et al. (2021) studied the effect of switching off equipment between productions for an entire production plant involving different pieces of equipment, including mixers, conveyers, cutters, feeders, ovens and coolers. While ovens had the largest share in the energy consumption (30-43%), the shutdown was only implemented for equipment with short start-up times, which excluded the ovens in this case. As a result, equipment switch off savings were between 0.4 and 0.5% of the total energy budget of the entire process. Practical guidelines towards energy savings in (food service) ovens (Pacific Gas and Electric Company, 1999) also state that preheat times are often half an hour, and it is not always recommended to turn it off between productions, unless for at least 2 hours.

Energy savings in batch ovens

$$= [\text{avoided overrun time} \times \text{steady state oven power}] \\ - [\text{preheating time} \times \text{max. oven power}]$$

The typical average steady state oven power will be only a fraction of the max. oven power depending on the magnitude of the heat losses of the oven, or the efficiency of the heat process. With a steady state heating power that is 25% of the max. oven power, and a typical preheating time of 30 min, the automatic shutdown savings will be substantial starting from 2 h non-operation. For an oven with a shorter preheating time of 15 min, the shutdown saves energy starting from 1 h intervals. For a 1h baking process, the expected energy savings are about 20% for each additional overrun hour that can be saved. For a more efficient oven to keep the steady state temperature, say consuming only 10% of the max. power, the savings are beneficial starting from 10 times the preheating time, with less than 10% energy savings for each additional hour saved. Switching off ovens directly after operational hours is also advised in the guide, instead of during later planned cleaning activities, for example, with potential large savings proportional to the amount of additional shutdown hours as above.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	10-20% of energy use for each non-useful heating hour saved. Reduced losses due to overheating: no data available.
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Quality of scope 1/2 emissions information	Rough estimate, not verified.
Availability barriers	L
TRL level	Timers: 8-9 Use of sensing technology: 1-4
Maintainability issues	-
Legislative concerns	-
Payback time (years)	Use of timer: 0 Use of sensing technology: not available: n/a

Pacific Gas and Electric Company. (1999). Ovens in Commerical Food Service Operations. End-use briefing.

<https://www.pge.com/includes/docs/pdfs/about/edusafety/training/pec/inforesource/ovens.pdf>.

Stojceska, V., Parker, N., and Tassou, S. A. (2021). Reducing GHG Emissions and Improving Cost Effectiveness via Energy Efficiency Enhancements: A Case Study in a Biscuit Industry. *Sustainability* 2022, Vol. 14, Page 69, 14(1), 69. <https://doi.org/10.3390/SU14010069>.

12.2.2 Drying – novel systems

Heat pumps

Heat pumps can be used for drying purposes. In this method, the evaporator of the heat pump is used to remove the moisture in the product via evaporation. By using the evaporator, heat pumps take advantage of low temperature drying compared to conventional dryers. Heat pumps may recover and use the latent and sensible heat of evaporation, and as a result, drying with heat pumps could reach higher efficiencies. Heat pump drying is reported to have 60%–80% energy savings compared to conventional dryers (WNA, 2011).

Industrial and HTHPs are a well-established, sustainable, and low-emission technology for processing temperatures below 100°C, especially when driven by renewable energy. The next frontier in heat pumping is to enhance the economic working envelope to serve the 100–200°C range, where an estimated 27% of industrial process heat demand is required. HTHPs are an effective technology for delivering heat and recovering waste heat from various industrial processes, hence reducing primary energy consumption and the resulting CO₂ emissions (Hamid et al, 2023). There are, however, development required which include: i) low-GWP refrigerants; ii) output temperature higher than 100°C; iii) heating capacity larger than 1 MW; iv) COP larger than 4 under 40°C temperature lift (Jiang et al, 2022).

Other technologies

Various products need various drying technologies to be dried optimally, and the various drying systems have different advances in product quality, energy consumption, efficiency and economic performances. The novel drying technologies include adsorption mediated, agitated thin film, electrotechnologies, hybrid systems, impingement, heat pumps, microwave, ohmic-heating, refractance window, rotating drum, superheated steam, and vacuum (Acar et al, 2022).

However, using sophisticated drying techniques might result in inconsistent food product drying and increased capital expenses. Hence, a multifaceted strategy that offers a foundation for choosing a specific drying method is of absolute need. Drying also involves a variety of pretreatment and hybrid drying procedures which increases the complexity of the entire process. Some of the pretreatment

methods discussed include osmotic dehydration (OD), ultrasound, PEF, cold plasma and pulsed vacuum treatment (PVT). Also, hybrid or combined drying methods have been discussed like electromagnetic waves assisted drying methods, solar assisted heat pump drying methods, convective drying followed by vacuum microwave drying technique to name a few (Bhattacharjee et al, 2024).

Scope 1 emissions savings (% or another quantifiable metric)	Replacement of fossil-fuel driven drying processes with electricity (100%)
Quality of scope 1 emissions information	Many review articles available
Scope 2 emissions savings (% or another quantifiable metric)	Heat pump drying systems (60-80%).
Quality of scope 2 emissions information	Hybrid and novel drying systems (0-80%)
Availability barriers	L
TRL level	7-9
Maintainability issues	Environmentally friendly refrigerants in heat pumps will reduce emissions due to leakage.
Legislative concerns	n/a
Payback time (years)	Varies between the drying technologies and operation

Acar, C., Dincer, I., Mujumdar, A., (2022). A comprehensive review of recent advances in renewable-based drying technologies for a sustainable future, *Drying Technology*, 40 (6), 1029-1050.

Bhattacharjee, S., Mohanty, P., Sahu, J.K., Sahu, J.N, (2024). A critical review on drying of food materials: Recent progress and key challenges, *International Communications in Heat and Mass Transfer*, 158, 107863.

Hamid, K., Sajjad, U., Ahrens, M.U., Ren, S., Ganesan, P., Tolstorebrov, I., Arshad, A., Said, Z., Hafner, A., Wang, C.C., Wang, R., Eikevik, T.M. (2023), Potential evaluation of integrated high temperature heat pumps: A review of recent advances, *Applied Thermal Engineering*, 230, 120720.

WNA, (2011). Comparison of lifecycle greenhouse gas emissions of various electricity generation sources. Report by World nuclear association. [WNA-Comparison-of-Lifecycle-GHG-2011.pdf](#).

12.2.3 Frying - efficiency improvements, novel options

In recent years, new alternative frying technologies have gained significant attention from researchers and industry due to their potential to maintain the healthiness and safety of fried foods. These emerging techniques, which produce fried products with comparable quality and safety to traditional methods, include air frying (Tian et al., 2017), spray frying (Udomkun et al., 2020), microwave frying (Quan et al., 2016), vacuum frying (Su et al., 2018), and ultrasound-assisted frying (Su et al., 2018).

Spray frying is another innovative technique where heated oil is sprayed onto the food rather than immersing it in oil. The efficiency of this method depends on the rate of oil spraying (Udomkun et al., 2020), but data on potential energy savings are still unavailable.

Microwave frying uses electromagnetic fields to directly interact with food components, resulting in internal and volumetric heating, contrasting the traditional thermal methods of convection and conduction during deep fat frying. Electromagnetic waves heat the interior of the food, while a hot medium (such as oil) may still be needed to dry and cook the outer layer. This method is thus often

combined with other technologies to ensure uniform heating and enhance the nutritional and sensory quality of the fried foods (Kutlu et al., 2021).

Vacuum frying, which operates under sub-atmospheric pressure, lowers the boiling point of both the frying oil and the moisture in the food. This results in higher quality fried products compared to atmospheric pressure frying, particularly for fruits and vegetables (Manzoor et al., 2022). Su et al. (2018) examined the effects of low-frequency ultrasound, and the combination of ultrasound and microwave, on the efficiency and quality of vacuum frying, specifically using potato chips. Ultrasound technology, a mechanical wave ranging from 20 kHz to 10 MHz, generates cavitation that facilitates the removal of strongly bound moisture during dehydration. The combination of ultrasound and microwave in vacuum frying resulted in better energy efficiency, reduced oil uptake, crispier texture, and superior shape and colour in the final product. The energy consumption for vacuum-fried potato chips was reduced by 18.4–24.1% with the use of low-frequency ultrasound. When compared with vacuum frying alone and microwave-assisted vacuum frying, the ultrasound-microwave-assisted vacuum frying process reduced energy consumption per kilogram of fried potato chips by 34.9–48.3% and 12.6–30.6%, respectively, depending on the product. This substantial reduction in energy consumption was attributed to higher moisture loss rates and shorter frying times.

Comparison of methods between studies proves difficult due to differences in size of equipment (either lab-scale or industrial) and the amount of water removed during frying. For example, Wu et al. (2012) found that the energy consumption for deep-fat frying typically ranges between 4 to 6 MJ per kilogram of fresh product in an industrial scale fryer. The vacuum frying study of Su et al. (2018) on the other hand was on lab-scale equipment, and their analysis showed an energy consumption of the vacuum frying of 396 MJ/kg dry basis, or 79 MJ/kg fresh product. In a direct comparison, ignoring the differences in scale, the energy savings due to lowering the oil frying temperature in vacuum frying, seems not enough to compensate for shorter frying times and the energy demand of the vacuum pump.

Zhang et al. (2020) also highlight several novel pre- and post-treatment methods that can impact the carbon footprint of frying. These include pre-drying, blanching, coating, structural modification, and oil removal processes, whose benefits and necessity depend on the frying method and product. However, more data is needed to assess their CO₂ emission impact.

Scope 1 emissions savings (% or another quantifiable metric)	-
Quality of scope 1 emissions information	-
Scope 2 emissions savings (% or another quantifiable metric)	Scarce data in peer reviewed journals is difficult to compare
Quality of scope 2 emissions information	Novel methods are electrified, so provide options to replace fossil fuel based oil heating
Availability barriers	No data
TRL level	6. Most novel methods are at prototype stage
Maintainability issues	-
Legislative concerns	-
Payback time (years)	-

Kutlu, Naciye, Ravi Pandiselvam, Irem Saka, Aybike Kamiloglu, Prashant Sahni, and Anjineyulu Kothakota. 2022. "Impact of Different Microwave Treatments on Food Texture." *Journal of Texture Studies* 53 (6): 709–36. <https://doi.org/10.1111/JTXS.12635>.

Manzoor, Shaziya, F. A. Masoodi, Rubiya Rashid, Shoib Mohamad Wani, Farah Naqash, and Mudasir Ahmad. 2023. "Advances in Vacuum Frying: Recent Developments and Potential Applications." *Journal of Food Process Engineering* 46 (2): e14219. <https://doi.org/10.1111/JFPE.14219>.

Quan, Xiaojian, Min Zhang, Weiming Zhang, and Benu Adhikari. 2014. "Effect of Microwave-Assisted Vacuum Frying on the Quality of Potato Chips." *Drying Technology* 32 (15): 1812–19. <https://doi.org/10.1080/07373937.2014.947428>.

Su, Ya, Min Zhang, Benu Adhikari, Arun S. Mujumdar, and Weiming Zhang. 2018. "Improving the Energy Efficiency and the Quality of Fried Products Using a Novel Vacuum Frying Assisted by Combined Ultrasound and Microwave Technology." *Innovative Food Science and Emerging Technologies* 50 (December): 148–59. <https://doi.org/10.1016/J.IFSET.2018.10.011>.

Tian, Jinhu, Shiguo Chen, Join Shi, Jianchu Chen, Donghong Liu, Yidi Cai, Yukiharu Ogawa, and Xingqian Ye. 2017. "Microstructure and Digestibility of Potato Strips Produced by Conventional Frying and Air-Frying: An in Vitro Study." *Food Structure* 14 (October): 30–35. <https://doi.org/10.1016/J.FOOSTR.2017.06.001>.

Udomkun, Patchimaporn, Janjira Tangsanthakun, and Bhundit Innawong. 2020. "Influence of Process Parameters on the Physico-Chemical and Microstructural Properties of Rice Crackers: A Case Study of Novel Spray-Frying Technique." *Innovative Food Science and Emerging Technologies* 59 (January): 102271. <https://doi.org/10.1016/J.IFSET.2019.102271>.

Wu, H., H. Jouhara, S. A. Tassou, and T. G. Karayiannis. 2012. "Modelling of Energy Flows in Potato Crisp Frying Processes." *Applied Energy* 89 (1): 81–88. <https://doi.org/10.1016/J.APENERGY.2011.01.008>.

Wu, H., S. A. Tassou, T. G. Karayiannis, and H. Jouhara. 2013. "Analysis and Simulation of Continuous Food Frying Processes." *Applied Thermal Engineering* 53 (2): 332–39. <https://doi.org/10.1016/J.APPLTHERMALENG.2012.04.023>.

Zhang, Xiaotian, Min Zhang, and Benu Adhikari. 2020. "Recent Developments in Frying Technologies Applied to Fresh Foods." *Trends in Food Science and Technology* 98 (April): 68–81. <https://doi.org/10.1016/J.TIFS.2020.02.007>.

12.2.4 High-pressure freezing and thawing

High pressure freezing makes use of the thermophysical properties of food products, specifically of the water (content) in food products. Water has a pressure dependent freezing temperature. For example, increasing the pressure to 200 MPa lowers the freezing temperature to -20.8 °C. If the product is cooled to -20 °C under this pressure, a rapid release of pressure (pressure shift) results in a uniform phase transition to a frozen state, thereby minimizing mechanical damage to the tissue structure. Since the phase transition achieved in this process is typically only partial, the cooling to the target freezing temperature is then completed under atmospheric pressure. (Balasubramaniam, 2016).

Different publications like Köprüalan et al. (2023) confirm that "high pressure freezing techniques are more efficient at preserving the microstructure of foods than conventional freezing techniques" (Aydın, Sarioğlu, Dirim, and Kaymak Ertekin, 2023). Specifically, a study on sea bass frozen with high pressure shifts, maintained cellular integrity due to an overall smaller ice crystal formation in the muscle (Tironi, Lamballerie de, and LeBail, 2020). However, studies indicate greater protein denaturation compared to conventional air-blast freezing in fish (Cheftel, Thiebaud, and Dumay, 2002).

Thus, the negative impact on protein denaturation and protein aggregation leading to muscle toughness can potentially outweigh the positive effect of small crystal formation and cellular integrity.

High pressure thawing utilises the same principle as high pressure freezing. Through the high pressure, the phase change temperature can be significantly decreased (e.g. -20.8°C at 200 Mpa for water). Since the phase change requires the most energy in the thawing process, lowering the phase change temperature increases the temperature difference in the area where the phase change occurs. This results in faster thawing times, even at low thawing temperatures. Further the spoiling reactions of microorganisms and enzymes can be decreased because of the lower achievable thawing temperatures (Aydın, Sarioğlu, Dirim, and Kaymak Ertekin, 2023). However, high pressure thawing can cause protein denaturation and texture change for certain products (Aydın, Sarioğlu, Dirim, and Kaymak Ertekin, 2023). In the review by Svendsen et al. a reduced drip loss is reported for certain fish species, while an increased drip loss is reported for other fish species (Svendsen, et al., 2022).

The GHG emissions saving potential needs to be determined, as no comprehensive life cycle assessment study was found. GHG savings could result from reduced processing time and improved product quality, but the additional energy required to generate high pressure must be included in the GHG emissions calculation and may countereffect GHG emission savings. Hence, further studies are required to do the life cycle assessment.

Scope 1 emissions savings (% or another quantifiable metric)	Not found
Quality of scope 1 emissions information	
Scope 2 emissions savings (% or another quantifiable metric)	Not found
Quality of scope 2 emissions information	
Availability barriers	Not at industrial level yet
TRL level	1-3
Maintainability issues	Not found
Legislative concerns	Not found
Payback time (years)	Not found

Aydın, Ö. K., Sarioğlu, H. Y., Dirim, S. N., and Kaymak Ertekin, F. (2023). Recent Advances for Rapid Freezing and Thawing Methods of Foods. *Food Engineering Reviews*, 667-690.

Cheftel, C. J., Thiebaud, M., and Dumay, E. (2002). Pressure-assisted freezing and thawing of foods: a review of recent studies. *High Pressure Research*, 601-611.

LeBail, A., Chevalier, D., Mussa, D., and Ghoul, M. (2002). High pressure freezing and thawing of foods: a review. *International Journal of Refrigeration* 25, 504-513.

Svendsen, E. S., Widell, K. N., Tveit, G. M., Nordtvedt, T. S., Uglem, S., Standal, I., and Greiff, K. (2022). Industrial methods of freezing, thawing and subsequent chilled storage of whitefish. *Journal of Food Engineering*.

Tironi, V., Lamballerie de, M., and LeBail, A. (2020). Quality changes during the frozen storage of sea bass (*Dicentrarchus labrax*) muscle after pressure shift freezing and pressure assisted thawing. *Innovative Food Science and Emerging Technologies*, 565-753.

12.2.5 High-temperature heat pumps (HTHPs)

HTHPs enable the utilisation of waste heat at low temperature levels by lifting it to temperature levels suitable for process heat supply. By decreasing or substituting fossil-fuelled process heat supply, HTHPs can contribute to the decarbonisation of the industry. Especially in the food industry often a demand for heating and cooling exists, and waste heat of chillers can be used as the heat source for HTHPs. According to the IEA (2022), heat pumps can in principle cover around 40 % of all processes in the food industry, mainly where temperatures below 150 °C are needed.

The project “Annex 58 – High Temperature Heat Pumps” (<https://heatpumpingtechnologies.org/annex58>) carried out within the International Energy Agencies Technology Collaboration Programme on Heat Pumping Technology (TCP HPT) gives an extensive overview of available and close-to-market technologies regarding HTHPs. The report for Task 1 (Zühlsdorf et al., 2023) documents the state of the art, especially regarding supplier technologies (including TRL for close-to-market technology) and demonstration cases. In addition, an updated version of this overview is given on the webpage <https://heatpumpingtechnologies.org/annex58/task1/>. The technologies listed cover HTHPs based on vapour compression cycles, mechanical vapour recompression (MVR), or other technologies such as Brayton or Stirling cycles. Task 2 focuses on possible integration concepts for selected industrial processes and systems. Task 3 aims to develop strategies for the conversion to HTHP-based process heat supply and 4 focuses on the definition and testing of HTHP specifications.

ENOUGH DEMONSTRATOR: ABSORPTION-COMPRESSION HEAT PUMP (ACHP)

The ammonia-water absorption-compression heat pump cycle combines the technologies of an absorption and vapour compression heat pump with a mixture of ammonia and water as the natural working fluid.

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 temperature up to 150°C, which is suitable for replacement of fossil fuel boilers. These properties make the ACHP a promising system for high-temperature applications in the food supply chain, such as meat processing, fish processing, and dairies.

RESULTS

The potential of implementing an ACHP for steam generation at the chicken processing factory Norsk Kylling AS was investigated. The plant was located in the municipality of Orkland, in Norway. A 150 °C ACHP for steam production was found to provide an energy-efficient solution for generating steam and hot water, with the potential for substantial CO₂ emission reductions. Compared to a conventional gas boiler, the ACHP steam generation system can reduce CO₂ 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 CO₂ emission savings of up to 75%.

The ACHP can deliver robust thermal performance in real industrial environments for steam generation, maintaining high efficiency even when operating with very low waste heat temperatures. As a practical alternative to fossil fuel boilers, the ACHP offers a promising solution for significantly reducing the carbon footprint of meat processing operations.

The efficiency of a heat pump is described with the Coefficient of Performance (COP_h) according to equation (1) as the ratio of the heating capacity $\dot{Q}_h$ and the electric power consumption P_{el} .

$$\text{COP}_h = \frac{\dot{Q}_h}{P_{el}} \quad \text{Eq. (1)}$$

A second law efficiency as defined in equation (2) comparing the actual COP with the COP of an ideal Carnot process (see equation (3)) can be used to provide a first estimate of the COP at given temperature levels.

$$\nu_{C,h} = \frac{\text{COP}_h}{\text{COP}_{h,\text{Carnot}}} \quad \text{Eq. (2)}$$

$$\text{COP}_{C,h} = \frac{T_{\text{sink}}}{T_{\text{sink}} - T_{\text{source}}} \quad \text{Eq. (3)}$$

Figure 67 (left) presents the COP depending on the temperature lift (difference between heat sink and heat source outlet) for selected HTHPs. As can be seen, most of the reported COPs correspond to second-law efficiencies between 0.4 and 0.65. In Figure 67 (right), CO₂ and final energy demand reductions are plotted as function of the COP. These reductions compare an HTHP replacing a gas boiler with an efficiency of 95 %, the emission factors for gas are 201 g/kWh and for electricity 133 g/kWh as reported by the Environment Agency Austria (Umweltbundesamt, 2023).

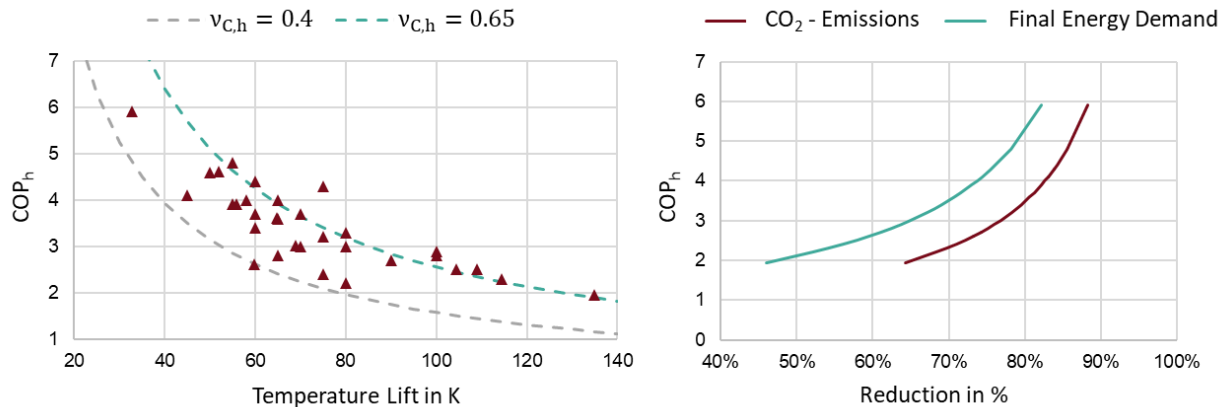


Figure 67: COP as a function of temperature lift for selected HTHPs (left) and CO₂ and final energy savings depending on the COP (right), based on Dusek et al. (2024) with data reported in Task 1 of the IEA HPT Annex 58 (<https://heatpumpingtechnologies.org/annex58/task1/>)

Figure 68 depicts processes in the food and beverages sector with the corresponding typical supply temperatures and corresponding TRL of the HTHP. According to Arpagaus (2022), relevant processes in dairies include high-temperature pasteurisation (100 to 120 C), sterilisation (115 C to 135°C) and UHT (135 to 150°C). Cleaning-in-Place systems operate at temperatures of up to 90°C.

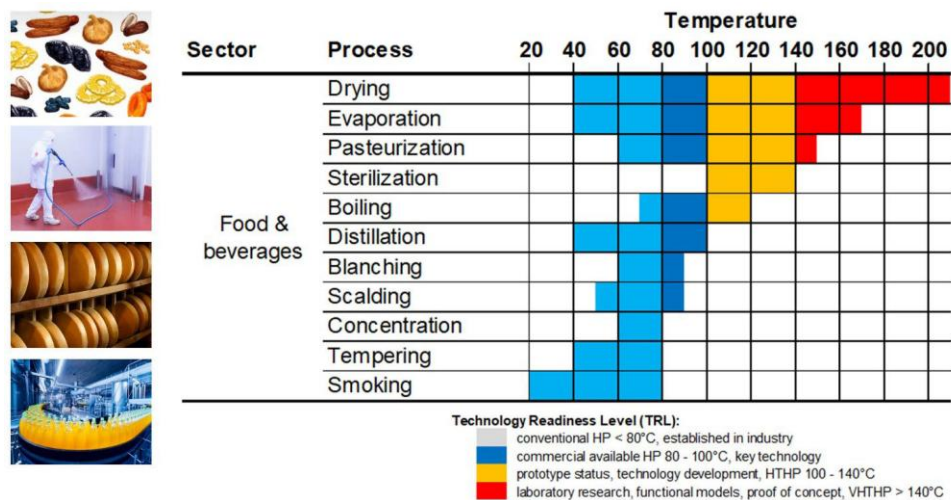


Figure 68: Typical supply temperature ranges of processes in the food and beverage sector. Source: Arpagaus et al. (2023)

Scope 1 emissions savings (% or another quantifiable metric)	Depending on the COP and emission factors for electricity and technology to be substituted, see Figure 1.
Quality of scope 1 emissions information	
Scope 2 emissions savings (% or another quantifiable metric)	Robust
Quality of scope 2 emissions information	n/a, unless electric heaters are substituted
Availability barriers	n/a
TRL level	Availability of a heat source (waste heat) at a suitable temperature and electrical power supply; if a high supply temperature is required TRL 9 available
Maintainability issues	Depending on the supply temperature and refrigerant:
Legislative concerns	up to 120 °C supply temperature
Payback time (years)	Trained personnel required

Arpagaus, C., Payá, J., Hassan, A. H., Bertsch, S. S., 2022. Potential Impact of Industrial HTHPs on the European Market. In: 3rd High-Temperature Heat Pump Symposium 2022: Book of Presentations. Copenhagen, Denmark, March 19-20. Technical University of Denmark.

Arpagaus, C., Bless, F., Paranjape, S., Bertsch, S. S., 2023. Integration of high-temperature heat pumps in Swiss food processes. In: Proc. 26th IIR International Congress of Refrigeration (ICR 2023). Paper 367. Paris, France, August 24-30. International Institute of Refrigeration. DOI: 10.18462/iir.icr.2023.0367.tDusek, S., Wilk, V., Verdnik, M., Rieberer, R., Zühlsdorf, B., 2024. Reduktion des Energiebedarfs durch den Einsatz von Hochtemperaturwärmepumpen in Industrieprozessen, In: Proc. 18. Symposium Energieinnovation 2024, https://www.tugraz.at/fileadmin/user_upload/tugrazExternal/f560810f-089d-42d8-ae6d-8e82a8454ca9/files/lf/Session_F4/LF_Dusek_NEU.pdf. (accessed 2024-10-30).tIEA, 2022. The Future of Heat Pumps, International Energy Agency, Paris, <https://www.iea.org/reports/the-future-of-heat-pumps> (accessed 2023-2-4).tZühlsdorf, B., Lundsted Poulsen, J., Dusek, S., Wilk, V., Krämer, J.,

Rieberer, R., Verdnik, M., Demeester, T., Vieren, E., Magni, C., Abedini, H., Leroy, C., Lang, L., Pihl Andersen, M., Elmegaard, B., Turunen-Saaresti, T., Uusitalo, A., De Carlan, F., Gachot, C., ... Arpagaus, C., 2023. IEA HPT Annex 58: High-Temperature Heat Pumps. Task 1 report: Technologies. <https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2023/09/annex-58-task-1-technologies-task-report.pdf>.

Umweltbundesamt, 2023. Berechnung von Treibhausgas (THG)-Emissionen verschiedener Energieträger, secure.umweltbundesamt.at/co2mon/co2mon.html (accessed 2024-1-29).

12.2.6 HPP (High Pressure Processing)

High-pressure – also often called as High Hydrostatic Pressure Process – processing has emerged as a leading nonthermal technology in the food industry. It offers a safe, efficient, and environmentally friendly alternative for food conservation to traditional thermal methods by using high hydrostatic pressure instead of heating. In HPP, food is sealed in a flexible container and subjected to extremely high pressures (100-600 MPa) at room temperature. A liquid, usually water, acts as a pressure transfer medium, ensuring even pressure distribution throughout the food. This process effectively pasteurises the food without affecting its flavour, nutritional value, or packaging.

HPP has become a popular method for preserving a wide range of foods, including meat, seafood, fruits, vegetables, dairy and beverages. This nonthermal technology effectively inactivates microorganisms and enzymes without compromising product quality. Data shows that in 2012, HPP was used to process over 350 million kg of food. Vegetable products accounted for the largest share (28%), followed by meat (26%), seafood (15%), juices and beverages (14%), and other products (17%).

HPP advantages and disadvantages

- **Energy Efficiency:** HPP operates at room temperature, eliminating the energy-intensive heating and cooling steps.
- **Minimal Processing:** It preserves quality and the natural flavour, texture, and nutritional content of the food without heating
- **Safety:** HPP ensures microbial safety without the need for preservatives, reducing the risk of secondary contamination.
- **Environmental Friendliness:** The pressure transfer medium can be recycled, and the process minimises energy consumption and waste.
- The process is compatible with several packaging materials, such as: bottles, pouches, cups or trays, vacuum or skin and MAP. The common factor is that packaging materials must be flexible and water resistant.
- Extended shelf-life for each compatible product.

HPP's success is largely due to its ability to maintain the sensory qualities of treated foods, making it a preferred choice among consumers. This consumer acceptance, coupled with its commercial viability, has solidified HPP's position as the leading nonthermal preservation technology. In addition, some manufacturers promise to extend the shelf life many times over by using this technology: In the case of cooked meats and Ready-to-eat (RTE) meals it can be 4 times longer, while in the case of vegetables dips is 10 times longer and for juices and beverages it goes up to 30 times longer.

However, HPP also has limitations. Most HPP products require refrigeration due to the potential for spore survival, particularly in low-acid foods. Additionally, HPP is not suitable for products with low water content or air bubbles, as the pressure transfer medium (water) can cause deformation. Furthermore, only plastic packaging materials with sufficient compressibility are compatible with HPP.

Research has indicated that HPP consumes less energy per kilogram of food than traditional thermal processes where heat is transferred to the food. HPP uses a specific amount of energy to apply pressure throughout the product, it is considered to reduce overall energy consumption in the food industry (Nabi et al., 2021).

In addition, the treatment process does not produce by-products, such as those produced by combustion. If the energy demand of the technology can be supplied from renewable energy sources, the GHG emissions of the process can be reduced to almost zero. It should be added that the technology is constantly evolving, so it is not yet possible to find accurate experimentally derived emissions data. What is certain is that this technology could be a solution to replace energy-intensive thermal treatments within 10 years for select applications (Hsiao-Wen et al., 2017). An increasing number of machine manufacturers are producing HPP machines for the food industry, which is increasing competition in the market, increasing supply and thus forcing manufacturers to compete on price. Continuous innovation can lead to solutions (in-process integration, use of materials, reduction of energy losses, mechanical energy recovery) that promise even more affordable prices.

The direct and indirect emission savings of HPP systems cannot yet be clearly defined. Some LCA and Life cycle costing (LCC) analyses have already been carried out to test the effectiveness of the method, but these have been compared with different methods for a small number of products. In one LCC studied, the unit cost of HPP is significantly higher than for other heat treatments, such as Thermal Pasteurisation (TP), and thus presumably the emissions are also higher. However, another analysis shows that HPP performs much better than MAP. Therefore, it can be concluded that the extent of emission reduction depends on the technology, the product, the production capacity and the equipment, since for a complete analysis it is necessary to know the amount of labour replaced, waste and loss reduction, packaging material savings, cost levels and maintenance data. In addition, the evolution of world prices of different fossil fuels and energy sources has a significant impact on the determination of production prices, which is also necessary for a complete analysis of emissions.

Scope 1 emissions savings (% or another quantifiable metric)	Not determinable
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	Not determinable
Quality of scope 2 emissions information	Low
Availability barriers	Equipment limitations, food properties, and operational factors. These barriers can affect the efficiency and effectiveness of HPP, limiting the overall availability of HPP-treated food products. In addition, the amount of initial investment is also significant, while this emerging technology has to fit the existing production technology which can also be a barrier.
TRL level	8
Maintainability issues	Primarily revolve around equipment accessibility, component durability, cleaning difficulty, and complexity. These factors can impact the equipment's lifespan and overall performance, affecting the availability and efficiency of the HPP process. Due to related LCA and LCC analyses, the costs of maintainability are higher than traditional methods. However, the development of the industry – which is quite competitive

	to other solutions – the expectations are that these issues will disappear.
Legislative concerns	The efficiency of the HPP method to control <i>Listeria monocytogenes</i> has already been evaluated by European Food Safety Authority (EFSA) experts, but so far only for RTE products and milk. This should be extended to other products. In addition, its effect on allergens and nutritional value should be investigated. The labelling of the method may be questionable and therefore longer and more in-depth studies need to be carried out and published.
Payback time (years)	n/a

Torres Bello, E.F., González Martínez, G., Klotz Ceberio, B.F., Rodrigo, D. and Martínez López, A., 2014. High pressure treatment in foods. *Foods*, 3(3), pp.476–490. doi: 10.3390/foods3030476.

Nabi, B.G., Mukhtar, K., Arshad, R.N., Radicetti, E., Tedeschi, P., Shahbaz, M.U., Walayat, N., Nawaz, A., Inam-Ur-Raheem, M. and Aadil, R.M., 2021. High-pressure processing for sustainable food supply. *Sustainability*, 13(24), p.13908. doi: 10.3390/su13241390.

Huang, H.-W., Wu, S.-J., Lu, J.-K., Shyu, Y.-T. and Wang, C.-Y., 2017. Current status and future trends of high-pressure processing in food industry. *Food Control*, 72, pp.1–8. doi: 10.1016/j.foodcont.2016.07.019.

Cacace, F., Bottani, E., Rizzi, A. and Vignali, G., 2020. Evaluation of the economic and environmental sustainability of high pressure processing of foods. *Innovative Food Science and Emerging Technologies*, 60, p.102281. doi: 10.1016/j.ifset.2019.102281.

Picart-Palmade, L., Cunault, C., Chevalier-Luca, D., Belleville, M.-P. and Marchesseau, S., 2019. Potentialities and limits of some non-thermal technologies to improve sustainability of food processing. *Frontiers in Nutrition*, 5, p.130. doi: 10.3389/fnut.2018.00130.

12.2.7 High-Temperature Short-Time (HTST) and UHT

Milk and dairy products are essential sources of nutrients and are considered staple foods in many diets. They can be consumed raw, without heat treatment, or pasteurised, which ensures microbiological safety and extends shelf life. Raw milk consumption has gained popularity in recent years, often associated with organic, natural, and eco-friendly lifestyles. Some believe that raw milk may have potential health benefits, but more research is needed to confirm these claims.

Generally, milk is pasteurised to ensure microbial safety. The US Department of Agriculture (USDA) defines pasteurisation as a process that effectively reduces the number of harmful microorganisms in food, ensuring its safety under typical storage and distribution conditions.

HTST and UHT are two methods used to heat-treat milk. HTST involves heating milk to 72°C for at least 15 seconds, while UHT heats it to 138-140°C for a few seconds. Both methods effectively kill harmful bacteria in milk, but UHT results in a longer shelf life without refrigeration.

The different combinations of temperature and time of heat treatments applied by the dairy industry to milk are summarised in Table 22.

Table 22. Combinations of temperature and time of heat treatments applied by the dairy industry.

Heat treatment	Temperature / °C	Time
Thermisation	63-65	15-20 s (Deeth, 2022)

LTLT pasteurisation	63	30 min
HTST pasteurisation	72-75	15-20 s
Indirect UHT	125-138	2-4 s
Direct UHT	135-140	A few seconds
Sterilisation in container	115-120	20-30 min

The combination of temperature and holding time can have the same effect on killing microorganisms or inactivating enzymes in food. Higher temperatures require shorter holding times to achieve the same result.

HTST and UHT are used not only for milk but also for other liquid foods. Liquid eggs, for instance, are pasteurised to eliminate Salmonella bacteria, as required by food safety regulations.

Fruit juices are often pasteurised using the HTST method. This involves rapidly heating the juice to a specific temperature, holding it for a short period, cooling it quickly, and then filling it into aseptic containers.

Researchers are exploring innovative and sustainable technologies to meet consumer needs. These include advanced thermal methods like superheated steam, ohmic heating, and microwave-assisted processing, which can better preserve nutrients. Nonthermal techniques, such as PEF, are also being developed.

Microwave-assisted processing is commonly used for tasks like pasteurisation, sterilisation, drying, and thawing food. Many industries combine microwaves with traditional heating methods. In the food industry, microwaves help reduce processing time and energy consumption while preserving sensory qualities and minimizing nutritional loss compared to traditional methods alone.

Pasteurisation and sterilisation involve both heating and cooling processes. A heat pump can be employed to couple the energy flow between the heating and cooling units during pasteurisation. The hot pasteurised milk is cooled by the cold side of the heat pump, while the cold raw milk is heated by the hot side. At a pasteurisation temperature of 72°C and a coagulation temperature of 32°C, the measured COP of the heat pump ranged from 2.3 to 3.1. The heat pump system can achieve a 66% reduction in primary energy consumption compared to traditional plate and double-jacketed milk pasteurisation systems.

Scope 1 emissions savings (% or another quantifiable metric)	Variable; potential for savings through optimised heat recovery systems (e.g., regeneration in heat exchangers). Direct savings from HTST vs. UHT as inherent processes are not typically reported as percentages between them, but rather overall plant efficiency improvements. Some dairy companies target 35% reduction in scope 1 and 2 emissions by 2030 across their operations, which would include pasteurization [EDA Factsheet, 2024].
Quality of scope 1 emissions information	Generally moderate to high quality, as direct fuel combustion (for steam generation) is measurable. However, specific savings depend on baseline comparisons and whether heat recovery is considered.
Scope 2 emissions savings (% or another quantifiable metric)	Variable: potential for savings through optimised electricity use for pumps, compressors, and heat recovery. Indirect emissions (electricity)

	often form the largest part of processing emissions. A study in Poland found indirect emissions (electricity) accounted for 50.21% of total GHG emissions from milk processing [Kasprzak et al., 2024].
Quality of scope 2 emissions information	High quality if electricity consumption is metered directly. Industry-wide GHG inventory guidance exists for dairy processing [Innovation Center for U.S. Dairy, 2019]. Some cases studies such as [Kasprzak et al., 2024] and Serbia.
Availability barriers	Low. HTST technology is fully mature and widely available globally. No significant barriers to acquiring or implementing standard HTST systems for dairy processing.
TRL level	9
Maintainability issues	Fouling of heat exchangers: Protein and mineral deposition on heat exchange surfaces, requiring frequent Cleaning-in-Place (CIP) cycles. This leads to downtime, increased water/chemical usage, and energy loss. [Ellab, 2020; New Food Magazine, 2012 (UHT but applies to HTST as well)]. Wear and tear on pumps and valves. Maintaining pressure differentials in regenerator sections to prevent cross-contamination. [Canada.ca, 2024].
Legislative concerns	Strict regulations for time-temperature parameters to ensure microbial safety (e.g., inactivation of <i>Coxiella burnetii</i>). [Canada.ca, 2024]. Hazard Analysis and Critical Control Points (HACCP) principles are universally applied. Regular validation and calibration of temperature and flow meters are mandatory. [Ellab, 2020]. Post-pasteurization contamination is a critical concern, leading to legislative focus on hygienic design and aseptic filling.
Payback time (years)	UHT technology is difficult to pinpoint due to the variables involved, the range of 4 to 10 years for a full-scale new plant investment seems reasonable, with shorter paybacks (1-3 years) for specific energy efficiency upgrades within existing UHT operations. The long-term benefits of market access, reduced logistics costs, and minimised spoilage are compelling drivers that often justify the initial capital outlay for UHT processing.

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Deeth, H. C. 2022. *Encyclopedia of Dairy Sciences* (Third Edition).

Wang, L., 2013. Energy consumption and reduction strategies in food processing. *Sustainable food processing*, pp.377-400.

European Dairy Association (EDA). (2024). Dairy Commitments on Environment and Nutrition. https://eda.euromilk.org/wp-content/uploads/2024/11/2024-09-12_EDA-Factsheet-on-Dairy-commitments-Environment-and-Nutritio-.pdf (Provides industry-wide GHG reduction targets).

Kasprzak, M., Konopka, E., & Konopka, E. (2024). Carbon Footprint of Milk Processing—Case Study of Polish Dairy. *Molecules*, 15(1), 62. <https://www.mdpi.com/2077-0472/15/1/62> (Provides specific data on GHG emission breakdown in a dairy plant, highlighting indirect emissions).

Canada.ca. (2024). Dairy processing: High temperature short time (HTST) pasteurization systems. <https://inspection.canada.ca/en/preventive-controls/dairy-products/htst> (Accessed July 2025). (Details on legislative/operational aspects for HTST).

Ellab. (2020). Validating UHT and HTST Pasteurization Processes | Challenges and Considerations. <https://core.ac.uk/download/5165017.pdf> (Details on validation and some maintainability/operational issues).

Tadini, C.C. and Gut, J.A., 2022. The importance of heating unit operations in the food industry to obtain safe and high-quality products. *Frontiers in Nutrition*, 9, p.853638.

12.2.8 Impingement cooking using air jets

Forced convection heat transfer by circulating heated air in ovens is widely used in units for cooking and baking (Cappelli et al., 2021). A special form of forced convection is *impingement*, which directs jets of hot gas perpendicularly towards the surface of the baking food at high speed, with the aim to reduce baking times and reduce the setpoint of the hot air temperature. The jets of heated fluid are addressed at high velocities (up to 50 m/s, but more commonly below 10 m/s) onto the surfaces of the food (Kerry, 2011). The impinging jets result in high convective heat transfer rates at the food surface. (Li and Walker, 1996) measured heat transfer coefficients during baking in conventional commercial conveyor ovens in comparison to impingement and reported average values of apparent convective heat transfer coefficients ranging from 22.8–84.8 W/m² K for the top and 17.4–110.9 W/m² K for the bottom of the oven, for the two types. Values over 200 W/m² K were reported for the convection heat transfer coefficient using air impingement systems (Gadiraju et al., presented 2003 IFT Annual Meeting-Chicago, 2003 as cited by (Marcotte and Grabowski, 2008)) compared to only about 10–20 W/m² K, in a conventional baking oven.

Impingement ovens use a variety of small nozzles, short tubes, perforated plates, or narrow slits to achieve impingement jets, therefore it has been found mainly beneficial for thin products such as pizza where the internal heat transfer resistance is small compared to that at the surface (Chhanwal et al., 2019; Walker, 2016). Impingement found its application in restaurants and food service on a wider scale than pizza only, and is used for casseroles, steaks, small bread loaves, cakes, pies and more. From the original application in small ovens, impingement now is also more and more used in large continuous ovens. These large-scale tunnel ovens use the principle of high-velocity air impingement from slots or nozzles for baking different types of products. High heat transfer rates also means high moisture removal rates by the impinging air, therefore the impingement will also increase water loss rates from the surface of the product, affecting e.g. the crust formation. Still, this may be balanced by the residence time in the oven that is reduced so much that products actually lose less moisture. The effects of changing to impingement cooking on food quality scale with the temperature adjustment as many transformation (such as leavening release, fat melting, sugar dissolution, protein denaturation, and starch gelatinisation) rates leading to quality changes are temperature dependent.

According to Walker (2016), “any savings in baking times, lower temperatures, and reduction in energy use vary with the nature of the product (thickness, water content, etc.) and with the nozzle design and locations, but most importantly with the air velocity.” It is claimed that “the product of ‘time’ and ‘driving temperature’ (as an energy saving parameter) can be reduced to about one-half, where ‘driving temperature’ = ‘oven temperature’ – ‘product initial temperature.’” (Walker, 2016). Still, there is no quantitative evidence to support this. For thicker products, the expected savings are claimed to be rather 1/3 instead of 1/2. (Wählby et al., 2000) reported, in an experimental oven intended for the domestic market using yeast buns (representing category bread) and pork cutlets (representing meats), that a jet impingement oven required 25 °C lower air temperature than a reference oven for baking buns in the same time, and a reduction of the cooking time of the meat by up to 50% at similar

air temperature as recommended. (Banooni et al., 2008) studied experimentally application of impingement for baking of very thin breads (such as the Iranian breads) in ranges of temperature (150°C-250°C) and jet velocity (1 m/s-10 m/s). The sample baking time in a conventional oven with 200°C air temperature was about 10 min, which was about two times the baking time in the impingement oven at the same temperature with similar bread quality.

The above studies seem to agree that impingement may lead to up to 50% energy savings, although an integral analysis is missing that also accounts for the additional energy requirement for the air impingement system to operate (fan power) and assesses overall system performances. Using data and a parameterised reduced order model for a French bread baking commercial oven the potential energy savings of a newly designed impingement system with an array of circular jets were calculated (Alamir et al., 2013). The analysis indicated that air impingement could lead up to 17.9% energy savings. (Li et al., 2013) used a mechanistic heat exchange model in another optimisation calculation and determined that almost 12% energy can be saved using jet impingement. An early review of the energy efficiency of ovens (Moreth, 1993, Morris, 1994 as cited by (Geedipalli et al., 2008) claims that jet impingement ovens are 65% efficient while standard gas fired ovens have only a 35% fuel efficiency.

Design features have a large impact on impingement heat transfer and will also affect the energy efficiency of the system. The rate of energy dissipation is largely dependent upon the shape of the nozzle, exit velocity of impinging fluid, length of nozzle and sharpness at nozzle exit, and adjustment of the plenum height (and tube distance from the product surface) clearly impacts on impingement efficiency (Kerry, 2011). The slot shape and length (i.e., 'short', orifice type, or 'long', finger type), and the layout of the arrays (i.e. uniform or staggered tube patterns), employed in various cooking systems clearly impact on the air velocity distribution and must be calculated during the design stages to ensure optimal heat transfer as a function of cooking time (Kerry, 2011). (Shevade et al., 2019) performed a computational fluid dynamics study of plenum and nozzle design parameters on the heat transfer rates to the surface of pizza type food product, for baking in a commercial conveyor oven. They only considered the turbulent airflow and heat transfer expressed by the surface heat transfer rates and air leakage. They suggested that with an optimal selection of the nozzle and plenum design features 20% energy savings could be achieved, but a comprehensive energy balance analysis of the complete system was again lacking.

Gains can also be expected when combining air impingement with other heating modes. (Mastrascusa et al., 2021) analysed, for continuous pizza baking, the CO₂ emissions and relative emission reduction of air impingement (AI) in combination with microwaves (MW), infrared heating (IR), superheated steam injection (SHS) and induction heating (IH). This was an experimental study performed in the laboratory by combining different apparatuses where needed. Energy consumption was computed as the sum of by power by run time of each technology. Emissions were calculated using data from the Mexican national electrical system, the value reported for the year 2019 was 0.505 kg CO₂ eq/kWh. Quality attributes were also assessed. The use of IR with AI presented the most significant reduction in cooking time (50%) and a reduction in energy consumption per pizza (27%) compared to the standard AI oven. The second higher reduction in energy and emissions is the combination which used MW and AI but failed on quality (insufficient browning). The relative savings of the successful AI and IR combination was calculated to be 27.1%.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	Air impingement compared to conventional heating: Baking time reduced by 30-50% (at same operational temperature and with similar baking quality) Energy savings 12-17.9% (from computational analysis in 2 studies)
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	Increased energy efficiency: 65% compared to 35% (90's work) Multimode heating with infrared (experimental work): 50% reduction of cooking time 27% energy reduction 27.1% reduction in CO ₂ emissions
Quality of scope 1/2 emissions information	Data from different peer reviewed journal papers on different applications, partly based on computational analysis using mechanistic and reduced order models. Few data on actual measurements.
TRL level	5-7 (hybrid) -8-9 (air impingement ovens for pizza)
Maintainability issues	Proper cleaning
Legislative concerns	-
Payback time (years)	Not available

Alamir, M., Witrant, E., della Valle, G., Rouaud, O., Josset, C., and Boillereaux, L. (2013). Estimation of energy saving thanks to a reduced-model-based approach: Example of bread baking by jet impingement. *Energy*, 53, 74–82. <https://doi.org/10.1016/J.ENERGY.2013.02.016>.

Banooni, S., Hosseinalipour, S. M., Mujumdar, A. S., Taheran, E., Bahiraei, M., and Taherkhani, P. (2008). Baking of Flat Bread in an Impingement Oven: An Experimental Study of Heat Transfer and Quality Aspects. <http://Dx.Doi.Org.Kuleuven.e-Bronnen.Be/10.1080/07373930802142614>, 26(7), 902–909. <https://doi.org/10.1080/07373930802142614>.

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Chhanwal, N., Bhushette, P. R., and Anandharamakrishnan, C. (2019). Current Perspectives on Non-conventional Heating Ovens for Baking Process—a Review. *Food and Bioprocess Technology*, 12(1), 1–15. <https://doi.org/10.1007/S11947-018-2198-Y/FIGURES/2>.

Geedipalli, S., Datta, A. K., and Rakesh, V. (2008). Heat transfer in a combination microwave–jet impingement oven. *Food and Bioprocess Technology*, 86(1), 53–63. <https://doi.org/10.1016/J.FBP.2007.10.016>.

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Marcotte, M., and Grabowski, S. (2008). Minimising energy consumption associated with drying, baking and evaporation. *Handbook of Water and Energy Management in Food Processing*, 481–522. <https://doi.org/10.1533/9781845694678.4.481>.

Mastrascusa, D., Vázquez-Villegas, P., Huertas, J. I., Pérez-Carrillo, E., García-Cuéllar, A. J., and Nevarez, R. (2021). Increasing productivity and reducing energy consumption in the pizza industry by the

synergetic combination of cooking technologies. *Journal of Food Processing and Preservation*, 45(3), e15286. <https://doi.org/10.1111/JFPP.15286>.

Shevade, S., Rahman, M., and Guldiken, R. (2019). Optimization of turbulent air jet impingement for energy efficient commercial cooking. *Energy Procedia*, 160, 691–698. <https://doi.org/10.1016/J.EGYPRO.2019.02.191>.

Wählby, U., Skjöldebrand, C., and Junker, E. (2000). Impact of impingement on cooking time and food quality. *Journal of Food Engineering*, 43(3), 179–187. [https://doi.org/10.1016/S0260-8774\(99\)00149-1](https://doi.org/10.1016/S0260-8774(99)00149-1).

Walker, C. E. (2016). Oven Technologies. In *Encyclopedia of Food Grains* (Vols. 3–4, pp. 325–334). Elsevier. <https://doi.org/10.1016/B978-0-12-394437-5.00159-5>.

12.2.9 Improve combustion efficiency (gas/oil)

Gas burners are typically 85–95% efficient (Therkelsen et al., 2014). Still, the energy efficiency of an average wafer baking machine is reported to be only 35%, with the rest of the total energy lost to “atmospheric discharge” (Sovacool et al., 2021). It has also been reported that electric ovens are more energy efficient than direct-fired natural gas ovens, which generate large amounts of heat from the exhaust gases. So, with respect to burner efficiency, it is mainly important to regularly check the efficiency and take appropriate measures to assure efficiency. It has been claimed that 5-25% or more savings in heat generation can be achieved by proper combustion efficiency in industrial applications such as steel production (Oakes and Bratcher, 2011).

Measures for oven combustion control have been adequately described by (Therkelsen et al., 2014). These authors state that oven burners are a critical component of oven energy efficiency. To optimise the efficiency, flue gas and temperature analysis can be used to determine burner operation and efficiency. For example, burners are typically running with excess O₂ greater than 4% in the flue gas, to avoid carbon monoxide (CO) development and soot deposits (Oakes and Bratcher, 2011). But there could be margins to reduce and save fuel. As part of installation and commissioning, burners should be adjusted for efficient operation, which is an action with a five-to-ten-month payback period. After completing burner commissioning, a reference flue gas and temperature sample should be taken. This reference measurement can be used to determine if burners are operating efficiently or not. When variations in flue gas and temperature are observed, the most common corrective action will be to adjust the burner air/fuel ratio. Potential fuel savings can be determined from published charts (Oakes and Bratcher, 2011). These authors also provide some examples with fuel saving costs of more than 20% in industrial furnaces. An oxygen trim control may be appropriate to manage combustion inefficiencies in a more continuous way. The oxygen trim system uses a sensor to measure the excess oxygen in the flue gas and will change the fuel or air flow to correct this level to match a pre-set level. Oxygen trim controllers cost between €6000 and €10,000 to install but will reduce the time required to assess efficiency and maintain oven efficiency in the future. An example is explained by (Anonymous, 2007). Return on investment depends on the savings expected. In some instances, a burner will be damaged and need to be repaired or replaced. Burner repair commonly has a payback period of 1.5 years and can be performed during periods of routine maintenance.

Therkelsen et al. (2014) also discusses flue gas monitors that can be used to maintain flame temperatures within optimal limits while monitoring CO, oxygen, and smoke levels, with respect to use in combustion boilers: “Oxygen measured in exhaust gas is a combination of deliberately added excess air and unintentional air infiltration. By combining an oxygen monitor with an intake airflow monitor, it is possible to detect even small levels of unwanted air infiltration. Elevated CO or smoke exhaust signals that either air/fuel ratios need to be adjusted, or combustion burners need to be maintained or replaced. Using a combination of CO and oxygen readings, efficiency can be maximised,

and air pollutant emissions reduced through optimisation of fuel/air mixture level. Case studies indicate an average payback period of 1.7 years for this measure and show that it is typically financially attractive only for large boilers.”

Furthermore, a portion of oven exhaust gas can be re-circulated in the oven or mixed with incoming combustion air to reduce fuel consumption (Therkelsen et al., 2014). See the respective review on this topic. Mukherjee et al. (2019) also states that measures to reduce secondary leak air flow by 30-35%, significantly reduce the dilution of hot products of combustion inside the oven and yields overall fuel savings of 8.5%.

An interesting alternative to gas recirculation in ovens where the consumption temperature is much higher than the required temperature for baking has been suggested by (Corina, 2017). It was shown that the technology of an integrated cogeneration engine (ICE) in (indirect heating) ovens is relevant from the energy efficiency point of view. The idea of ICE is to avoid the losses during recycling and mixing direct burner gasses with oven gasses, but rather use the surplus heat of the burner for other purposes. The energy efficiency of the process of obtaining gases in the combustion chamber of ICE was calculated to be 10,6% higher (92,6% instead of 82%) than the same process in the combustion chamber of the classic oven. Therefore, the integration of cogeneration in baking installations increases energy efficiency of the analysed process as a whole which also produces electricity and warm water of 70°C that are included as useful outputs. It was noted “that the proposed technology can be implemented in any enterprise equipped with natural gas ovens, regardless of the type of products cooked/baked”. In the particular case studied, the electricity produced by the ICE integrated with the bakery oven, will account for 38% of the total electricity demand for the analysed enterprise. To establish this efficiency, however, the total gas consumed increased by a factor 2.4 for the production of the same amount of oven heat. The return on investment was also not analysed.

The analysis made by the Carbon Trust in UK (Carbon Trust, 2016) for 89 bakery sites, showed that improved combustion efficiency leads to average reduction of 196 tons of CO₂ per site with a payback time of 3 years, mainly for indirect-fired ovens. Actions include regular servicing of the burners and use of an oxygen trim, with estimated savings of 10%.

Scope 1 emissions savings (% or another quantifiable metric)	Maximal range 5-25% energy use savings, but likely between 5-10% (for indirect fired ovens). 196 tons CO ₂ e per site (bakery sector).
Quality of scope 1 emissions information	Savings depends on the extent of deviation of the optimal efficiency of the combustion burning process, which can be assessed by measurement flue temperature and excess oxygen concentration. Too high O ₂ will be less efficient. Established in many industrial combustion applications.
Scope 2 emissions savings (% or another quantifiable metric)	ICE provides electrical energy.
Quality of scope 2 emissions information	n/a
TRL level	8-9
Maintainability issues	Routine maintenance: Regular measurement of flue gas concentrations and temperature to assure reference values are maintained. Repair/replace burner if needed.

	If full control system is preferred, additional installation (sensors, controller, actuators) and maintenance costs are expected for an oxygen trim controller
Legislative concerns	-
Payback time (years)	1.5 years for burner repair 3 years for oxygen trim

Anonymous. (2007). Oxygen Trim Control - a disregarded option. Trim System. https://www.scantronic.dk/Articles/trim_control_article.pdf.

Carbon Trust. (2016). Industrial Energy Efficiency Accelerator. Guide to the Industrial Bakery Sector. <https://issuu.com/mikeglanfield/docs/ctg034-bakery-industrial-energy-eff> (visited on 18/10/2022).

Corina, C. (2017). Increasing energy efficiency of the gases production process in bakery ovens. 8th international conference on energy and environment (CIEM), 207–210. <https://ieeexplore-ieee.org.kuleuven.e-bronnen.be/stamp/stamp.jsp?tp=&arnumber=8120830>.

Mukherjee, S., Asthana, A., Howarth, M., McNeill, R., and Frisby, B. (2019). Achieving Operational Excellence for Industrial Baking Ovens. Energy Procedia, 161, 395–402. <https://doi.org/10.1016/J.EGYPRO.2019.02.100>.

Oakes, J., and Bratcher, D. (2011). Operational efficiency improvements resulting from monitoring and trim of industrial combustion systems. TMS Light Metals, 1189–1191. https://doi.org/10.1007/978-3-319-48160-9_201.

Sovacool, B. K., Bazilian, M., Griffiths, S., Kim, J., Foley, A., and Rooney, D. (2021). Decarbonizing the food and beverages industry: A critical and systematic review of developments, sociotechnical systems and policy options. Renewable and Sustainable Energy Reviews, 143, 110856. <https://doi.org/10.1016/j.rser.2021.110856>.

Therkelsen, P., Masanet, E., and Worrell, E. (2014). Energy efficiency opportunities in the U.S. commercial baking industry. Journal of Food Engineering, 130, 14–22. <https://doi.org/10.1016/j.jfoodeng.2014.01.004>.

12.2.10 Improved oven control

Zareifard et al. (2006) improved heating uniformity in an infrared oven by better control of the heating power of different infrared heaters. Standard deviation of product heat fluxes among nine positions varied to over 250 W/m² K or 29%. The improved IR heating control was able to reduce the differences to less than 5%, improving uniformity and reducing total baking time by 10%.

Papasidero et al. (2016) presented an approach to optimise the total energy absorbed by the food product (bread), in a batch process with different energy sources (convection and radiation), at the level of adjusting the control. The optimisation showed that the highest temperatures and the most important energy contribution are related to the initial dough heating part, while the final part is more related to achieve the targeted quality and require less energy. A 20% energy save with respect to the base case was achieved where levels of air temperature and IR temperature were allowed to vary across 4 periods of the total baking time. The study was not conclusive on the final solution as a different number of baking periods further changed the optimal temperature profiles.

Afkar et al. (2020) evaluated by modelling and experiments the effects of different dynamic heat flux profiles on the quality and the energy consumption of the baking of flat bread. The study revealed that the heat flux profile has a significant effect on the bread quality. The amount of energy required for baking the bread using an ascending or descending heat flux profile was 360 kJ per heating element,

while the base case with a constant heat flux used 504 kJ. This would mean an energy saving of 28.6%. The bread quality assessments revealed that the bread baked using the ascending heat flux profile was of a better quality compared to the other profiles in terms of brightness and sensory quality characteristics.

The performance of a convection oven cavity can be improved by implementing more advanced control algorithms to the unit (Ryckaert et al., 1999). These authors showed with experimental results that the dynamic behaviour of the oven cavity is modified significantly through the implementation of a model-based tuned Proportional–Integral–Derivative (P.I.D.) controller, in comparison to a simple on-off control. The temperature inhomogeneity is much smaller with the P.I.D. controller, as compared to the classical on-off controller. Furthermore, the average temperature in the cavity, obtained with the P.I.D. controller, tracks the setpoint temperature much better. The performance of the P.I.D. controller for a setpoint of 70°C indicated that uniformity is improved and a reduction of required heating power by 75% was achieved during steady state temperature control of the cavity.

Stigter et al. (2001) applied classical control theory to a heat conduction model with convective boundary conditions to obtain optimal heating strategies. The methodology was applied to two case studies, namely, a cylindrically shaped geometry (with mashed potato) and a commercially available container geometry (with ready-made lasagne). The results indicate a ΔT type heating profile, including a final oscillating behaviour that fine-regulates the temperature to an almost uniform temperature of 100°C. Such improved uniformity will help in reducing losses (over- or under-heating) and may affect total heating time, thereby allowing energy savings. The energy impact was however not investigated.

Active control strategies for hybrid heating modes (e.g., microwave and convection) have been for long subject of research (Sanchez et al., 2000). Oven temperature controllers should be designed by inverting a model of the process for them to be optimal, which may lead to complexities in the case of highly non-linear processes such as food baking. Still, simple control structures can be proposed to overcome these limitations without risking robustness and tracking efficiency. These use easily derived time varying linear models which are inverted to guarantee efficiency. Robustness is induced by continuously updating model parameters through recursive estimation from input–output data. Both characteristics were demonstrated via experiments performed under realistic conditions (Sanchez et al., 2000), but energy aspects were not addressed in this work.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	Optimised profiles of heating power can reduce energy consumption by 20-30%. Heating time reductions up to 10% Improved control leads to better uniformity, reducing losses.
Quality of scope 1/2 emissions information	Based on peer reviewed research articles.
TRL level	4-9
Maintainability issues	Regular calibration of sensors.
Legislative concerns	-
Payback time (years)	No information. Expected short due to low cost of components (electronics and sensors).

Afkar, H., Kianifar, A., and Zamani, H. (2020). Investigation of the effect of variable heat flux on energy consumption and bread quality in the flat bread baking process by experimental and numerical methods. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. <https://doi.org/10.1080/15567036.2020.1845255>.

Papasidero, D., Pierucci, S., and Manenti, F. (2016). Energy optimization of bread baking process undergoing quality constraints. *Energy*, 116, 1417–1422. <https://doi.org/10.1016/j.energy.2016.06.046>.

Ryckaert, V. G., Claes, J. E., and van Impe, J. F. (1999). Model-based temperature control in ovens. *Journal of Food Engineering*, 39(1), 47–58. [https://doi.org/10.1016/S0260-8774\(98\)00142-3](https://doi.org/10.1016/S0260-8774(98)00142-3).

Sanchez, I., Banga, J. R., and Alonso, A. A. (2000). Temperature control in microwave combination ovens. *Journal of Food Engineering*, 46(1), 21–29. [https://doi.org/10.1016/S0260-8774\(00\)00065-0](https://doi.org/10.1016/S0260-8774(00)00065-0).

Stigter, J. D., Scheerlinck, N., Nicolai, B., and van Impe, J. F. (2001). Optimal heating strategies for a convection oven. *Journal of Food Engineering*, 48(4), 335–344. [https://doi.org/10.1016/S0260-8774\(00\)00176-X](https://doi.org/10.1016/S0260-8774(00)00176-X).

Zareifard, M. R., Marcotte, M., and Dostie, M. (2006). A method for balancing heat fluxes validated for a newly designed pilot plant oven. *Journal of Food Engineering*, 76(3), 303–312. <https://doi.org/10.1016/j.jfoodeng.2005.05.037>.

12.2.11 Keeping oven loaded

An energy analysis of the bakery industry conducted in the UK sheds light on the specific energy consumption (SEC) of baking processes in (large) gas fired tunnel ovens (Carbon Trust, 2016). Measured throughput (kg/h) and average power (kW) were used to calculate the SEC for direct and indirect fired ovens. Low throughputs of less than 1000 kg/h had SECs above 1 kWh/kg, while high throughputs (> 2000 kg/h), resulted in SEC values below 0.5 kWh/kg. A high negative sensitivity of energy use per load mass was seen in this range. The direct fired ovens had much higher throughput (> 4000 kg/h), with SECs below 0.3 kWh/kg and much lower sensitivity to changes in loads. The reason for this, is that for lower throughputs the total time to produce the same quantity increases with consequently more heat losses. In the study losses accounted for 90% of the total energy balance of the ovens considered but should on average be around 65% for gas fired ovens (Mukherjee et al., 2019). The reason may be the age of the oven considered (> 30 years old). It can be reasonably argued that in (electric heated) batch ovens, that are claimed more energy efficient due to no losses caused by gas exhaust (Klimes et al., 2008) as cited by (Ladha-Sabur et al., 2019)), the effects of assuring high loads on energy consumption savings are less. As an example, compare 2 ovens with different efficiency, say oven 1 with 20% efficiency and oven 2 with 50% efficiency. Halving the load in the two ovens, will lead to a specific energy use increase by up to 80% for oven 1 and 50% for oven 2. Therefore, for producing the same amount of product one should run ovens at full capacity as much as possible in all cases.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	Up to 50% energy savings per kg for doubling the throughput load on inefficient low throughput ovens (e.g., indirect fired tunnel ovens) Up to 33% energy savings per kg for doubling the throughput load on efficient high throughput ovens (e.g., direct fired tunnel ovens, or electric ovens)
Quality of scope 1/2 emissions information	Savings are dependent on overall oven efficiency and throughput. No data on batch ovens. Above are from measurements in case studies in larger UK study of the Carbon Trust.
TRL level	8-9
Maintainability issues	-
Legislative concerns	-
Payback time (years)	0

Carbon Trust. (2016). Industrial Energy Efficiency Accelerator. Guide to the Industrial Bakery Sector. <https://issuu.com/mikeglanfield/docs/ctg034-bakery-industrial-energy-eff>.

Klemes, J., Smith, R., and Kim, J. (2008). Handbook of water and energy management in food processing. https://books.google.com/books?hl=nl&lr=&id=4KOjAgAAQBAJ&oi=fnd&pg=PP1&ots=-_2JHAOjLO&sig=JmH5tpHvn557lyjpdFda3fGNWek.

Ladha-Sabur, A., Bakalis, S., Fryer, P. J., and Lopez-Quiroga, E. (2019). Mapping energy consumption in food manufacturing. *Trends in Food Science and Technology*, 86, 270–280. <https://doi.org/10.1016/j.tifs.2019.02.034>.

Mukherjee, S., Asthana, A., Howarth, M., McNeill, R., and Frisby, B. (2019). Achieving Operational Excellence for Industrial Baking Ovens. *Energy Procedia*, 161, 395–402. <https://doi.org/10.1016/J.EGYPRO.2019.02.100>.

12.2.12 Microwave/ultrasonic combination cooking

According to Li et al. (2023) a combination of microwave and ultrasonic technologies in food processing has the potential to enhance efficiency and product quality. Microwaves are effective for heating, thawing, drying, and sterilisation, but often suffer from uneven heating, which can be improved by combining them with ultrasonic methods. Microwaves can be used for a number of processes:

- Thawing
Microwave and ultrasonic techniques improve thawing efficiency and product quality, offering better water retention and less damage to muscle fibres compared to traditional methods
- Drying
Combining microwaves with ultrasonic pre-treatment enhances drying efficiency, colour retention, and nutrient content, although it may increase energy consumption
- Vacuum frying
The combined technique improves frying efficiency and reduces oil content, resulting in better texture and flavour in fried foods
- Extraction
Microwave and ultrasonic-assisted extraction increase the yield and quality of bioactive compounds, such as antioxidants, by enhancing heat and mass transfer
- Liquid food processing
The combined sterilisation technique effectively inactivates microorganisms while preserving food quality, applicable to various liquid foods

Viji et al (2022) reviewed the use of microwaves, primarily in sea fish processing. They state that microwaves can reduce heating rates, reduce process time and provide enhanced energy efficiency. It is clear that energy savings depend on the process applied and the product being heated. Products with higher water content (such as fish) make them more appropriate for microwave applications. Foods can be grouped into different types according to their relevance for microwave heating:

1. High dielectric loss materials or absorbers, which absorb most of the microwave energy.
2. Low dielectric loss materials or transparent materials showing little microwave absorption characteristics.
3. Conductors or opaque materials which mostly reflect the microwaves passed

Some work to assess energy saving opportunities for microwave cooking are for domestic use. This may not directly apply to industrial use but provides an indication of the energy savings. Lakshmi et al (2007) assessed the energy savings when cooking rice. They found that in controlled cooking trials that the energy used to cook both soaked and unsoaked rice was reduced compared to conventional cooking. The energy used to cook unsoaked rice reduced by 14–24% and for pre-soaked rice it reduced

by 12–33%. Cooking times increased by up to 2 minutes compared to conventional cooking. In terms of energy consumption microwave cooking was found to be similar to pressure cooking but had shorter cooking times.

Microwave and traditional cooking for beef burgundy was compared by Jouquand et al (2015). They found that traditional cooking consumed 6.52 kWh whereas microwave cooking consumed 4.67 kWh (56 % reduction in energy). This was due to higher energy losses in traditional cooking. The microwave cooking was also quicker than the conventional cooking method.

It is clear that although microwaves may in many instances provide energy savings that there may be compromises in terms of product quality or increased weight loss from products that are microwaved (Pathare and Roskilly, 2016). Controversy in some instances, for example microwave drying, pasteurisation or sterilisation can have advantages such as inactivation of microorganisms, reduced enzyme activity and can have less impact on antioxidant activity, texture and colour of food products (Guo et al, 2017).

Scope 1 emissions savings (% or another quantifiable metric)	Savings if microwaves replace fossil fuels.
Quality of scope 1 emissions information	Reasonable. Some limitations in industrial cooking information.
Scope 2 emissions savings (% or another quantifiable metric)	Potentially up to 56% energy saving (potentially as low as 12%). However, very dependent on product and process.
Quality of scope 2 emissions information	Reasonable. Some limitations in industrial cooking information.
Availability barriers	None
TRL level	8-9 (ultrasonic and microwave 4-5)
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Very dependent on process and food. Very limited information.

Guo, Q., Sun, D.W., Cheng, J.H. and Han, Z., 2017. Microwave processing techniques and their recent applications in the food industry. *Trends in Food Science and Technology*, 67, pp.236-247.

Jouquand C, Tessier FJ, Bernard J, Marier D, Woodward K, Jacolot P, Gadonna-Widehem P, Laguerre J-C (2015) Optimization of microwave cooking of beef burgundy in terms of nutritional and organoleptic properties. *LWT Food Sci Technol* 60(1):271–276.

Lakshmi, S., Chakkaravarthi, A., Subramanian, R. and Singh, V., 2007. Energy consumption in microwave cooking of rice and its comparison with other domestic appliances. *Journal of Food Engineering*, 78(2), pp.715-722.

Li, M., Zhou, C., Wang, B., Zeng, S., Mu, R., Li, G., Li, B. and Lv, W., 2023. Research progress and application of ultrasonic-and microwave-assisted food processing technology. *Comprehensive Reviews in Food Science and Food Safety*, 22(5), pp.3707-3731.

Pathare, P.B. and Roskilly, A.P., 2016. Quality and energy evaluation in meat cooking. *Food Engineering Reviews*, 8(4), pp.435-447.

Viji, P., Rao, B.M., Debbarma, J. and Ravishankar, C.N., 2022. Research developments in the applications of microwave energy in fish processing: A review. *Trends in Food Science and Technology*, 123, pp.222-232.

12.2.13 Motor efficiency (fans and conveyors)

In food processing facilities, electrical motors typically run conveyors, combustion air fans and convection fans (Stojceska et al., 2021).

Energy efficiency could be improved by use of the control systems in the ovens to lower the speed of the motor (Therkelsen et al., 2014). These authors discuss an innovative oven hood design that includes adjustable speed drives on its oven air supply and exhaust fan motors with a control system to run motors at a low speed with reduced energy consumption, until loaded. The claimed reduction of energy use by the oven hood controls were nearly 75% compared to standard designs. This could lead to 2% to 4% overall energy savings.

Another way of improving energy efficiency is to replace the existing electric motors with modern high efficiency motors. The electric motor that drives the metallic conveyor belt in the tunnel ovens studied by Stojceska et al. (2021) had an efficiency of 70.6%. According to the authors, modern motors should obtain efficiencies of around 80% for the same size range. In the analysis of the application in this study, the motor efficiency increase could result in 11.8% energy use reduction for the same oven load. This estimate could be on the high end, as conveyor belt motors are relatively low power (0.5 kW), according to (Carbon Trust, 2016): the contribution of electricity to specific energy consumption of baking ovens was 32 kWh/t (5.1% of total) for 590 kWh/t gas use in an indirect fired oven, and only 6 kWh/t (2.6% of total) for 221 kWh/t gas use in a direct fired oven. Therefore, a 10% increase in motor efficiency should have a limited impact on total energy consumption of this type of ovens, in the order of 0.2 to 0.5%.

Electric ovens should be more heat-source efficient (not having exhaust losses), so the relative impact could be slightly larger compared to gas fired ovens, and savings could be reasonably estimated as 0.5-1.0% energy savings in electric ovens.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	More efficient motors: 0.2-0.5% energy savings in gas fired ovens 0.5-1.0% energy savings in electric oven Variable speed control motors (for fans): 2-4% energy savings
Quality of scope 2 emissions information	Re-estimated based on literature data of actual measurements.
TRL level	8-9
Maintainability issues	-
Legislative concerns	-
Payback time (years)	Not available.

Carbon Trust. (2016). Industrial Energy Efficiency Accelerator. Guide to the Industrial Bakery Sector. <https://issuu.com/mikeglanfield/docs/ctg034-bakery-industrial-energy-eff>.

Stojceska, V., Parker, N., and Tassou, S. A. (2021). Reducing GHG Emissions and Improving Cost Effectiveness via Energy Efficiency Enhancements: A Case Study in a Biscuit Industry. *Sustainability* 2022, Vol. 14, Page 69, 14(1), 69. <https://doi.org/10.3390/SU14010069>.

Therkelsen, P., Masanet, E., and Worrell, E. (2014). Energy efficiency opportunities in the U.S. commercial baking industry. *Journal of Food Engineering*, 130, 14–22. <https://doi.org/10.1016/j.jfoodeng.2014.01.004>.

12.2.14 Ohmic heating

The application of Ohmic heating in the food industry has been the subject of research for approximately 50 years. This method primarily delivers volumetric heating to products, with surface heating being a secondary benefit. Thanks to its high volumetric heating capacity, uniform heat distribution, and relatively low investment costs, Ohmic heating is emerging as a viable alternative to conventional thermal heating methods for various food items (Barrett et al., 2015; Mirmoghtadaie et al., 2010). The heating occurs when an electric current flows through the material, generating heat through the electrical resistance of the product. This transformation of electrical energy into heat is executed efficiently, rendering the most significant advantage of Ohmic heating as its capability for rapid and volumetric heating (Zhang and Ramaswamy, 2005). As a result, thermal damage to food products is minimised in comparison to traditional thermal heating techniques (Wang et al., 2013). Despite the benefits of highly uniform heating, consistent results, and reduced processing times, Ohmic heating remains to be adopted on a commercial production scale (Guan et al., 2019).

Ohmic heating provides significant economic benefits and is both economical and practical, as well as traditional and healthy. Importantly, it also ensures food safety during the sterilisation process. The use of ohmic heating in the food industry and presents findings from recent research and patents on its application in various food processing areas such as blanching, dehydration, baking, roasting, frying, pasteurisation, and sterilisation. Research indicates that ohmic heating technology has led to significant reductions in processing time, improved energy efficiency, enhanced product quality, and, in some cases, reduced operating costs. Commercial applications of ohmic heating technology in the food industry result in processing time reductions in the order of 60-80% for liquid foods; 60-75% for jam or jam-like products; 40-60% for hams; 50% for liquid egg products; and 50% for mock turtle soup. The reduction in processing time required for sterility has a direct relation to the heat damage of the nutritional compounds in food. (Alkanan et al. 2021), (Astráin-Redín et al. 2024), (Aurina and Sari 2022), (Silva et al. 2022), (Morya et al. 2022), (Gavahian and Chu, 2022).

Ohmic heating technologies for solid food products have not been developed to the same level as that for liquid foods, predominantly due to concerns about the generation of electrochemical products at the electrodes. Studies on scaling up of food processing applications at different frequencies (Abea, A. et al, 2022) as well as the environmental and energy impact of the application of Ohmic heating (Astráin-Redín et al, 2024) refer to energy savings up to 65% in pasteurisation treatments (Ghnimi et al., 2021). The overall energy efficiency of the ohmic system was 77% while that of the conventional system was 25%. In the same study, a 41% reduction in CO₂ emissions was determined. Similarly, 73% energy savings was reported (Balthazar et al. 2022) when pasteurizing sheep's milk at near mains frequency while achieving the same ≥ 3.5 –6 log reductions bacterial counts as conventional heating.

Advancements in ohmic heating include innovative electrode designs, a combination of ohmic and microwave heating, and electrohydrodynamic-ultrahigh-voltage microelectrical discharge machining for a 3D-shaped ohmic heater. The mentioned 3D-shaped ohmic heater can markedly improve the heat generation rate so it can effectively heat a food product rapidly and uniformly. These two heaters can be fabricated using ceramics, such as SiC, Ni, and carbon nanocomposites (CNC), making them quite suitable for food processing, which is required to satisfy the strict demands of hygiene, and their

working principles and advantages make them a very promising additional sustainable technology for other fruits, vegetables, and liquid foods (Majid et al, 2023, Chinnamayan et al, 2024).

Unlike other emerging food processing technologies, ohmic heating is not yet widely accepted in the food industry. Instead, it is mainly used in some niche applications such as the production of fruit juices, jams, soups, and to a lesser extent, milk products.

The implementation of ohmic boosting technologies is anticipated to facilitate the incorporation of ohmic heating at an industrial scale. Today, the monitoring of the electric and electrochemical properties of the products allows us to understand how the heterogeneity and inhomogeneity can affect the treatment, and also the product colour and texture, providing optimal electrical paths.

Scope 1 emissions savings (% or another quantifiable metric)	100% if original heating was fossil fuel
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	41-73%
Quality of scope 2 emissions information	Medium
Availability barriers	Scaling up to the capacity of well-established technologies
TRL level	6-7
Maintainability issues	Low – only the electrodes are affected but can be changed easily.
Legislative concerns	No restrictions on the technology
Payback time (years)	

Alkanan, Z. T., Altemimi, A. B., Al-Hilphy, A. R., Watson, D. G., and Pratap-Singh, A. (2021). Ohmic heating in the food industry: Developments in concepts and applications during 2013–2020. *Applied Sciences*, 11(6), 2507. [mdpi.com](https://doi.org/10.3390/app11062507).

Astráin-Redín, L., Ospina, S., Cebrián, G., and Álvarez-Lanzarote, I. (2024). Ohmic heating technology for food applications, from ohmic systems to moderate electric fields and pulsed electric fields. *Food Engineering Reviews*, 16(2), 225-251. [springer.com](https://doi.org/10.1007/s12393-024-00000-0).

Aurina, K., and Sari, A. (2022, March). Ohmic heating: A review and application in food industry. In 2nd International Conference on Smart and Innovative Agriculture (ICoSIA 2021) (pp. 107-113). Atlantis Press. [atlantis-press.com](https://www.atlantispress.com/).

Chinnamayan, S., Anvarsha, N. and Palanichamy, K., 2024. Carbon-Based Nanocomposites: A Comprehensive Review of Their Multifunctional Applications. In: *Nanocomposites - Properties, Preparations and Applications* [online]. IntechOpen. <https://doi.org/10.5772/intechopen.114402>.

Silva, R., Rocha, R. S., Ramos, G. L. P., Xavier-Santos, D., Pimentel, T. C., Lorenzo, J. M., ... and Cruz, A. G. (2022). What are the challenges for ohmic heating in the food industry? Insights of a bibliometric analysis. *Food Research International*, 157, 111272.

Morya, S., Awuchi, C. G., Chowdhary, P., Goyal, S. K., and Menaa, F. (2022). Ohmic Heating as an Advantageous Technology for the Food Industry: Prospects and Applications. In *Environmental Management Technologies* (pp. 307-327). CRC Press.

Gavahian, M. and Chu, R. (2022). Ohmic heating extraction at different times, temperatures, voltages, and frequencies: a new energy-saving technique for pineapple core valorization. *Foods*. mdpi.com.

Abea, A. et al. (2022) 'Dielectric Heating: A Review of Liquid Foods Processing Applications', *Food Reviews International*, 39(8), pp. 5684–5702. doi: 10.1080/87559129.2022.2092746.

Astráin-Redín, L., Ospina, S., Cebrián, G. et al. (2024) Ohmic Heating Technology for Food Applications, From Ohmic Systems to Moderate Electric Fields and Pulsed Electric Fields. *Food Eng Rev* 16, 225–251. doi: 10.1007/s12393-024-09368-4.

Ghnimi S, Nikkhah A, Dewulf J, Van Haute S (2021) Life cycle assessment and energy comparison of aseptic ohmic heating and appertization of chopped tomatoes with juice. *Sci Rep* 11:13041. doi: 10.1038/s41598-021-92211-1.

Balthazar CF, Cabral L, Guimarães JT et al. (2022) Conventional and ohmic heating pasteurization of fresh and thawed sheep milk: Energy consumption and assessment of bacterial microbiota during refrigerated storage. *Innov Food Sci Emerg Technol* 76:102947. doi: 10.1016/j.ifset.2022.102947.

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12.2.15 Recovery of exhaust heat

Exhaust heat from cooking/baking operations has been reported an important energy loss of food processing operations (Sovacool et al., 2021). For example, the energy efficiency of wafer baking machines has been reported to be only 35%, with the rest of the total energy lost through the exhaust (Mukherjee et al., 2019). These authors propose waste heat recovery as a very effective technique to offset these losses. In their review (Mukherjee et al., 2020) they state that most ovens in industry rely on the heat released from burning fossil fuels, mainly natural gas or propane and 'Less than half of this heat contributes to the actual processing of the product and the remaining is released to the surroundings as waste heat, primarily through exhaust gases at 150 to 250 °C. In the UK alone, the food and drink manufacturing sector releases circa 2.8 TWh of recoverable waste heat into the atmosphere, annually.' Their rough estimation of waste heat recovery from the UK Food and Drink sector alone amounts to 500,000 tonnes of CO₂ emissions, based on previous work by (Law et al., 2013). Enjay GmbH claim that in a food production facility in Sweden that 99% of the heat demand could be reclaimed by an exhaust heat exchanger. The findings of Mukherjee et al. (2020) for a pilot scale and industrial scale wafer baking oven study indicate that utilising an oven's exhaust gases to preheat combustion air can deliver up to 7% fuel savings, provided a sufficiently large heat sink in the form of oven combustion air is available. The analysis was based on experiments on the pilot scale system, using only an electric preheater to simulate system performance, and computational analysis using energy analysis software for the industrial scale. The relatively simple technology was assessed to also offer a short payback period of only 1.57 years, with CO₂ savings of 71 tonnes per year from a single oven. The solution for preheating combustion air was compared to other ways of heat recovery, namely reheating of process water, a combination of preheating and reheating, and alternative heat recovery options such as Regenerative Organic Rankine Cycles (RORC) and Vapour Absorption Refrigeration (VAR), requiring somewhat more complex technical installations. This was done also by a computational analysis. The result shows that the effectiveness and oven productivity in kWh/kg wafer are most optimal for preheating, reheating and their combination. The effectiveness is for each technology a reflection of the rate of gas/electricity saved (in kW) per rate at which the recoverable heat is released (in kW). CO₂ savings of RORC and VAR options were limited to 28 and 41 tonnes per year, respectively. Interestingly, heat recovery of a single oven was able to serve preheating of multiple

ovens, leading to the largest possible savings when based on the exhaust from that single oven. But this analysis did not account for the large remaining losses of the other ovens that should counted in.

Detailed economic models for the different waste heat recovery options investigated were also developed to evaluate the return on investment. Payback periods were between 1.57 and 5.13 years for the preheating and reheating options, and 15.75 and 32.75 years for the RORC and VAR solutions. The authors then provided a route for electing the best fit technology, also requiring prior oven optimisation and measurement of exhaust properties before starting any (computational) analysis. As far as understood from the reported studies of these researchers (Mukherjee et al., 2017, 2019, 2020), no actual experimental validation of the findings has yet been performed.

Scope 1 emissions savings (% or another quantifiable metric)	Up to 7% fuel savings for a single ovens. CO ₂ emission savings: 71 tonnes per year for a single oven
Quality of scope 1 emissions information	Based on a parameterised computational study that was not verified with actual experimental data, for a very specific wafer baking system. Therefore, it may prove difficult to translate the impact of heat recovery to other types of ovens.
Scope 2 emissions savings (% or another quantifiable metric)	90% reduction in heating. claimed by Enjay GmbH.
Quality of scope 2 emissions information	Reasonable number of case studies that appear to justify claims for advanced heat exchangers (Enjay GmbH)
TRL level	8-9
Maintainability issues	Need to make sure that particles do not block heat exchanger (in kitchens)
Legislative concerns	-
Payback time (years)	1.57-5.13 years depending on the type of heat recovery, and for the specific oven that was studied 1-2 years for Enjay GmbH system.

Enjay GmbH. 2025 <https://content.enjaysystems.com/articles-english/lepido-by-enjay-a-heavy-duty-heat-exchanger>.

Law, R., Harvey, A., and Reay, D. (2013). Opportunities for low-grade heat recovery in the UK food processing industry. *Applied Thermal Engineering*, 53(2), 188–196. <https://doi.org/10.1016/J.APPLTHERMALENG.2012.03.024>.

Mukherjee, S., Asthana, A., Howarth, M., and Chowdhury, J. I. (2020). Techno-Economic Assessment of Waste Heat Recovery Technologies for the Food Processing Industry. *Energies* 2020, Vol. 13, Page 6446, 13(23), 6446. <https://doi.org/10.3390/EN13236446>.

Mukherjee, S., Asthana, A., Howarth, M., McNeill, R., and Frisby, B. (2019). Achieving Operational Excellence for Industrial Baking Ovens. *Energy Procedia*, 161, 395–402. <https://doi.org/10.1016/J.EGYPRO.2019.02.100>.

Mukherjee, S., Asthana, A., Howarth, M., and McNiell, R. (2017). Waste heat recovery from industrial baking ovens. *Energy Procedia*, 123, 321–328. <https://doi.org/10.1016/J.EGYPRO.2017.07.259>.

Sovacool, B. K., Bazilian, M., Griffiths, S., Kim, J., Foley, A., and Rooney, D. (2021). Decarbonizing the food and beverages industry: A critical and systematic review of developments, sociotechnical systems

and policy options. *Renewable and Sustainable Energy Reviews*, 143, 110856. <https://doi.org/10.1016/j.rser.2021.110856>.

12.2.16 Reduce heating up time

Warm up of the oven is required to reach the desired baking temperature. Generally, the time should be minimised to save energy, and this is more important when the oven is more regularly shutdown between bakes. Usually, the heating up requires higher heating power levels due to the high temperature difference between the ambient and set point temperature to be overcome. Minimum oven heat-up time can be determined by recording how long after the oven is turned on temperature sensors indicate a desired baking temperature has been reached. According to (Therkelsen et al., 2014), one bakery reduced heat-up time by 20–25 min for cabinet ovens and by 40–50 min for tunnel ovens, without giving details about the particular measures taken. These could include reducing thermal mass of the oven, optimised heat distribution (e.g., improved convection) from the burners/heating elements and a higher efficiency (less direct losses from the heat source) and improved control.

If the shorter heat-up time is due to using a higher initial set-point temperature and/or by installing a higher heating power, the likely energy savings with respect to the base case are negligible.

The preheating contribution to the total energy use depends on the number of successive bakes that are made after the initial preheat. Consider a 10 kW oven baking 7 kg of product in 1 h with a specific energy consumption of 1.5 kWh/kg (Ladha-Sabur et al., 2019), and a typical preheat time of 30 min. For a single bake, the contribution of the preheat will be 32% of the total, for 8 successive bakes it will reduce to 6%. A 10% reduction of the preheat time would reduce the contribution by 2% for 1 bake and 1% for 8 bakes, with respect to the total energy consumption per day for baking.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	1-2% energy savings for a 10% reduction in preheat time.
Quality of scope 1/2 emissions information	Rough estimate. No data available.
TRL level	8-9
Maintainability issues	Regular checking by recording temperature profiles during preheating will learn if preheat times increase due to aging of the system.
Legislative concerns	-
Payback time (years)	Depends on measures taken. No data available.

Ladha-Sabur, A., Bakalis, S., Fryer, P. J., and Lopez-Quiroga, E. (2019). Mapping energy consumption in food manufacturing. *Trends in Food Science and Technology*, 86, 270–280. <https://doi.org/10.1016/j.tifs.2019.02.034>.

Therkelsen, P., Masanet, E., and Worrell, E. (2014). Energy efficiency opportunities in the U.S. commercial baking industry. *Journal of Food Engineering*, 130, 14–22. <https://doi.org/10.1016/j.jfoodeng.2014.01.004>.

12.2.17 Reduce thermal mass of tins

As part of the energy efficiency analysis for the bakery sector (Carbon Trust, 2016), the heat absorbed by the tins to bake the foods in was assessed. In their analysis, a steel tin had a capacity to bake 4.8 kg bread loaves and weighed 6 kg; if a steel lid was used, the weight increased to 8.5 kg (a mass ratio of

tins:bread of 2:1). After heating, tins are cooled and used again. The thermal mass (product of mass and specific heat capacity) of the steel tins consumes energy to bring the tin to the baking temperature of about 250°C. Reducing the energy consumed by the tins requires a lower mass and/or an alternative material with lower specific heat capacity. According to the reported thermal analysis, tins make up 10 to 30% of the consumed natural gas in indirect and direct fired ovens, respectively, while the product baking only uses 12 to 35% of the gas, with direct fired ovens the more efficient. A 30% reduction in tin mass would lead to a gas use savings of 3.5% in the indirect oven, and thus about 10% in the direct fired oven. Alternative materials such as thermoplastics and other metals have been suggested to reduce heating requirements of the tins by 50% or a 6% reduction in gas consumption.

Paton et al. (2013) also considered tins in the energy analysis of a large direct gas fired oven. Tins and lids accounted for 6.5% of the total energy and the product energy taking 55% of the total; thus, representing a much more efficient baking process. In this case the % saving of a reduced tin mass would be considerably lower than in the case discussed above.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	3.5% gas consumption savings in ovens for a 30% reduction in tin mass 70-115 tons CO ₂ /year per site Expected smaller in more efficient ovens.
Quality of scope 1/2 emissions information	Carbon Trust funded analysis from 89 sites in the UK. Reported in the Industrial Energy Efficiency Accelerator Guide to the Industrial Bakery Sector. 2016.
TRL level	5-7
Maintainability issues	Need for adapted handling, cooling and cleaning systems for tins
Legislative concerns	-
Payback time (years)	Not available

Carbon Trust. (2016). Industrial Energy Efficiency Accelerator. Guide to the Industrial Bakery Sector. <https://issuu.com/mikeglanfield/docs/ctg034-bakery-industrial-energy-eff>.

Paton, J., Khatir, Z., Thompson, H., Kapur, N., and Toropov, V. (2013). Thermal energy management in the bread baking industry using a system modelling approach. *Applied Thermal Engineering*, 53(2), 340–347. <https://doi.org/10.1016/j.applthermaleng.2012.03.036>.

12.2.18 Retorts (variable temperature control)

Research on energy consumption in retort processes remains limited. Since the 1930s, batch retorts have been the predominant method for commercial sterilisation in canning plants, used for a wide range of products from fish to agricultural foods. While continuous sterilisation systems have occasionally been adopted, their high installation costs and lack of versatility in handling various package sizes, shapes, and product types have led to the continued widespread use of batch systems. These systems typically operate in multiple stages: venting, heating, and cooling. The process begins with venting, where steam is introduced at maximum flow to purge atmospheric air from the retort. The retort is then heated to the desired pressure and temperature, after which the steam flow is reduced to maintain the process temperature. The product is held at this temperature for the duration necessary to achieve the required lethality. After this period, the steam is shut off, cooling water is introduced, and once cooled, the retort can be opened and unloaded.

Foundational work by Barreiro et al. (1984) and Bhowmik et al. (1985) developed detailed methods for estimating the total energy consumption of the retort process. Simpson et al. (2006) further advanced this by creating a procedure to quantify both total and transient energy consumption.

Simpson and Almonacid (2008) introduced methods to minimise energy consumption in retort operations. A better understanding of thermal food processing using variable retort temperature profiles (VRTPs) was provided by Simpson et al. (2020). These profiles were evaluated for their potential to optimise processing by enhancing quality or reducing process time. While VRTPs showed promise for improving product quality retention, the improvements were not significant enough to be noticed by consumers, limiting their industrial application. However, VRTPs did present opportunities for processors to enhance productivity by reducing process time and energy use. According to Barreiro et al. (1984), Bhowmik et al. (1985), and Simpson et al. (2006), energy consumption during the holding phase, or process time, accounts for approximately 30% or more of the total energy used per batch, with condensate removal alone comprising over 25% of this energy. The steam mass consumed during the process is directly related to the retort's operating pressure and the process time. Energy consumption during processing can be estimated through thermodynamic analysis of steam flow, with reductions in process time leading to significant energy savings—around 9% in some cases. Further exploration of product shape modifications could reduce heating rate factors, decrease process time, and create more opportunities for VRTPs. Pitarch et al. (2021) confirmed that VRTPs offer energy savings compared to constant retort temperature processes.

Mathematical models and simulation tools, validated through experiments, can be employed to identify optimal process conditions (both for constant and variable retort temperatures) and package designs through multi-objective optimisation. This approach can simultaneously control contaminant formation, maximise the retention of nutritional and functional compounds, and shorten processing times (Kubo et al., 2023).

Scope 1/2 emissions savings (% or another quantifiable metric)	Up to 9% energy use savings through reduced steam consumption
Quality of scope 1/2 emissions information	Calculations of different independent authors of peer reviewed journal articles
Availability barriers	Is product and package dependent. Need to account for quality and safety of sterilisation process. Requires a multi-objective optimisation approach.
TRL level	6
Maintainability issues	-
Legislative concerns	Lethality of sterilisation needs to be demonstrated
Payback time (years)	<1 (estimate)

(Barreiro, Perez, and Guariguata 1984; Bhowmik, Vichnevetsky, and Hayakawa 1985; R. Simpson, Cortés, and Teixeira 2006; Ricardo Simpson and Almonacid 2008; Ricardo Simpson et al. 2020) (Pitarch et al. 2021; Berteli et al. 2012; Peesel et al. 2016; Kubo et al. 2023).

Barreiro, J. A., C. R. Perez, and C. Guariguata. 1984. "Optimization of Energy Consumption during the Heat Processing of Canned Foods." *Journal of Food Engineering* 3 (1): 27–37. [https://doi.org/10.1016/0260-8774\(84\)90005-0](https://doi.org/10.1016/0260-8774(84)90005-0).

Bhowmik, S. R., R. Vichnevetsky, and Kan ichi Hayakawa. 1985. "Mathematical Model to Estimate Steam Consumption in Vertical Still Retort for Thermal Processing of Canned Foods." *LWT - Food Science and Technology* 18 (1): 15–23.

Kubo, Mirian T.K., Adina Baicu, Ferruh Erdogdu, Maria Fátima Poças, Cristina L.M. Silva, Ricardo Simpson, Alfredo A. Vitali, and Pedro E.D. Augusto. 2023. "Thermal Processing of Food: Challenges,

Innovations and Opportunities. A Position Paper.” *Food Reviews International* 39 (6): 3344–69. <https://doi.org/10.1080/87559129.2021.2012789>.

Peesel, Ron H., Matthias Philipp, Gregor Schumm, Jens Hesselbach, and Timothy G Walmsley. 2016. “Energy Efficiency Measures for Batch Retort Sterilization in the Food Processing Industry.” *Chemical Engineering Transactions* 52: 163–68. <https://doi.org/10.3303/CET1652028>.

Pitarch, J. L., C. Vilas, C. de Prada, C. G. Palacín, and A. A. Alonso. 2021. “Optimal Operation of Thermal Processing of Canned Tuna under Product Variability.” *Journal of Food Engineering* 304 (September): 110594. <https://doi.org/10.1016/J.JFOODENG.2021.110594>.

Simpson, R., C. Cortés, and A. Teixeira. 2006. “Energy Consumption in Batch Thermal Processing: Model Development and Validation.” *Journal of Food Engineering* 73 (3): 217–24. <https://doi.org/10.1016/J.JFOODENG.2005.01.040>.

Simpson, Ricardo, and Sergio Almonacid. 2008. “Minimising Energy Consumption Associated with Retorting.” *Handbook of Water and Energy Management in Food Processing*, January, 523–43. <https://doi.org/10.1533/9781845694678.4.523>.

Simpson, Ricardo, Diego Jiménez, Sergio Almonacid, Helena Nuñez, Marlene Pinto, Cristian Ramírez, Oscar Vega-Castro, Lida Fuentes, and Alejandro Angulo. 2020. “Assessment and Outlook of Variable Retort Temperature Profiles for the Thermal Processing of Packaged Foods: Plant Productivity, Product Quality, and Energy Consumption.” *Journal of Food Engineering* 275 (June): 109839. <https://doi.org/10.1016/J.JFOODENG.2019.109839>.

12.2.19 Roasting - efficiency and innovative methods

Microwave roasting involves volumetric heating, which generates internal vapours that are forced outward by the rising pressure gradient, allowing for rapid moisture removal. In microwave roasting, the core temperature of the food rises higher than the surface temperature, unlike in hot air roasting, where the surface may become over-roasted before the core is adequately heated. A combined microwave/hot air roasting approach has been shown to produce superior roasted products while consuming less energy than either method alone. Specifically, microwave roasting reduced energy use by 14%, and the combined microwave/hot air roasting method reduced energy consumption by 50% compared to hot air roasting. When compared to conventional processes, combined microwave–hot air roasting reduced total energy use by approximately 40%, 26%, and 26% for coffee, chocolate, and black malts, respectively (Gunel et al., 2020; Akkarachaneeyakorn et al., 2010).

Superheated steam roasting is a modern technique in which water is heated beyond its boiling point at a given pressure to create superheated steam (Suleman et al., 2020; Chindapan et al., 2019; Idrus et al., 2017). This method offers a higher heating rate than hot air roasting, resulting in shorter roasting times and lower losses of heat-sensitive compounds. Additionally, the reduced or absent oxygen environment helps prevent unwanted oxidation. However, energy usage in superheated steam roasting has not yet been compared to other roasting methods.

Vibration roasting uses a combination of electrical heat generation and vibrational transport, such as in a closed stainless-steel spiral, to achieve rapid and efficient heating (Sruthi et al., 2021). The continuous movement of food particles in close contact with a heated spiral surface, along with a small amount of injected steam, ensures effective and uniform heating, with minimal condensation due to the higher temperature of the food by the heat supplied from the surface. This process is often referred to as a dry steam process. Although vibration roasting could potentially be more energy-efficient than superheated steam due to the low steam usage, empirical data on energy use in comparative studies is lacking. Also, issues such as thin layer deposition of particles inside the vibration pipe and

electrostatic effects can increase residence time, necessitating frequent cleaning to maintain consistent performance (Keppler et al., 2016).

Far infrared (IR) radiation, with electromagnetic waves ranging from 3 to 1000 μm in wavelength, is another method used in roasting (Bagheri et al., 2016). IR radiation heats the surface of the material and penetrates only a few millimetres into agricultural products, making it suitable for thin-layer roasting. This direct surface-to-surface heating method can reduce heat losses compared to hot air heating while speeding up the process by avoiding the surface boundary layer. Studies on IR roasting, including its combination with hot air roasting, have demonstrated significant reductions in roasting time—up to 69% and 62%, respectively, for peanuts—based on desired colour changes (Yang et al., 2010). These time reductions align with findings by Hebber et al. (2004), who reported similar reduced energy usage when using IR or combination heating instead of hot air during the drying of pieces of potatoes and carrots.

Microwave, vibration and IR roasting are electrified processes, offering pathways toward emission reduction by replacing fossil fuel-based heating (often used on hot air and steam generation), alongside their shown potential for improving roasting efficiency.

Payback times were estimated based on typical energy consumption of a coffee roasting process (Tsai et al., 2025) and average investment cost ranges of industrial roasters (Porter, 2024) (

Table 23).

Table 23. Payback times for coffee roasting.

Scenario	Annual through-put (tons)	Conventional energy use (kWh/ton)	Advanced energy use (kWh/ton)	Energy cost (€/kWh)	Added investment cost (€)	Energy saved (kWh/ton)	Savings per ton (€)	Annual savings (€)	Payback time (years)
Small operation	30	600	400	0.1	10000	200	20	600	17
Medium plant	90	600	400	0.1	20000	200	20	1800	11
High-efficiency, large-scale	300	600	300	0.1	50000	300	30	9000	6

Scope 1 emissions savings (% or another quantifiable metric)	50% reduction in energy use by combined roasting methods compared to hot air roasting.
Quality of scope 1 emissions information	Peer reviewed journal articles
Scope 2 emissions savings (% or another quantifiable metric)	Up to 100% by increasing levels of electrification by replacing fossil fuel heating by zero emission electrical heating (microwave, IR, vibration roasting)
Quality of scope 2 emissions information	Peer reviewed journal articles
Availability barriers	None
TRL level	9
Maintainability issues	Cleaning of some systems is tedious and costly (vibration roasting)
Legislative concerns	Microbiological safety
Payback time (years)	6-17 years (estimate based on size of operation)

(Hebbar, Vishwanathan, and Ramesh 2004; Yang et al. 2010; Bagheri et al. 2016; Idrus et al. 2017; Chindapan, Soydok, and Devahastin 2019; Suleman et al. 2020; Keppler et al. 2016; Schoeman, Du Plessis, and Manley 2016; Sruthi et al. 2021; Akkarachaneeyakorn et al. 2010; Gunel, Torun, and Sahin-Nadeem 2020).

Akkarachaneeyakorn, S., J. C. Laguerre, J. Tattiyakul, B. Neugnot, P. Boivin, F. J. Morales, and I. Birlouez-Aragon. 2010. "Optimization of Combined Microwave–Hot Air Roasting of Malt Based on Energy Consumption and Neo-Formed Contaminants Content." *Journal of Food Science* 75 (4): E201–7. <https://doi.org/10.1111/J.1750-3841.2010.01567.X>.

Bagheri, Hadi, Mahdi Kashaninejad, Aman M. Ziaifar, and Mehran Aalami. 2016. "Novel Hybridised Infrared-Hot Air Method for Roasting of Peanut Kernels." *Innovative Food Science and Emerging Technologies* 37 (October): 106–14. <https://doi.org/10.1016/J.IFSET.2016.08.014>.

12.2.20 Steaming - efficiency improvements, novel options

Karayannakidis et al. (2014) compared the energy consumption of direct steam injection (DSI) and conventional steam-jacketed (SJ) heating systems during a hydrolysis operation. DSI proved to be more energy-efficient, using approximately 30% less energy, with faster heat-up times and shorter total processing durations. Additionally, incorporating a steam filtration unit in DSI not only filtered

incoming steam but also minimised condensation. Their findings suggest that DSI heating with steam filtration is both energy-efficient and reduces fouling during the preparation of various enzymatic protein hydrolysates.

Brooks et al. (2021) explored the potential of steam infusion technology to lower energy use and emissions. Steam infusion heats food materials in a specialised pumping device where steam is introduced into the material in a smaller volume, leading to reduced steam usage and shorter processing times. The study found that this technology decreased energy consumption by 17.3% compared to basic DSI, resulting in 277.8 fewer processing hours and an annual reduction of 8.7 tonnes of GHG emissions per kettle production line. Similar to infusion, steam sparging is commonly used in open tanks or kettles containing liquids, where culinary steam is bubbled into the liquid from nozzles at the tank's bottom. However, no specific studies were found that assess the energy use impact of this system.

Concerning costs, the company OAL (Anon., 2021) estimates retrofit costs for steam infusion are in the range of €25,000 to €75,000. Energy consumption of a typical food steaming process is approximately 96 kWh per batch of 1 ton (Brooks et al. 2021). Estimated pay back times are given in Table 24, dependent on yearly production volumes.

Table 24. Pay back times (Bowser 2017; Karayannakidis, Apostolidis, and Lee 2014; Brooks et al. 2021).

Scenario	Annual throughput (tons)	Conventional energy use (kWh/ton)	Advanced energy use (kWh/ton)	Energy cost (€/kWh)	Added investment cost (€)	Energy saved (kWh/ton)	Savings per ton (€)	Annual savings (€)	Payback time (years)
Low upgrade cost	2500	96	60.2	0.1	25000	36	4	8952	3
High upgrade cost	2500	96	60.2	0.1	75000	36	4	8952	8
Low upgrade cost	10000	96	60.2	0.1	25000	36	4	35808	1
High upgrade cost	10000	96	60.2	0.1	75000	36	4	35808	2

Scope 1 emissions savings (% or another quantifiable metric)	30% DSI compared to SJ 17.3% steam infusion compared to DSI
Quality of scope 1 emissions information	Peer reviewed journal articles
Scope 2 emissions savings (% or another quantifiable metric)	-
Quality of scope 2 emissions information	-
Availability barriers	-
TRL level	9
Maintainability issues	Nozzle cleaning for injection/infusion systems
Legislative concerns	Use clean steam only

Payback time (years)	1-2 years (high production volumes, estimate) 3-8 years (low production volumes, estimate)
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Anon. 2021. How much does Steam Infusion cost? <https://steaminfusion.oalgroup.com/blog/cost>. Consulted on 30/4/2025.

Bowser, T.J. 2017. "Steam Basics for Food Processors." Robert M. Kerr Food and Agricultural Products Center. Food Technology Fact Sheet FAPC-142: 1–8. www.fapc.biz.

Brooks, C., Swainson, M., Beauchamp, I., Campelos, I., Ishak, R., Martindale, W. 2021. "Transformational Steam Infusion Processing for Resilient and Sustainable Food Manufacturing Businesses." *Foods* 2021, Vol. 10, Page 1763 10 (8): 1763. <https://doi.org/10.3390/FOODS10081763>.

Karayannakidis, P.D., Apostolidis, E., Lee, C.M. 2014. "Comparison of Direct Steam Injection and Steam-Jacketed Heating in Squid Protein Hydrolysis for Energy Consumption and Hydrolysis Performance." *LWT - Food Science and Technology* 57 (1): 134–40. <https://doi.org/10.1016/J.LWT.2014.01.012>.

12.3 Other

12.3.1 Advanced evaporation technologies

Evaporation is one of the most widely used unit operations in the food processing industry, particularly in the concentration of liquid foods and beverages. This method involves removing water or other solvents from a solution by applying heat, resulting in a more concentrated product. The process is essential for reducing the volume of liquids, preserving flavour and nutrients, and extending shelf life. Some common applications include juice concentration, dairy products, sauces and soups, sugar syrups, and tomato paste and fruit purees etc.

Traditional evaporation systems, such as single-effect evaporators (SEE), natural circulation evaporators, and forced circulation evaporators, often require significant energy input, typically from fossil fuels, making them a key area of focus for sustainability and carbon reduction efforts.

Various well-established technologies demonstrate energy-saving benefits in continuous evaporation across diverse industrial applications. These technologies include multi-effect evaporation (MEE) technology (Liu et al. 2020), heat pump technology (He et al, 2019), air humidification technology (Chen et al. 2020), and mechanical vapour recompression (MVR) technology (Han, 2015). However, due to the intricate characteristics of batch evaporation processes, challenges persist, including high energy consumption, substantial waste heat emission, and difficulties in energy recovery.

SEE technology remains widely used in beer boiling, lactose crystallisation, and drug concentration, constrained by batch time considerations. Although the circulating heating line can be substituted with a boiler, copper, or heating tank, a necessary steam heat source is accompanied by significant waste heat from secondary steam and wastewater. It is worth noting that implementing cogeneration/trigeneration technology, aimed at capturing waste heat and reusing wastewater, coupled with replacing outdated equipment, can positively impact energy and water consumption (Liu et al. 2020).

The importance of evaporation technology lies in its ability to efficiently reduce the volume of liquid products, thereby increasing their shelf life and facilitating transportation (Giner Santonja et al, 2019). This concentration process enhances the product's flavour and nutritional value while minimising storage and transportation costs (Fellows, 2017). Moreover, it provides microbiological stability to the food product (Prakash et al, 2019). As a result, evaporation technology is a key enabler for sustainable food production, helping reduce water waste through product concentration and water reuse, while also cutting energy use across storage, transport, and further processing.

In recent years, advancements in evaporation technology have focused on improving energy efficiency, reducing environmental impact, and enhancing process control. Innovations include integrating heat pump technology, utilising waste heat, and developing intelligent control systems to optimise energy consumption and product quality (Giner Santonja et al, 2019) (Chen et al, 2021). Advanced technologies like MEE and MVR can dramatically cut energy use in evaporation processes — up to 90% — making them key to sustainable and cost-effective food processing (Atuonwu and Tassou, 2021). A prominent example comes from McCain Foods (New Zealand), where the integration of energy-efficient vapor recompression technologies in frying and evaporation processes led to annual emissions savings of approximately 3,990 tonnes of CO₂-equivalent, alongside energy savings of 39,943 GJ (EECA, 2022). A case study of Chivas Brothers distilleries in Scotland reported an annual reduction of over 4,300 tonnes of CO₂ after installing mechanical vapor recompression systems in their distillation operations. These savings represented a 53% cut in carbon emissions, achieved through enhanced energy recovery and reduced dependence on fossil-fuel-generated steam (Renewable Thermal Collaborative, 2018).

Evaporation technology has reached a high TRL with well-established and widely adopted industrial applications. Ongoing research and development efforts continue to enhance its efficiency, sustainability, and applicability to diverse food processing scenarios. While evaporation technology is generally reliable, maintenance challenges may arise due to scaling and fouling heat exchange surfaces. Regular cleaning and maintenance practices are essential to ensure optimal performance and longevity of the equipment.

As with any industrial process, compliance with environmental regulations and food safety standards is paramount. Evaporation technology must adhere to legislative guidelines to ensure the quality and safety of the final food products.

The payback time for implementing evaporation technology varies depending on factors such as the scale of operation, energy costs, and product value. Generally, the investment in evaporation technology is justified over time through increased product market-value, reduced waste, and operational efficiency.

Evaporation technology stands as a cornerstone in the food processing industry, offering numerous benefits in terms of product quality, sustainability, and operational efficiency. With ongoing advancements and a high TRL, this technology plays a key role in shaping the future of food processing, addressing maintainability issues, and legislative concerns, and providing a favourable payback time for businesses investing in its implementation.

Scope 1 emissions savings (% or another quantifiable metric)	Advanced evaporation technologies, such as mechanical vapor recompression (MVR) and multi-effect evaporators (MEE), can reduce energy consumption by up to 90% compared to traditional single-effect evaporators. (Atuonwu and Tassou, 2021)
Quality of scope 1 emissions information	-
Scope 2 emissions savings (% or another quantifiable metric)	-
Quality of scope 2 emissions information	-
Availability barriers	-
TRL level	8-9

Maintainability issues	maintenance challenges may arise due to scaling and fouling heat exchange surfaces. Regular cleaning and maintenance practices are essential to ensure optimal performance and longevity of the equipment
Legislative concerns	-
Payback time (years)	Not available

Atuonwu, J., and Tassou, S. (2021). Decarbonisation of food manufacturing by the electrification of heat: A review of developments, technology options and future directions. *Trends in Food Science and Technology*, 107, 168-182.

Chen, J., Han, D., He, W., Liu, Y. and Gu, J., 2020. Theoretical and experimental analysis of the thermodynamic and economic performance for a packed bed humidifier. *Energy Conversion and Management*, 206, p.112497.

Chen, J., Han, D., Hang, Z. and Si, Z., 2021. Experimental investigation of a novel batch evaporation system coupled mechanical vapor recompression technology and steam heat storage technology. *Innovative Food Science and Emerging Technologies*, 68, p.102616. ECA (2022). McCain Shares its Emissions Reduction Journey. Energy Efficiency and Conservation, <https://www.eeca.govt.nz/insights/case-studies-and-articles/mccain-shares-its-emissions-reduction-journey/>.

Han, D. 2015. "Study on Zero-emission Desalination System Based on Mechanical Vapor Recompression Technology." *Energy Procedia* 75: 1436-1444.

He, W., Yang, H. and Han, D., 2019. Thermodynamic investigation and optimization of a heat pump coupled open-air, open-water humidification dehumidification desalination system with a direct contact dehumidifier. *Desalination*, 469, p.114101. Liu, C., Bi, M., Zhou, Y. and Cui, G., 2020. A novel model for evaporator structural design in the multi-effect evaporation plant. *Applied Thermal Engineering*, 176, p.115351.

Prakash, A., Patil, C., Vinodhini, S., Panneerselvam, A. and Rajeswari, V.D., 2019. Engineering Approach in Beverage Industry. In *Engineering Tools in the Beverage Industry* (pp. 1-25). Woodhead Publishing.

Renewable Thermal Collaborative (2018). Case Study: MVR Heat Pumps and Thermal Efficiency at Chivas Brothers Distillery.

Santonja, G. G., Karlis, P., Stubdrup, K. R., Brinkmann, T., and Roudier, S. (2019). Best Available Techniques (BAT) reference document for the food, drink and milk industries. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control), 3.

12.3.2 Alternative fuels for fishing vessels

Nowadays, fuels for fishing vessels are heavily fossil fuel based and a shift is required to meet the decarbonisation goals.

Within the near future (2022 – 2030), Hellström et al. (2024) estimate that the usage of LNG, biodiesel and biogas are the short-term alternative fuels within ships.

LNG offers the advantage that it can be operated more sustainably, being compliant with future regulations known to date and potentially be cheaper than the current fuel. Operative GHG emissions are typically reduced by 20%, but well to tank GHG emissions are required to be accounted for. The technical adoption is hindered by concerns regarding safety, investment costs, space onboard and practicability of operation in a dual fuel use engine. However, an uptake of LNG technology is expected. (Gabrielii og Jafarzadeh 2020)

The availability of biodiesel is regarded as low, however, the adaption to fishing vessels is at a rather high maturity level. Furthermore, the CO₂ emissions are reduced by about 50 % compared to diesel oil (Gabrielii and Jafarzadeh 2020) when biodiesel is utilised. The study by Lin and Huang (2012) showed that the pollutant emissions would decrease by 44 % for the Taiwanese fishing boats, and costs would increase by 25.85 % for fuel. Lin and Huang (2012) conclude that 20 wt% of biofuel blended with diesel has the highest cost-benefit ratio (Lin and Huang, 2012).

On a long-term perspective (2030 – 2050), the use of hydrogen, batteries and methanol is foreseen to be used in ships (Hellström, et al. 2024).

Comparing onboard generated emissions from the use of diesel vs. hydrogen in fishing vessels, the application of hydrogen cuts 75 % emissions with an average production factor of hydrogen included (Gabrielii and Jafarzadeh 2020), with the possibility of being an almost carbon neutral fuel source when produced “green” (Karvounis, et al. 2022).

While the current status of batteries deployed in fishing vessels requires further advancements, Gabrielii and Jafarzadeh (2020) report on different mechanical-electric propulsion systems, where the integration of the electric system allows to run the engine closer to its design point and thereby allows to reduce energy consumption and emissions. (Gabrielii and Jafarzadeh 2020)

Methanol as a fuel source cuts SO_x emissions, decreases particulate matter emissions and NO_x emissions are dependent on the engine type. CO₂ emissions are dependent on the type of methanol production, and significant CO₂ savings are achieved when the production is based on renewable sources. (Gabrielii and Jafarzadeh 2020)

As the technical maturity level is generally low, except for LNG, batteries and natural gas and biomass-based methanol with a medium technology maturity level, it is uncertain if the technologies are all scalable to the usage in fishing vessels, hence their exact impact on GHG emission savings difficult to foresee.

Scope 1 emissions savings (% or another quantifiable metric)	20 – 75 % depending on the fuel and its production and source
Quality of scope 1 emissions information	Several studies, variety of fuels makes definitive conclusion difficult
Scope 2 emissions savings (% or another quantifiable metric)	Moving from fossil fuels to other fuels increases Scope 2 emissions
Quality of scope 2 emissions information	n/a
Availability barriers	H-M
TRL level	4-7
Maintainability issues	Not found
Legislative concerns	Not found
Payback time (years)	Not found

Aydın, Ö. K., Sarioğlu, H. Y., Dirim, S. N., and Kaymak Ertekin, F. (2023). Recent Advances for Rapid Freezing and Thawing Methods of Foods. *Food Engineering Reviews*, 667-690.

Dettner, F., and Hilpert, S. (2023). Modelling CO₂ emissions and mitigation potential of Northern European shipping. *Transportation Research Part D*.

Gabriell, C. H., and Jafarzadeh, S. (2020). Alternative fuels and propulsion systems for fishing vessels. Trondheim: Sintef Energy AS.

Hellström, M., Rabetino, R., Schwartz, H., Tsvetkova, A., and Haq, S. H. (2024). GHG emission reduction measures and alternative fuels in different shipping segments and time horizons – A Delphi study. Marine Policy.

Karvounis, P., Tsoumpris, C., Boulougouris, E., and Theotokatos, G. (2022). Recent advances in sustainable and safe marine engine operation with alternative fuels. Frontiers in Mechanical Engineering.

LeBail, A., Chevalier, D., Mussa, D., and Ghoul, M. (2002). High pressure freezing and thawing of foods: a review. International Journal of Refrigeration 25, 504-513.

Lin, C.-Y., and Huang, T.-H. (2012). Cost–benefit evaluation of using biodiesel as an alternative fuel for fishing boats in Taiwan. Marine Policy.

Svendsen, E. S., Widell, K. N., Tveit, G. M., Nordtvedt, T. S., Uglem, S., Standal, I., and Greiff, K. (2022). Industrial methods of freezing, thawing and subsequent chilled storage of whitefish. Journal of Food Engineering.

12.3.3 Centrifugation (advanced design features and technologies)

Centrifugation is a method used to separate mixtures with multiple phases, where one phase is continuous. This process relies on differences in density among the phases, and the separation is sped up by applying centrifugal forces through rotation.

Centrifugation is a common process used in various industries, including food and beverage production. It's employed to separate components in liquids, such as milk, cream, whey, and fruit juices. For instance, it's used to remove impurities from milk, concentrate cream, and extract casein from dairy products. In the beverage industry, centrifugation helps clarify juices, process coffee, and even produce wine. It's also valuable in oil and sugar production. The extent of the force is influenced by the speed and radius of rotation. In raw milk, for instance, the continuous phase is skimmed milk, while fat globules (a discontinuous phase) and solid particles such as hairs, udder cells, and straw make up the other phases. When density differences are significant and time isn't a constraint, gravity can be used for separation, a process known as sedimentation or skimming. In beer production, the hot wort needs to be clarified to remove particles like hot trub to achieve a clear liquid. This clarification is typically done using a whirlpool, which separates trub particles through tangential flow.

Three main types of centrifuges are used in food processing:

- Tubular/disc bowl centrifuges: These are used to separate liquids that don't mix (like oil and water).
- Solid bowl/nozzle valve discharge centrifuges: These are used to remove small amounts of solid particles from liquids.
- Conveyor bowl/reciprocating conveyor centrifuges: These are used to remove water from thick, muddy substances (sludges).

Although a well-established technology, achieving up to 70% energy savings in centrifugation processes within the food industry is feasible by integrating advanced design features and technologies. A paper (Szepessy and Thorwid, 2018) discusses how specific design modifications can lead to substantial energy savings in centrifugation processes, collectively resulting in an average energy reduction of 50%, with specific energy consumption dropping from industry standards of 0.7–1.5 kWh/m³ to as low as 0.25 kWh/m³ in optimal cases.

Alfa Laval's eMotion™ technology exemplifies how significant energy reductions are possible. This system creates a low-pressure environment around the centrifuge bowl, substantially reducing air friction during operation. When combined with a bottom-fed, fully hermetic design, this approach can lead to energy savings of up to 70% compared to conventional top-fed centrifuges. Specifically, the bottom-fed design contributes to a 30–60% reduction, and the eMotion™ system adds an additional 10–15% savings. These innovations not only decrease energy consumption but also offer ancillary benefits such as reduced noise levels, lower cooling requirements, and improved cleanability, enhancing overall operational efficiency. While Alfa Laval's technologies have been prominently applied in the brewing sector, their principles are transferable to other areas of the food industry. For instance, in dairy processing, Alfa Laval's hermetic design separators have achieved up to 60% energy savings, with the eMotion™ add-on providing an extra 20% reduction.

These advancements underscore the potential for substantial energy savings in food processing operations that utilise centrifugation, making them a compelling consideration for companies aiming to enhance sustainability and reduce operational costs.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	high
Scope 2 emissions savings (% or another quantifiable metric)	Up to 70%
Quality of scope 2 emissions information	High
Availability barriers	n/a
TRL level	9
Maintainability issues	Food residue buildup: centrifuges operate at high speeds, subjecting components to significant stress and wear. Rotor bearings are critical components that experience high loads and require regular maintenance and replacement. Centrifuges must be accurately calibrated and aligned to ensure optimal performance and separation efficiency.
Legislative concerns	n/a
Payback time (years)	Not determinable

Szepessy, S. and Thorwid, P., 2018. *Low energy consumption of high-speed centrifuges*. Chemical Engineering and Technology, 41(12), pp.2466–2471. <https://doi.org/10.1002/ceat.201800292>.

Alfa Laval, n.d. *Brew 701 eMotion*. [online] Available at: <https://www.alfalaval.co.uk/products/separation/centrifugal-separators/separators/brew-series/brew-emotion-701/emotion/>.

12.3.4 Compressed air optimisation

Lowering the system pressure of the compressed air system is a simple method by which to save energy. A case study in the food industry in Indonesia (Widayati and Nuzahar, 2016) showed reducing pressure from 7.5 barg to 6.8 barg would reduce energy consumption and running costs by approximately 4.2 %. Every 1 bar of extra air pressure requires 7% more energy in production (Anglian compressors and Atlas Copco, 2025).

Šešlija et al. (2016) showed a systematic approach for reducing compressed air system energy. This was to:

- Audit and system analysis. During this analysis the system characteristics, characteristics of consumption and characteristics of a production of compressed air have to be assessed.
- The establishment of internal standards. This includes defining of the pressure in the main line (header), adequate pressure and flow level as well as appropriate level of compressed air quality for every consumer of compressed air. Using ISO 50001, which is a global standard for business energy management can assist businesses in tracking, managing, and reducing air compressor energy usage.
- Minimisation of losses. Significant amount (in some systems up to 50%) of compressed air is spent on various losses, which, in most cases, can be remedied quickly and efficiently without large investments. According to IFM and Atlas Copco (2025) systemic air leaks can waste up to 20 to 30% of a compressor's output.
- Harmonisation of production and consumption.
- Identification of peak loads. This information enables proper dimensioning of compressed air distribution system and give support in determination of reservoir capacity.
- Automation and integration of equipment.
- Equipment maintenance. Change filters regularly and conduct regular leak detection.
- Performance monitoring.

An idling compressor uses around 40% of its full load (IFM, 2025). Therefore, it is important to switch off compressors when they're not in use, especially overnight or during breaks. As air demand often fluctuates, controllers and multiple compressors allow compressor demand to be better matched with supply, saving energy. VSDs also allow an efficient way of meeting fluctuating demand.

Multi-stage compressors are more efficient, run cooler and have longer life than single-stage compressors. Typical specific power for a two-stage, reciprocating compressor at 100 psig is 19 to 21 kW/100 cfm, compared to 24 kW/100 cfm for single stage. For rotary compressors, multi-stage specific power is approximately 16 to 18 kW/100 cfm, compared to 18 to 19 kW/100 cfm for single stage (Ambrosino, 2008).

Double acting reciprocating compressors uses both sides of the piston for compression, resulting in higher capacity and efficiency. Typical specific power is 100 psig is approximately 15 kW to 16 kW/100 cfm (Ambrosino, 2008).

Air compressors generate a lot of heat, according to CompAir (2025) 94% of the energy needed to run a compressor gets converted to heat. Air compressors can be purchased which incorporate heat recovery options, with water outlet temperatures up to 90°C (CompAir, 2025) or air cooled.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Up to 50%.
Quality of scope 2 emissions information	High
Availability barriers	None
TRL level	9

Maintainability issues	n/a
Legislative concerns	None
Payback time (years)	Some solutions are very simple and therefore payback is very fast.

AtlasCopco, 2025. 10 ways to make your compressor installation more energy efficient. AtlasCopco Group. <https://www.atlascopco.com/en-uk/compressors/customer-offers/e-book/air-compressor-energy-savings>.

CompAir, 2025. Sustainable Heat Recovery Systems for Oil-free Compressors. <https://www.compair.com/en-gb/air-treatment-and-accessories/heat-recovery-oil-free>.

Widayati, E. and Nuzahar, H., 2016. Compressed air system optimization: Case study food industry in Indonesia. In *IOP Conference Series: Materials Science and Engineering* (Vol. 105, No. 1, p. 012018). IOP Publishing.

Šešlija, D.D., Milenković, I.M., Dudić, S.P. and Šulc, J.I., 2016. Improving energy efficiency in compressed air systems-practical experiences. *Thermal Science*, 20(suppl. 2), pp.355-370.

IFM, 2025. How to increase air compressor efficiency: Industrial guide. Ifm Efector, inc. <https://www.ifm.com/us/en/us/energy-optimization/compressed-air-f/increase-air-compressor-efficiency-industrial-guide>.

Anglian compressors, 2025. Understanding ISO 50001 and How Air Compressors Fit In. Anglian Compressors and Equipment Ltd. <https://angliancompressors.com/blog/understanding-iso-50001-and-how-air-compressors-fit-in/#:~:text=Optimise%20System%20Pressure,minimum%20acceptable%20bar/psi%20level>.

12.3.5 Efficient conching

Conching is the processing step in which chocolate mass is subjected to long-term, moderate heat, mechanical shear forces to smoothen the chocolate solids' particles in the dry conching phase and the mixing action in the wet conching phase through the addition of fat and emulsifiers. There is an important relationship between the chocolate smoothness, flavour and the type of conching process. The heat from the shearing of the mass drives off the residual moisture and volatile acids from the ingredients and helps to develop the characteristic flavour profile of the chocolate. However, it is a costly processing step – an example for the utilised energy during a conching process: 20 minutes in Ningbo Newtang (model NTM-JMJ3000C, China) conche machine, capacity 3000 L, 55 kW – 26.4 MJ/ton chocolate. Several studies have sought to address the high energy and time costs associated with the chocolate conching process. Commercial grade chocolates are conched typically 4 to 8 hours while the highest quality artisan chocolates as well as certain special chocolates using fat substitute gums (xanthan - Medina-Torres et al., 2014) rely heavily on long conching time, up to 36 hours.

The concept as well as the equipment behind the conching have changed a lot in the past 100 years, moving from the reciprocal motion to continuous shearing, mixing and ventilation of the chocolate mass. Studies have focused on developing low-cost and shorter conching processes for milk chocolate production, particularly aiming to eliminate the dry conching phase. These studies have explored two primary approaches: developing alternative conching systems and optimizing existing ones.

Bolenz and his colleagues conducted research to reduce energy consumption and investment costs by modifying the conching process and decreasing production time for milk chocolate. Franke and Tscheuschner (1991) conducted a modelling study on the energy required for structural modification in continuous conching systems. Medina-Torres et al. (2014) successfully used rotor-stator (RE) type impellers to produce a reduced fat chocolate flavoured coating with improved flow properties,

homogeneity, and thermal stability. Tan and Balasubramanian (2017) found that particle size in chocolate conched for 2.5 hours remained relatively unchanged, suggesting potential for process time optimisation.

In enrobing (coating) applications where the flow properties of the chocolate or compound are of greater concern than its smoothness or flavour, Jolly et al. (2003) demonstrated up to 32% energy savings by using a reciprocating multi-hole extruder compared to traditional conching. Ball mills, though an alternative approach, require higher fat content and struggle to remove water and undesirable volatile compounds.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	Medium – the power source for the process is largely electricity
Scope 2 emissions savings (% or another quantifiable metric)	up to 32%
Quality of scope 2 emissions information	Low – genuine savings in specific applications only however most savings are coming from the shortening of the process time.
Availability barriers	Very application specific, cannot be upscaled for all confectionery masses
TRL level	6-8
Maintainability issues	Wear of high shear parts, must be accessible and adjustable.
Legislative concerns	None
Payback time (years)	Not yet available.

Omer Said Toker, Ibrahim Palabiyik, Nevzat Konar (2019): Chocolate quality and conching. Trends in Food Science and Technology 91 (2019) 446–453.

Mustafa Özilgen (2016): Energy utilization and carbon dioxide emission during production of snacks; Journal of Cleaner Production 112 (2016) 2601-2612.

Medina-Torres, L. M., Sanchez-Olivares, G., Nuñez-Ramirez, D. M., Moreno, L., and Calderas, F. (2014). Rheological of chocolate-flavored, reduced-calories coating as a function of conching process. Journal of Food Science and Technology-Mysore, 51(7), 1375-1382.

Tan, C. P., and Balasubramanian, V. (2017). Effect of conching time on the physical and chemical properties of dark chocolate. Journal of Food Processing and Preservation, 41(3), e12815.

Franke, F., and Tscheuschner, H. (1991). Modelling of the continuous high shear rate conching process for chocolate. Journal of Food Engineering, 14(1), 103-115.

Jolly, S., Sharma, R., and Singh, R. P. (2003). Energy Efficient Processing of Chocolate Using a Reciprocating Multihole Extruder. Journal of Food Science and Technology, 40(4), 315-319.

12.3.6 Efficient grinding

In addition to traditional grinding methods, new techniques and equipment have been developed for specific purposes. Examples include vacuum superfine grinding and low-temperature milling/cryogenic grinding.

Currently, there are innovative superfine grinding devices for food materials, such as low-temperature and vacuum superfine pulverisers, which are particularly useful for processing special food raw

materials. Among these, cryogenic grinding (also known as freezer grinding or cryomilling) involves freezing a material and then reducing it to a small particle size. A typical cryogrinding system mainly consists of a cryogenic precooler and a cryogenic grinder.

When grinding heat-sensitive materials – such as spices, vegetable extracts, or biopolymers – conventional milling methods can generate heat that leads to smearing, caking, oxidation, flavour loss or degradation. During cryogenic grinding, lower temperatures (e.g., dry ice, liquid carbon dioxide, or liquid nitrogen) are introduced to prevent recrystallisation and embrittle materials, making them easier to fracture with mechanical milling. Cryogenic grinding is often performed in impact mills, hammer mills, and agitated ball mills. Using an internally agitated ball mill can provide additional benefits, achieving a finer particle size range. The choice of grinding technique largely depends on the characteristics of the raw materials, particularly their hardness and content of fibre, fat, sugar, and volatiles. While cryogenic grinding improves the processability and physical properties of the powder – and grinding in an inert atmosphere prevents oxidation – the heat generated during the process cannot be recovered. In fact, the additional energy required for cryogenic cooling largely offsets the mechanical energy savings of the entire process.

Enhancing the energy efficiency of grinding machines should start in the layout and design phase. The international standard ISO 14955-1 provides a method to evaluate the energy supplied for main machine-tool functions, helping identify areas for improvement. The total energy efficiency index (TEEI) was developed to quantify each component's efficiency and utilisation, leading to better optimisation. Power measurements often reveal issues like component oversizing and lack of need-based control, stemming from the belief that "more is better" (Wegener, 2017; Gao et al, 2020).

Gontarz et al (2013) presented a case study showing that configuring the analysed grinding machines can reduce their direct energy consumption by 20%. Reducing the runtime of a grinding machine by shortening setup times, minimizing test pieces and iterations, and optimizing main and ancillary times with expert systems can significantly improve energy efficiency. This could account for up to 50% of energy expenditure, excluding material savings and productivity gains.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Energy saving through configuration and optimisation of process: 20% to 50%.
Quality of scope 2 emissions information	Low, very specific to the use case.
Availability barriers	Availability barriers in grinding processes in the food industry primarily include equipment limitations, food properties, and operational factors. These barriers can affect the efficiency and effectiveness of grinding, limiting the overall availability of ground food products.
TRL level	7-9
Maintainability issues	Maintenance costs represent a significant portion of total cost of ownership, about 40%.
Legislative concerns	Legislative concerns in grinding processes in the food industry primarily revolve around food safety, energy efficiency, and consumer protection. These concerns often result in regulations and standards that govern the design, manufacture, and use of grinding equipment.

Payback time (years)	
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Gao, W., Chen, F., Wang, X. and Meng, Q., 2020. Recent advances in processing food powders by using superfine grinding techniques: A review. *Comprehensive Reviews in Food Science and Food Safety*, 19(4), pp.2222-2255.

Gontarz, A.M., Hänni, F., Weiss, L.B. and Wegener, K., 2013. Machine tool optimization strategies for ecologic and economic efficiency. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 227(1), pp.54-61.

Wegener, K., Bleicher, F., Krajnik, P., Hoffmeister, H.W. and Brecher, C., 2017. Recent developments in grinding machines. *CIRP Annals*, 66(2), pp.779-802.

12.3.7 Hot boning (meat)

The chilling rate of large food objects such as meat carcasses is largely dependent on conduction of heat from the deep tissues. By boning and portioning the meat immediately post slaughter and cooling the much smaller joints of meat, the chilling time can be reduced considerably. There is also no need to chill bones and fat from the carcass thereby reducing the overall amount of heat removed from a carcass. In addition, there are benefits in terms of reduced evaporative weight loss during the shorter chilling process, better hygiene from more rapid chilling and increases in throughput (Taylor, 1985). The fast-chilling rates and release of the muscles from the restraint of being connected to the rest of the carcass can lead to shortening of the muscles and resultant toughness, so an accompanying process of electrical stimulation is often applied immediately post slaughter to prevent 'cold shortening' (White et al, 2006).

little work to investigate the potential energy savings although these are claimed to be substantial (40 - to 50% claimed by Taylor, 1985 and repeated by Pisula and Tyburcy, 1996).

Scope 1 emissions savings (% or another quantifiable metric)	Potentially benefits from reduced refrigerated space for chilling could lead to smaller refrigeration plant with lower refrigerant charge.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Claimed to save 40 – 50% of refrigeration energy, but no measured data presented (Taylor, 1985, repeated in Pisula and Tyburcy, 1996).
Quality of scope 2 emissions information	Poor.
Availability barriers	Despite potential savings and advantages, the additional complexity of processing and risk of detriment to product quality has led to little uptake in the meat industry.
TRL level	8 -9.
Maintainability issues	Nothing unusual for abattoir facilities.
Legislative concerns	None.
Payback time (years)	No information.

Pisula, A. and Tyburcy, A., 1996. Hot processing of meat. *Meat Science*, 43, pp.125-134.

Taylor A. A. (1985), Optimal chilling and ES parameters for hot boning, EEC Report of Working Party, Rome, 29-31st Oct. 'Accelerated Processing of Meat'. (Romita A, Valin C and Taylor A A eds), 3-19, Elsevier Applied Science Publishers Ltd.

White A., O’Sullivan A., Troy D.J. and O’Neill E.E. (2006). Effects of electrical stimulation, chilling temperature and hot-boning on the tenderness of bovine muscles.

12.3.8 Internet of Things (IoT) and Artificial Intelligence (AI)

Internet of Things (IoT) and Artificial Intelligence (AI) can be used to reduce GHG in food processing, but can themselves have a high energy consumption. As a result, there is a trade-off between the GHG reduction they enable and the additional GHG emission they introduce. For this reason, together with the fact that the overall reduction depends on numerous factors, it is difficult to accurately globally predict the GHG emission reduction in food processing using IoT and AI. However, there are still some studies on the subject that allow us to roughly estimate GHG reductions (Misra et al. 2020).

Scope 1 and 2 emission savings

IoT and AI can have beneficial effects in food processing in the following areas.

Scope 1 and 2 Emissions

- **Optimised energy consumption:** AI-enabled energy management systems can analyze real-time data from IoT sensors to optimise processes such as heating, cooling, and cooking, resulting in significant energy savings. Savings of 10-20% or more are possible depending on the specific application and existing infrastructure (Subash et al., 2024; Bunian et al., 2024; Biswas et al., 2024).
- **Predictive maintenance:** IoT and AI applications in predictive maintenance prevent inefficiencies and reduce emissions tied to machinery malfunctions.
- **Reduced food waste:** IoT sensors monitoring production lines can detect inefficiencies and anomalies, allowing for timely interventions and minimizing waste. AI algorithms can further optimise production planning and inventory management, potentially reducing waste by 5-15%. This directly translates to lower emissions from waste processing and disposal (Ahmadzadeh et al., 2023).
- **Renewable energy integration:** IoT and AI can facilitate the integration of renewable energy sources like solar and wind power into food processing facilities. AI algorithms can optimise energy usage based on the availability of renewable energy, maximizing its use and minimizing reliance on grid electricity, thus significantly reducing Scope 2 emissions (Miller et al., 2023; Cowell, 2024).

Barriers to adoption of IoT and AI in food processing

There are several factors that can act as a barrier to the adoption of IoT and AI in food processing.

- **High initial investment:** Implementing IoT and AI solutions often requires significant upfront investments in sensors, hardware, software, and integration with existing systems. This can be a major barrier, especially for SMEs with limited budgets.
- **Security and Privacy Concerns:** The vulnerability of IoT devices and AI systems to hacking poses significant risks to confidentiality and data integrity, potentially exposing sensitive production data. Cyberattacks can also disrupt production lines, compromising product quality and personnel safety, creating substantial obstacles for all businesses, including food processing companies.
- **Lack of Standardisation and Interoperability:** The lack of standardised protocols and data formats can make it difficult to integrate different IoT devices and systems. This can lead to compatibility issues and hinder data sharing and analysis.

- **Technical Expertise and Skills Gap:** Implementing and managing IoT and AI solutions requires specialised technical expertise. Many food processing companies lack the in-house skills needed to deploy and maintain these technologies, leading to a need for external consultants or training programs.
- **Legacy Systems and Infrastructure:** Many food processing facilities rely on outdated equipment and infrastructure that may not be compatible with IoT and AI technologies. Upgrading these systems can be costly and disruptive.
- **Resistance to Change:** Some companies may be resistant to adopting new technologies due to concerns about disruption to existing workflows, the need for employee training, and uncertainty about the return on investment.
- **Lack of Clear Business Case:** Some food processors may struggle to develop a clear business case for investing in IoT and AI, as the benefits may not be immediately obvious or easily quantifiable.

European laws

While there is not one single law specifically for IoT and AI in food processing, several EU regulations and initiatives are relevant:

- **EU Official Controls Regulation:** This regulation establishes a framework for official controls along the food chain, which can be supported by IoT and AI technologies for monitoring and traceability purposes (European Parliament, 2017).
- **EU Cybersecurity Act/Cyber Resilience Act:** This act aims to enhance cybersecurity and cyber resilience across the EU [(European Parliament, 2019; European Parliament, 2024a).
- **EU Artificial Intelligence Act:** This act aims to ensure the safe and ethical use of AI (European Parliament, 2024b).

Scope 1 emissions savings (% or another quantifiable metric)	5-20%, excluding the IT emissions.
Quality of scope 1 emissions information	Peer reviewed publications.
Scope 2 emissions savings (% or another quantifiable metric)	5-20%, excluding the IT emissions.
Quality of scope 2 emissions information	Peer reviewed publications.
Availability barriers	High Initial Investment. Data Security and Privacy Concerns. Lack of Standardisation and Interoperability. Technical Expertise and Skills Gap. Legacy Systems and Infrastructure. Resistance to Change. Lack of Clear Business Case.
TRL level	4-9
Maintainability issues	No particular issues

Legislative concerns	EU Official Controls Regulation (European Parliament, 2017), EU Cybersecurity Act/Cyber Resilience Act (European Parliament, 2019; European Parliament, 2024a). EU AI Act (European Parliament, 2024b).
Payback time (years)	Not available.

Misra, N. N., Dixit, Y., Al-Mallahi, A., Bhullar, M. S., Upadhyay, R., and Martynenko, A. (2020). IoT, big data, and artificial intelligence in agriculture and food industry. *IEEE Internet of things Journal*, 9(9), 6305-6324. Available at <https://ieeexplore.ieee.org/abstract/document/9103523>.

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European Parliament (2024a). EU Cyber Resilience Act. EU. Available at <https://eur-lex.europa.eu/eli/reg/2024/2847/oj>.

European Parliament (2024b). EU Artificial Intelligence Act. EU. Available at <https://eur-lex.europa.eu/eli/reg/2024/1689/oj>.

12.3.9 Milling

The most common examples of processed food that involve milling are the grain-based products, which are flour (wheat, corn, rice and another grains), cereal, pasta with durum wheat usage. Roller milling uses a series of smooth or fluted rollers to crush and grind grain. It offers greater control over particle size and is widely used in commercial milling operations (Pingle, 2025). There are several

traditional milling methods that can be listed: stone milling, where this age-old technique involves grinding grains between two stones – examples products include nut butter, spices and coffee and tea. While slow and labour-intensive, it produces flour with a distinct flavour and texture (Tufts Food Lab, 2025). Traditional mills are not suitable for large-scale industrial production, so modern methods like ball and hammer mills have been developed. Hammer mills use rotating hammers to shatter grains into smaller pieces. They are efficient and versatile, capable of handling a variety of grains and producing different particle sizes.

Differences between hammer mills and roller mills are related to the grinding method, where the hammer mills rely on impact and shear forces, while roller mills use compression and shearing forces. The other difference is particle size control: hammer mills generate more dust, even if the roller mills are generally more energy-efficient than hammer mills (Pingle, 2025).

Energy optimisation in milling is crucial for sustainable and cost-effective operations. Key strategies include optimising mill design, fine-tuning settings, and regular maintenance to reduce energy losses. Implementing energy-efficient equipment, such as high-efficiency motors and VFDs can significantly reduce energy consumption. Improving building infrastructure, incorporating renewable energy sources, and leveraging digital technologies like predictive maintenance and real-time monitoring can further enhance energy efficiency.

Advanced milling techniques

Advanced milling techniques, such as cryogenic milling and microwave-assisted milling, have been developed primarily to improve product quality and either increase throughput or reduce the energy consumption of a given milling installation. Energy savings in these techniques result from separating the effective grinding action from the inefficient friction and mixing processes typical of traditional mill designs.

Cryogenic milling uses liquid nitrogen or CO₂ to cool the particles before milling which makes them more brittle and easier to grind and also displaces and excludes oxygen during the milling process. This reduces the mechanical energy required for size reduction and prevents heat buildup, which is critical for preserving flavour, aroma, and nutrients. Estimated energy savings: 20 to 30% (Murthy, 2008), especially for oily, elastic, or heat-sensitive materials like spices herbs and certain dairy powders (Kutz, 2018). Given the cost of coolant however, cryogenic cooling is suitable mostly for heat-sensitive seeds and spices where its volatile essential oils or other components shall be preserved.

Jet Milling (Fluid Energy Milling) uses high-velocity air or steam to cause particle collisions, grinding the material without mechanical contact. This reduces friction and heat generation, making it suitable for ultrafine, thermally sensitive food powders (e.g. starches, proteins). Jet mills can offer energy savings of about 10–20% (mainly on refrigeration or cryogenic input) in specific scenarios, such as when used on very fine powders (under 10 µm) where mechanical mills require several passes, when no cooling is needed due to low heat generation or when classification is integrated, eliminating post-processing steps (Onwulata, 2009). Compressed air use is a limiting factor in energy efficiency of jet milling. While not inherently energy-saving, it can be more efficient overall in processes where thermal degradation or repeated grinding (and their associated energy costs) would otherwise occur.

Ultrasonic Milling (Ultrasound-Assisted Comminution) uses high-frequency sound waves (typically 20–40 kHz) to create cavitation in liquid or slurry systems, causing localised high pressures and temperatures that weaken or break down particles. It is useful for emulsions, nano-dispersions, or bioactive extraction, and often used in wet milling setups. Estimated energy saving of the unit operation ranges between 15 to 40% (Chemat, 2011), particularly when integrated as a pre-treatment to reduce the hardness or viscosity of the material prior to conventional milling however available only in a very niche and specific application.

Scope 1 emissions savings (% or another quantifiable metric)	4% (industrial cereal mills equipped with VFDs)
Quality of scope 1 emissions information	Low and very application specific
Scope 2 emissions savings (% or another quantifiable metric)	5% (industrial cereal mills equipped with VFDs)
Quality of scope 2 emissions information	Medium
Availability barriers	Hard to reduce this process CO ₂ emission, and the only adaptable solution is using a renewable energy source usage and some improving on the waste
TRL level	7-9
Maintainability issues	Complex system with high costly maintainable spare parts
Legislative concerns	Generally, no concern unless entering the nanoparticles range.
Payback time (years)	3.5 years (industrial cereal mills equipped with VFDs)

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12.3.10 Polygeneration

Polygeneration uses multiple energy inputs to provide multiple energy outputs. The primary energy can include fossil fuels, biofuels and renewable energy and the energy outputs are generally defined as energy that is useful in an activity. In the food industry the outputs are generally electricity or processing conditions (heating or cooling) at different levels suitable for cooking, chilling or freezing.

Combined Heat and Power (CHP) technologies are generally based on reciprocating engines or turbines usually fuelled by gas to generate heat and power. The feasibility of using CHP within the food industry depends on the requirement for heating and whether electricity can easily be bought and sold into the grid. Although cogeneration plants are not uncommon in the food industry a study on opportunities for CHP in the Swedish food industry carried out by Fritzson and Berntsson (2005) found that alternative heat exchanger networks or heat pumps generally had better energy saving potential and payback than CHP systems.

The UK Government (2020) estimated that CHP installations could save as much as 30% of the carbon compared to separate heat and power generation.

Trigeneration systems produce heat, power and refrigeration. In a trigeneration system all or some of the heat is used within an absorption cycle to generate cooling. Absorption cycles are usually based on lithium bromide and water or ammonia and water and depending on the cycle can generate cooling down to -40°C . Although not so common, adsorption systems can also be used in trigeneration. These systems commonly use water, methanol and ammonia as the refrigerants and adsorbents such as zeolites, active carbon, silica gels and salts in mesoporous silica or alumina (Critoph and Zhong, 2005). In addition, ejector powered refrigeration cycles have also been proposed to provide cooling in trigeneration systems but have been shown to have rather low COPs (Invernizzi and Iora, 2005).

As with CHP, the most suitable applications are those where demand for cooling and/or heating are constant. If this is not the case thermal energy storage systems can be utilised but these are bulky and add cost to the system. A useful review of trigeneration in the food industry has been presented by Sonar et al, 2014. In efficient trigeneration systems with a good balance of electricity/heating/cooling, electricity consumption for chilling and freezing can almost be eliminated and additional electricity can be co generated by the CHP unit. Some examples of trigeneration in the food industry, in a margarine, vegetable freezing, dairy and a meat factory) were presented by Bassols et al (2001).

Waste and by-products can be used to generate thermal energy and electrical power by either direct combustion, thermal gasification or anaerobically treated to give biogas. The biogas that is rich in methane can be burnt and used directly or used in a reciprocating engine or turbine as part of a CHP system.

Scope 1 emissions savings (% or another quantifiable metric)	NA
Quality of scope 1 emissions information	NA
Scope 2 emissions savings (% or another quantifiable metric)	Variable depending on application.
Quality of scope 2 emissions information	Information is limited in scope.
Availability barriers	Technology is available, feasibility and cost effectiveness depend on application.
TRL level	8
Maintainability issues	Not reported.
Legislative concerns	None.
Payback time (years)	Variable.

Bassols J, Kuckelkorn B, Langreck J, Schneider R and Veelken H (2002), Trigeneration in the food industry, Applied Thermal Engineering 22, 595-602.

Critoph R E and Zhong Y (2005), Review of trends in solid sorption refrigeration and heat pumping technology, Proc. ImechE, Vol. 219, Part E, J. Process Mechanical Engineering.

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Freschi, F., Giacccone, L., Lazzeroni, P. and Repetto, M., 2013. Economic and environmental analysis of a trigeneration system for food-industry: A case study. *Applied energy*, 107, pp.157-172.

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12.3.11 Refining and extraction

De Rosa et al. (2022) report that producing Roundtable for Sustainable Palm Oil (RSPO) certified palm oil results in 3.41 kg CO₂-equivalent per kilogram of oil. Specifically, the production of refined, bleached, and deodorised palm oil (RBDPO) from crude palm oil (CPO) accounts for 2.1% (0.07 kg CO₂-equivalent/kilogram of oil) of the total CO₂ emissions. Consequently, it is essential to focus on decarbonising the primary processes in palm oil refineries.

A case study was conducted at a multi-product physical refinery in Malaysia to explore ways to reduce CO₂ emissions. The physical refining process, typically performed under vacuum conditions, involves two main stages: bleaching and deodorisation. This process produces refined, bleached, and deodorised palm oil (RBDPO) as the main product and palm fatty acid distillate (PFAD), a by-product rich in free fatty acids. The simulation model was developed to cover the production of RBDPO and palm fatty acid distillate (PFAD) from CPO. After verifying the process parameters with the plant's engineers, the output data was used to calculate CO₂ emissions for 60 tons/hour CPO input. (De Rosa et al, 2022)

The direct carbon intensity for each unit was determined by dividing its direct CO₂ emissions by its economic output. The study found that the total carbon footprint of the system was 2339.97 kg. Similarly, the carbon intensities for the products were calculated by dividing their carbon footprints by their final economic values. Consequently, the carbon intensities for RBDPO and PFAD were 0.0088 and 0.0392 kg CO₂/\$, respectively. Although RBDPO has a higher overall carbon footprint, PFAD is more carbon-intensive due to its significantly lower final demand. This higher intensity is attributed to the fact that most of the PFAD is recycled back into the vacuum scrubber to improve the stripping of free fatty acids.

While the total CO₂ emissions were found to be 2339.97 kg, within an average carbon intensity of 0.0432 kg CO₂/\$. The target is to reach the average carbon intensity reduction of refinery by 20%, which means 0.0345 kg CO₂/\$ based on the article (Ramanath et al, 2023).

There are four scenarios proposed to achieve the 20% reduction in CO₂ emissions:

1. Improved energy recovery: lowering the minimum temperature approach (ΔT_{min}) in heat exchangers to enhance heat recovery and reduce steam demand.
2. Heat recovery from deodorising column vapour: Utilizing the heat from hot vapour to reduce steam requirements or generate low-pressure steam.

3. Boilers: replacing liquefied natural gas (LNG) boilers with biomass-powered boilers to achieve carbon neutrality.
4. Co-firing biomass with LNG: using a combination of biomass and LNG to reduce CO₂ emissions while managing capital costs.

Results from the different scenarios, the first with lowering $\Delta T_{\min}$ to 10°C or 15°C reduced CO₂ emissions by 25% and 13.9%, respectively, with significant cost savings. Other scenarios: heat recovery from deodorizing column vapour, reduced CO₂ emissions by 33.6% and 15% for different options (with potential cost savings) and implementing biomass boilers achieved a 24.9% reduction in CO₂ emissions (but required high capital investment). The fourth scenario reduces the CO₂ emissions by 26.1% with more manageable costs.

Among the scenarios evaluated, it was determined that recovering heat from the inlet to the vapor scrubber and co-firing 50% palm kernel shell with LNG successfully met the benchmark. Another approach involves converting the LNG boiler to a fully biomass-powered boiler, which results in a 24.9% reduction in CO₂ emissions (Ramanath et al, 2023).

Alternative refining techniques include

- **Cold pressing:** this method involves extracting oils and juices without using heat, preserving nutrients and reducing energy consumption (Moore, 2024).
- **Membrane filtration:** utilises semi-permeable membranes to separate components based on size and charge, often used in dairy processing to concentrate proteins and remove lactose. (Charcosset, 2021).
- **Supercritical CO₂ extraction:** uses supercritical CO₂ as a solvent to extract essential oils and flavours, offering a cleaner alternative to traditional solvent-based methods (Wang et al, 2020).
- **Ultrasonic processing:** employs high-frequency sound waves to enhance extraction and refining processes, improving efficiency and reducing the need for chemical additives (McHugh, 2016).
- **Enzymatic refining:** uses specific enzymes to break down unwanted components, such as fats and proteins, in a controlled manner, leading to more precise and environmentally friendly processing.
- **Pulsed electric field (PEF) technology:** applies short bursts of high voltage to food products, improving extraction efficiency and preserving nutritional quality. (Raso et al, 2022)
- **Fermentation:** leveraging natural fermentation processes to refine and enhance food products, reducing the need for synthetic additives and improving sustainability (Siddiqui et al, 2023).
- **Hydrothermal processing:** involves using water at high temperatures and pressures to break down biomass into valuable components, useful for producing bio-based materials and chemicals (Wang et al, 2022).

Heat recovery in refining

To optimise energy use, heat recovery systems can be implemented in these refining processes:

- **Heat exchangers:** capture heat from hot oil or sugar solutions and use it to preheat incoming raw materials.
 - Shell and tube heat exchangers: consist of a series of tubes, one set carrying the hot fluid and the other the cold fluid. Heat is transferred through the tube walls.

- Plate heat exchangers: made up of multiple thin, corrugated plates that create channels for the fluids. They offer high efficiency and are compact. (Luo et al, 2022)
- **Heat pumps** can upgrade low-grade waste heat to a higher temperature, making it suitable for reuse in processes like pasteurisation, drying, or cleaning. They work by absorbing heat from a source and transferring it to a sink at a higher temperature.
- **Thermal energy storage:** store excess heat generated during refining for later use in other processes.
- **Organic Rankine Cycle (ORC) systems:** ORC systems convert low-grade waste heat into electricity. They use organic fluids with low boiling points, which allows them to operate efficiently at lower temperatures compared to traditional steam cycles.

Scope 1 emissions savings (% or another quantifiable metric)	Minimum 20% (Ramanatha et al, 2023).
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	
Quality of scope 2 emissions information	
Availability barriers	High capital costs, operational complexity, many maintenance issues, economic feasibility, energy sources availability, lack of the policy/regulatory frameworks
TRL level	8-9 However, the TRLs ranging from 6 to 8, depending on the specific technology and the level of integration.
Maintainability issues	Costly maintenance, both in the preventive and predictive as well. Automation is the key point to make more effective refining and produce less waste, the digital tools also contribute to control and analysis. Refineries must balance the costs of maintenance with the benefits of improved efficiency and reduced downtime
Legislative concerns	Several legislative concerns related to edible oil industry, some key food safety regulations, QA standards, environmental regulations, import-export regulations, which may also affect to the carbon footprint.
Payback time (years)	No information

Charcosset, C. 2021, Classical and Recent Applications of Membrane Processes in the Food Industry.

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12.3.12 Reverse osmosis

Reverse osmosis (RO) is a water purification method that eliminates dissolved salts, contaminants, and other impurities by forcing water through a semi-permeable membrane. This membrane allows water molecules to pass while blocking larger particles like salts, bacteria, and other impurities. By applying pressure, water is pushed from a high-solute concentration area to a low-solute concentration area, reversing the natural osmosis process.

In food processing, RO is commonly used for concentrating liquids such as fruit juices (Ma et al., 2024) and dairy products (Chamberland et al., 2020). RO removes excess water without applying heat, helping to preserve flavours and nutrients that could be lost during traditional evaporation-based methods.

RO offers a more energy-efficient alternative to evaporative heating for liquid concentration. Evaporative heating requires substantial thermal energy to boil off water, with approximately 2,260 kJ needed to evaporate 1 kg of water. In contrast, RO uses mechanical pressure to separate water from the liquid, consuming only 100 to 200 kJ per kg of water removed, depending on system specifications and liquid properties. This can result in energy savings of up to 90% compared to evaporative heating (Cheryan, 1990; Rautenbach and Albrecht, 1989). However, while RO consumes about 10% of the energy used by a six-stage evaporator with thermocompression, its energy savings are less significant when compared to mechanical vapor recompression. Thus, the effectiveness of using RO as a pre-concentration step is more limited when thermocompression is already employed (Patil et al., 2021). Often, RO is used only as a pretreatment for evaporative processing, therefore lowering the energy saving impact.

Chamberland et al. (2020) used predictive models to assess the impact of applying RO at different stages in an industrial cheesemaking plant. The most resource-efficient approach was to apply RO to cheese whey and milk ultrafiltration (UF) permeate before evaporation. Pre-concentrating these by-products to 20% and 22% total solids, respectively, resulted in a 36% reduction in natural gas consumption and a 10% reduction in electricity consumption compared to scenarios where only condensed water was reclaimed.

Operational costs, including production run times and cleaning requirements, must be factored in to optimise performance (Patil et al., 2021). Depping et al. (2017), building on the findings of Stefansdottir et al. (2018), observed that increasing skimmed milk concentration from 30% to 35% w/w dry matter (DM) using RO led to a 58% reduction in run time due to increased fouling and cleaning frequency.

RO processes can be optimised further for greater energy savings. Blais et al. (2021) developed a cascade membrane process using microfiltration and RO to concentrate skimmed milk to 18% DM. They found that operating RO at 50°C, rather than 15°C, resulted in a 57% reduction in energy consumption per unit volume of water removed.

To address the concentration limitations of RO, emerging membrane technologies like cascade membrane systems, forward osmosis (FO), and membrane distillation (MD) are becoming areas of increasing research interest (Patil et al., 2021).

Payback times were analysed by Chamberland et al. (2020) and Ma et al. (2024) for dairy and juices, respectively. A relatively short payback period, typically within 2–4 years, was found depending on product type, plant size and energy costs.

Scope 1 emissions savings (% or another quantifiable metric)	- Assuming the evaporation was scope 1 emissions, e.g. natural gas 100% - When used as pretreatment (more usual): 36%.
Quality of scope 1 emissions information	Peer reviewed publications
Scope 2 emissions savings (% or another quantifiable metric)	- Optimisation of RO: 57% - When used as pretreatment (more usual): 10%.
Quality of scope 2 emissions information	Peer reviewed publications
Availability barriers	-
TRL level	9
Maintainability issues	Increased cleaning needs for membrane technology with respect to evaporator technology
Legislative concerns	-
Payback time (years)	2 to 4 years

Chamberland et al. 2020; Ma et al. 2024; Cheryan, Veeranjanyulu, and Schlicher 1990; Rautenbach and Albrecht 1989; Patil et al. 2021; Depping et al. 2017; Stefansdottir et al. 2018; Blais et al. 2021).

Blais, H., Ho, Q.T., Murphy, E.G., Schroën, K. and Tobin, J.T., 2021. A cascade microfiltration and reverse osmosis approach for energy efficient concentration of skim milk. *Journal of Food Engineering*, 300, p.110511.

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Stefansdottir, B., Depping, V., Grunow, M. and Kulozik, U., 2018. Impact of shelf life on the trade-off between economic and environmental objectives: A dairy case. *International Journal of Production Economics*, 201, pp.136-148.

12.3.13 Smoking – efficient technologies

Recent advancements in smoking technology focus on improving efficiency, productivity, quality, precision, and sustainability (Addy 2021). Advanced smoke generators (Protech 2024), controlled atmosphere smoking chambers, and automated systems contribute to better control over the smoking process. Additionally, innovations in the development of alternative smoking agents, such as botanical extracts and advanced liquid smoke formulations, are gaining traction for their potential health and environmental benefits.

One of the key advancements in smoking technology is the reduction of direct emissions. Traditional smoking methods often resulted in the release of significant amounts of particulate matter and volatile organic compounds (VOCs). Modern smoking technologies (euomeat 2024) incorporate filtration and recirculation systems to minimise environmental impact, making the process more sustainable and compliant with air quality standards. For example, The Clean Smoke (euomeat 2024) smoking process emerges as an environmentally conscious solution, generating stable smoke for smoking chambers through compressed air and primary smoke condensate. This method, endorsed by the Clean Smoke Coalition (CSC), aligns with the EU's push for eco-friendly technologies. Traditional smoking methods, notably friction and smouldering smokers, fall short in comparison, as validated by a life cycle assessment by the German Institute of Food Technologies (DIL). Recognizing its efficiency, the EU has designated Clean Smoke as the "Best Available Technology." The Clean Smoke technology, championed by the CSC, has the potential to make substantial contributions to sustainability. According to DIL, it can reduce energy consumption by approximately 50% and, considering the current energy mix, cut greenhouse gas emissions by around 30% in the German smoked products market. Despite its proven benefits, Clean Smoke is currently employed in only 10% of smoked foods in Germany, leading to a modest reduction of 7.2% in energy consumption and 8% in greenhouse gases. In contrast, Sweden has embraced Clean Smoke on a larger scale, with over 80% of smoked products utilising this technology (euomeat 2024).

Smoking technology has reached a high TRL, indicating its maturity and widespread acceptance in the food processing industry. Continuous research and development efforts have contributed to refining the technology, ensuring its reliability and effectiveness across various applications (euomeat 2024).

While modern smoking technology systems are generally reliable, maintenance can be a concern. Regular cleaning of smoke generators, monitoring of filtration systems, and preventive maintenance of automated controls are essential to ensure optimal performance and longevity. Training programs for operators play a crucial role in addressing potential maintenance challenges.

As with any food processing technology, smoking technology is subject to stringent regulations to ensure food safety and environmental compliance. Emission control measures, adherence to safety standards, and labelling requirements are critical considerations for manufacturers using smoking technology.

Scope 1 emissions savings (% or another quantifiable metric)	CSC: 30% considering the current energy mix in Germany.
Quality of scope 1 emissions information	1 article
Scope 2 emissions savings (% or another quantifiable metric)	-
Quality of scope 2 emissions information	-
Availability barriers	-
TRL level	8-9
Maintainability issues	Regular cleaning, monitoring of filtration systems, preventive maintenance of automated controls
Legislative concerns	-
Payback time (years)	Not available

Addy, R. 2021. Meat smoking tech from GEA offers smokehouse-style taste. August 13.

euomeat. 2024. euomeatnews.com. January 06. Accessed January 22, 2024. <https://www.euomeatnews.com/Article-Closer-to-the-climate-targets-with-Clean-Smoke/4397>.

12.3.14 Solar power

Under the European Green Deal and the REPowerEU plan, solar power is a building block of the EU's transition to cleaner energy. Its accelerated deployment contributes to reducing the EU's dependence on imported fossil fuels. As part of the REPowerEU plan, the Commission adopted in May 2022 an EU solar energy strategy (EU, 2022, which identifies remaining barriers and challenges in the solar energy sector and outlines initiatives to overcome them and accelerate the deployment of solar technologies. The EU's renewable energy policies helped bring PV costs down by 82% over the last decade, turning it into one of the most competitive sources of electricity in the EU.

Solar power is a fundamental shift towards a more sustainable and responsible food industry. By embracing solar energy, food manufacturing businesses can reduce their environmental impact, lower operational costs, and contribute to a greener future. Implementation of photovoltaic (PV) technologies may be applied in order to supply electric energy for food production processes. The power generation may be introduced to food processing by the application of hybridised technologies encompassing the use of PV and biofuels. Payback time of 2–7 years (investment cost of about 4750 €/kW) is estimated (Iten et al., 2021).

Solar-powered food processing, such as using solar dehydrators to preserve fruits and vegetables, offers significant benefits for small-scale farmers in low-income countries by reducing post-harvest losses and generating extra revenue. However, its impact will likely remain limited to small quantities of food due to infrastructure challenges and the scale of operations in these regions (IRENA, 2022). In contrast, larger economies like the EU and USA, with established industrial food processing systems, would see minimal direct benefits from decentralised, solar-powered solutions such as solar cold storage units for perishables; solar-powered bulk milk chillers, butter churners and cream separators.

Hybrid photovoltaic-thermal systems generate both electricity and a useful thermal output simultaneously from the same aperture area, achieving a higher overall efficiency than separate PV and solar-thermal collectors. This combined generation makes photovoltaic-thermal collectors an interesting solution in combination with solar-driven cooling technologies for heating, cooling and

power provision, supporting the rapidly growing cooling sector. Hybrid photovoltaic systems are particularly effective in the fruit and vegetable processing and canning sector, where they can simultaneously meet cooling and hot water demands, reducing both energy costs and environmental impact. This is especially true when PV systems directly power electrical chillers, which decreases reliance on grid electricity and maximises energy savings (Herrando et al., 2020).

Such a level of electrical power can be easily supplied by locally generated electricity from solar, wind, and hydro energy (Bhunia et al., 2024).

12.3.14.1 Solar power management

Recent advancements in the integration of solar photovoltaics, battery storage, and demand response programs have made peak shaving even more attractive (Zachari et al., 2024). Solar electric power can be used in food processing by integrating solar panels with battery storage systems, ensuring a continuous energy supply. New types of solar power storage batteries utilise AI installed in the battery, which ensures that unused electrical energy is stored as efficiently as possible. The AI module in the battery predicts the generation of the solar plant, uses tomorrow's weather forecasts, takes electricity prices from the market exchange (Wang et al., 2025).

Mo (2016) conducted a thorough analysis of the potential annual energy savings for a food manufacturer using photovoltaic technology to harvest solar energy for the factory's power supply. The system design methodology has taken into account the objective of reducing grid power while maintaining it at a level that does not require back-feeding of solar energy to the grid. The detail load profile analysis shows that the optimum system size is determined at a level that will not exceed the normal power demand level, and the changes in load requirements over years. The feasibility study has considered different scenarios under a number of reasonable assumptions that assist in speedy resolution of the system size. Two advantages are realised from this design: (1) Saving on the installation of the solar system which does not include power back-feeding control devices; (2) Minor changes to the manufacturing process to adjust the consumption pattern on the day maximises the use of solar energy when it is available Mo (2016).

12.3.14.2 Environmental impact of solar power

LCA studies have focused on assessing the energy payback time (EPBT) and carbon footprint of solar energy technologies to understand their environmental performance. A study by Celic et al. 2016 conducted an LCA of different PV technologies. The study reported EPBT values ranging from 1 to 1.5 years, depending on the PV technology and location. The carbon footprint of PV systems was estimated to be around 100–150 gCO₂e/kWh, indicating relatively low emissions compared with conventional electricity generation sources. In terms of energy storage solutions, a study by Yudhistira et al., 2022 conducted an LCA of lithium-ion batteries used for energy storage in PV systems. The study assessed the environmental impacts associated with battery manufacturing, use, and end-of-life treatment. It reported that the carbon footprint of lithium-ion batteries ranged from 50 to 140 kg kgCO₂e/kWh, emphasizing the importance of optimizing battery production and recycling processes.

Solar energy in particular can be used to power several processes within the fisheries and aquaculture value chain. This includes operations like powering lights for fishing, aquaculture equipment (feeders, pumps, aerators, security lighting), charging electric motors for fishing, running processing equipment, ice making, chilling and cold storage, including in transport and retail applications (Puri et al., 2023). The integration of solar PV in fish processing can significantly reduce cold storage operating costs by utilizing solar energy, leading to more affordable fish storage and improved fish quality (Puri et al., 2023).

The case studies of Croatian fish industry indicate, that fish processing factory with a capacity of 5030 t/year could use PV combined with wind power plant. For the annual amount of energy consumption

in the factory, two wind turbines (20 kW each) are needed for an output of 226458 kWh. PV cells cover 1000 m² in this case study, but to fully replace energy consumption in the industry process, 3460 PV cells are needed (830 kWp), to cover an area of 5674 m². If a combination of wind and solar energy is used, then one wind turbine and 1702 PV cells (408 kWp) are needed to cover the total amount of energy used in the factory (Bujas et al., 2022).

Using RESs in some part of the process could be a significant environmental improvement. For example, in industrial processes, a large-area installation of PV cells and wind turbines reduces the costs of electric energy by 48%, the installation of only PV cells by 18%, and the installation of only wind turbines by 24% (Bujas et al., 2022).

The model analyses have been performed on the Milford Haven port with five buildings and a solar farm based on which the entire fish processing workflow is conducted. The task of this study was to model and analyse energy use in the Milford Haven port in a smart energy cluster model and to understand energy demand and supply with their associated constraints. Packaway building is the main building in the port and contains several appliances consuming energy: a flake ice machine, ice store freezer, box washing machine, lighting systems and smart meter. Also, there are four storage rooms in the Packaway building, and each storage room has a double tube lighting system. The box washing machine has a power capacity of 50 kW, and it works only when the fishers need to clean boxes during the day. Ice storage is under operation all the time to meet the demand for fish storage with the quantity required. The Packaway building has installed a PV system on the roof of the building with 50 kW panels that feed the building during the daytime. They have a total power output of 275 W per panel with two DC–AC inverters. A simulation-based optimisation for scheduling appliances has been developed for determining the optimised operation intervals of appliances and optimal use of local renewable energy sources (Alzahrani et al., 2020).

More than 50% of the energy consumed by a bakery is dedicated to baking (Guimbretiere et al., 2023). Another way is to substitute the electricity supply locally, using a stand-alone renewable energy system such as solar PV panels coupled with storage (Meyer and Von Solms, 2018). The 52 kW containerised solution is being developed by German start-up Solarbakery. The bakery's production process was adapted in such a way that the majority of electricity consumption is already incurred during the day and is only baked briefly in the dark before dawn (Lichner, 2021).

PV can also provide indirect or direct heating, depending on the technology connected to the electrical supply. The analysis examines the county-level opportunities for few PV solar technologies to meet industrial process heat demand: PV-connected electric boilers; PV-connected ambient heat pumps with hot water storage; PV-connected waste heat recovery heat pumps (WHRHP); PV-connected resistance heating. Important to mention that the PV DC system is sized to be approximately 1.2 MW_{th}, which with a DC-to-AC inverter ratio of 1.2 would provide a 1-MWe (megawatt-electric) system (McMillan et al., 2021).

Available data from the slaughterhouse shows that between 20-30 cattle are slaughtered daily. HOMER software was used to model and simulate the system. HOMER is an optimisation tool for distributed power, developed by National Renewable Energy Laboratory, USA. An assessment of one-year energy production and consumption operation of the system indicates that 38% of electricity was provided by the PV system (Sanni et al., 2019). Implementation of PV technologies may be processed in order to supply electric energy. The power generation may be processed by the application of PV. The foreseen payback time of 2–7 years (investment cost of about 4750 EUR/kW) (Iten et al., 2021).

Indian case study shows that applying efficient solar based refrigeration system for milk cooling at village level society and solar based vapour absorption system for milk and milk related cooling operations are feasible solutions (Desai et al., 2013).

The research of a free-stall dairy barn located in southern Bavaria, Germany, with a rooftop PV plant that has a capacity of 205.2 kWp and mean milk production of 1847.3 kg milk/day was performed. The electric energy production of a dairy farm with a rooftop PV plant can be sufficient, to provide enough energy for the milk production system. However, the temporal distribution is crucial to increase the self-sufficient energy supply. Energy storage in the production process is a method to compensate for this (Höhendinger et al., 2023).

Scope 1 emissions savings (% or another quantifiable metric)	PV electricity contributes 92% to 96% less greenhouse gases than the European electricity mix.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	Verified in the peer-reviewed environmental engineering literature
Availability barriers	None.
TRL level	8-9
Maintainability issues	
Legislative concerns	Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions. EU Solar Energy Strategy. Brussels, 18.5.2022. COM (2022) 221 final.
Payback time (years)	Dependent on technological solution and processing industry – from 2 to 7 years.

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12.3.15 Thermal energy storage systems (TES)

Thermal energy storage (TES) offers several advantages that contribute to increased efficiency, flexibility, and cost-effectiveness. Thermal energy can be stored as sensible, latent, or chemical heat. In each of these categories there is a very large selection of different materials is available for the temperature ranges low, medium and high, which can, however, be of varying degrees of maturity (TRL). Therefore, this review focusses only on sensitive and latent TES. Also, to reflect differences in

application and context, the review is structured into two parts: TES in land-based processing facilities and TES onboard fishing vessels.

12.3.15.1 Integration at processing plants; low, medium and high temperature

In food processing, TES are categorised by temperature range to optimise processes like freezing, cooling, pasteurisation, and cooking. Low-temperature CTES ($<0^{\circ}\text{C}$) supports freezing and refrigeration, medium-temperature MTES (0°C - 100°C) aids in cooling and pasteurisation, while high-temperature HTES ($>100^{\circ}\text{C}$) is used for cooking and drying. Many food industry processes require both hot and cold thermal energy, making refrigeration systems that utilise both heat sink and source highly efficient. However, to fully optimise this, TES must be carefully designed and integrated with suitable TES materials and the right capacity.

For CTES there are several review papers summing up the state of the art. For example, glycol can be used for sensible storage and water or paraffin for latent storage as the phase change material (PCM). (Li et al. 2013; Selvnnes et al. 2021; Yang et al. 2021). Examples of the use of CTES have been around for a long time, for example in the dairy industry where ice banks have been and are used. However, a case study in (Boone 2012) showed that switching to ice slurry as CTES can increase energy efficiency by up to 36%.

MTES offer great potential, particularly in the utilisation of waste heat, as the heat generated during cooling or freezing is not simply dissipated into the environment but can be stored and used at a later point in time, e.g. for cleaning in place (CIP) processes, for heating, etc.

For temperatures above 100°C , sensible HTES can be used with pressurised water tanks, as well as thermal oils and glycol. In addition, hot vapour can be stored in special concrete pipes such as those from Energynest (2024) or in Ruth steam accumulators (Thermal energy storage (TES) offers several advantages that contribute to increased efficiency, flexibility, and cost-effectiveness. Thermal energy can be stored as sensible, latent, or chemical heat. In each of these categories there is a very large selection of different materials available for all the temperature ranges (low, medium and high), which can, however, be of varying degrees of maturity (TRL). Therefore, this review focusses only on sensitive and latent TES. In food processing, TES are categorised by temperature range to optimise processes like freezing, cooling, pasteurisation, and cooking. Low-temperature CTES ($<0^{\circ}\text{C}$) supports freezing and refrigeration, medium-temperature MTES (0°C - 100°C) aids in cooling and pasteurisation, while high-temperature HTES ($>100^{\circ}\text{C}$) is used for cooking and drying. Many food industry processes require both hot and cold thermal energy, making refrigeration systems that utilise both heat sink and source highly efficient. However, to fully optimise this, TES must be carefully designed and integrated with suitable TES materials and the right capacity.

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various latent PCM TES that can vary depending on the application and temperature range. Further information can be found in these papers. (Beck et al. 2021; Energynest 2024; Puschnigg et al. 2021; Wolde, Cardemil, and Escobar 2024)

Scope 1 emissions savings (% or another quantifiable metric)	n/a, relates heavily on selected method and comparison benchmark, increasing energy efficiency, reduced fossil fuel consumption, for the complete processing industry (also outside of food and beverage) the potential is estimated to save 513 Mt CO ₂ equivalent per year (Kauko et al. 2022)
Quality of scope 1 emissions information	Many review articles available, difficult to get concrete numbers
Scope 2 emissions savings (% or another quantifiable metric)	n/a, can help to integrate and store more renewable energy
Quality of scope 2 emissions information	Many review articles available, difficult to get concrete numbers
Availability barriers	Sensible: L; Latent: H, M, L
TRL level	9 sensible (liquid, all temperature levels) 7 sensible (solid, all temperature levels) 4-7 latent (all temperature levels)
Maintainability issues	For PCMs. increase heat transfer rates while managing charge/discharge rates, streamline the standardisation and commercialisation of phase change materials (PCMs), reduce the need for customised solutions, improve PCM durability, and enhance the purity of thermal storage materials
Legislative concerns	n/a
Payback time (years)	Depends on selected method and application

Beck, Anton, Alexis Sevault, Gerwin Drexler-Schmid, Michael Schöny, and Hanne Kauko. 2021. 'Optimal Selection of Thermal Energy Storage Technology for Fossil-Free Steam Production in the Processing Industry'. *Applied Sciences (Switzerland)* 11 (3). MDPI AG: 1–23. doi:10.3390/app11031063.

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Energynest. 2024. 'Thermal Energy Storage to Unlock Clean Process Heat for Food & Beverage Production'. *ENERGYNEST*. <https://energy-nest.com/industry/food-beverage/>.

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Puschnigg, Stefan, Johannes Lindorfer, Simon Moser, and Thomas Kienberger. 2021. 'Techno-Economic Aspects of Increasing Primary Energy Efficiency in Industrial Branches Using Thermal Energy Storage'. *Journal of Energy Storage* 36 (April): 102344. doi:10.1016/j.est.2021.102344.

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12.3.15.2 Integration on fishing vessels

Onboard fishing vessels, thermal energy is required for a range of purposes, including freezing and chilling of catch, as well as hot water production, space heating, snow melting and process heat for RRM handling. The primary objective of the onboard refrigeration system is to rapidly chill or freeze the catch to ensure product quality and food safety, which often results in oversized systems designed to handle peak cooling demands. Integrating TES offers potential for improving the overall energy efficiency of thermal systems and thereby reducing GHG emissions. TES can enable peak shaving, particularly for RSW systems which must handle short periods of high load when catch is brought onboard, followed by long periods of relatively low demand. By storing cooling capacity in periods of lower demand, refrigeration units can operate at more stable and energy-efficient conditions. To fully optimise this, TES must be carefully designed and integrated with suitable TES materials and the right capacity, and limited available space onboard requires special consideration to size (Vingelsgård et al. 2022; Saeed et al. 2020).

Freezing fish onboard requires low temperatures, typically between -30°C and -50°C, which are often achieved using ammonia-based refrigeration systems, but CO₂-based systems are also well-suited for the low temperature range. Hafner et al. (2011) introduced a novel concept for CTES using solid CO₂ as a PCM, showing up to 30% energy savings in a modelled tunnel freezer application by avoiding inefficient part-load compressor operation. Building on this work, Verpe et al. (2019) explored the application of CO₂-based CTES focusing on onboard plate freezing. Their simulations demonstrated that maintaining more stable plate temperatures with CTES reduced freezing times and increased production capacity. Saeed et al. (2020) further extended the approach by dynamically simulating an integrated system combining CTES and heat recovery from the CO₂ gas cooler. Their results showed that CTES could help manage peak refrigeration loads while recovered heat could be used for onboard fish oil production, significantly improving total system efficiency.

For catch chilling, many fishing vessels rely on RSW or ice slurry systems in addition to traditional methods such as icing. A conventional RSW system consists of chilling and storing seawater in tanks at approximately 0°C to -1.9°C into which the catch is pumped after capture. While not typically referred to as TES, the chilled seawater functions as sensible TES, buffering the initial thermal load when large catches of 'warm' fish is introduced (Vingelsgård et al. (2022)). Saeed et al. (2021) proposed the integration of a PCM-based TES tank into the return line of an RSW system. In simulations, a 1 m³ PCM tank (phase change temperature 3°C) achieved an average charging capacity of 31.6 kWh and discharging capacity of 30 kWh. This indicated higher energy density and a more compact footprint than sensible.

Ice slurry is a mix of small spherical ice crystals and liquid, which offers better cooling efficiency for fish by providing greater heat transfer and easier handling compared to traditional ice. Since the ice crystals serve as latent energy storage, the specific energy density is much higher than in RSW systems,

depending on the ice fraction (up to 60% pumpable). However, the slurry's sub-zero temperature can negatively affect certain fish species (Widell et al. 2023). Vingelsgård et al. 2022 found that using a 20% ice slurry concentration (onboard slurry production unit) in a fish chilling system could reduce cool-down time of the catch from 6.36 to 2.79 hours compared to a standard RSW system, while also cutting maintenance cooling energy demand and CO₂ emissions by enabling shorter full-load operation instead of prolonged part-load use.

For the warm thermal demands like hot water, space heating, snow melting and processing of fish RRM, hot water tanks are usually used as sensible TES. Saeed et al. (2020) has found out in a case study that on a long journey vessel that freezes fish fillets, heat recovery from the refrigeration system, averaging 298 kWh, exceeds the 261 kWh heating demand for fish oil production, making integrated freezing and heating a viable option for sustainable fishing, though system design depends on RRM quantity and hot water thermal storage capacity.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a, reduced freezing time has a positive effect on fish quality and thus reduces food loss and waste
Scope 2 emissions savings (% or another quantifiable metric)	n/a, up to 30% electric energy savings (Hafner, Nordtvedt, and Rumpf 2011)
Quality of scope 2 emissions information	
Availability barriers	Many review articles available, difficult to get concrete numbers
TRL level	Sensible <3; Latent: >3 (max 9)
Maintainability issues	
Legislative concerns	
Payback time (years)	n/a

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12.3.16 Utilisation of processing waste: anaerobic digestion

Presently, about one third of fresh harvest is wasted in the food processing chain, often discarded as landfill and in marine environments (Kaur, 2023). Industrial contribution is to identify, recover, and hence reutilise this stream. Over the next decade, worldwide food waste production is projected to rise by 33% (Pour and Makkawi, 2021). Food waste affects the environment negatively through its contributions to greenhouse gas emissions, exhaustion of natural resources, use of energy to produce food, and interruption of natural biological cycles (Bartek et al., 2021). The intensive production of animal proteins has a direct impact on climate change, as it results in 12% of total GHG emissions and 30% of all human-induced terrestrial biodiversity loss (Henchion et al, 2017). These wastes are rich source of energy, micronutrients and dietary fibre (Freier, 2019), and can be recycled into biofuel, essential oils, phenolic compounds, high-value prebiotics and carotenoids.

Meat waste and by-products include trimmings, cuttings, bones, collagen, carcasses, skins, fatty tissues, hoofs, internal organs and blood. Bovine slaughterhouse releases 27.5% of solid waste from animal sources, i.e., 275 kg/ton of total live weight killed. Similarly, caprine slaughtering, releases 2.5 kg/head almost 17% of animal weight. Furthermore, meat production through porcine releases 2.3 kg/head, equivalent to 4% of animal weight (Kaur, 2023).

Food processing waste can be managed in a number of ways, but anaerobic processing is one of the best alternatives to food waste management in terms of greenhouse gas emissions. One reason for this is that food waste is rich in readily available nutrients for methane-producing anaerobic bacteria. Another reason is that the main product, methane, can replace fossil fuels and the waste produced during the biogas production process (digestate) can be used as a substitute for mineral fertilisers returning nutrients to agricultural soil and closing the nutrient cycle. The supply of carbon-rich digestate to soils helps to store carbon into soil organic matter, thereby contributing to atmospheric CO₂ removal.

As a renewable biofuel, biogas can play a very important role in alleviating concerns related to the rapidly increasing energy demand and the instability of the energy resource market. Biogas can be used in various ways: for electricity and heat production by combustion of biogas in cogeneration plants, supplied to natural gas networks or used as fuel in transport vehicles. Based on LCA studies, it has been shown that biogas can have positive environmental impacts, including volatile GHG emissions, eutrophication, acidification, and the generation of photochemical oxidants (Evans et al., 2023).

Anaerobic digestion of solid or pasty by-products is aimed at meeting waste management legal restrictions, e.g. due to the biological stabilization of organic waste or the generation of a nearly inert waste fraction for further use or disposal. If necessary, the anaerobic digestion process can also include a material sanitation process (Pesta et al., 2025).

The digestion of solid or pasty by-products from the food and beverage industry takes place on-site or in external co-digestion facilities not directly located on-site. By-products with a high total solids content (e.g. cellulose, spent grains) have a smaller volume and usually a higher biogas potential, making their transportation to another location relatively economically justified. Biomethane generated from slaughter by-products is encouraged to be employed for generating electricity and

heat, which can be utilised in the meat processing plant to enhance the environmental sustainability of the meat industry.

A study of the energy efficiency of anaerobic digestion of a mixture of fish processing waste and animal manure at ratio 1:5 (Venslauskas et al., 2021) found that all technological processes (transportation, raw material preparation and processing, digestate utilization) required 2548 MJ/t, and the energy obtained reached 9992 MJ/t.

Largest slaughterhouse in Austria process about 10000 t of slaughterhouse waste a year (Wöss et al., 2019) and produce 3.6 million kWh electricity and 3.6 million kWh heat. The company can cover 33% of their electricity demand, 75 % of their heat demand and reduce their CO₂ emissions by 2464 t/year.

The biogas plant on the sugar factory in Hungary is able to provide around 80% of the primary energy demand of the sugar factory with the biogas produced on-site during the sugar beet campaign and reduce their CO₂ emissions by 34540 t/year (Pesta et al., 2025).

Scope 1 emissions savings (% or another quantifiable metric)	n. a.
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	n. a.
Quality of scope 2 emissions information	Low
Availability barriers	None
TRL level	9
Maintainability issues	Control of certain process key parameters (e.g. C/N, pH, temperature, feed rate, alkalinity) is required
Legislative concerns	Under the Regulation (EU) 2019/1009 and Regulation (EC) No 1069/2009 for animal by-products and derived products not intended for human consumption
Payback time (years)	From 4 to 8 years - dependent on processing industry and size of installations

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12.4 Ancillaries

12.4.1 Building fabric optimisation

A building is enclosed between the internal and exterior environments by the building envelope, which is made up of the walls, windows, and foundation (Cheekatamarla, et al., 2022). Energy utilisation in buildings is heavily influenced by energy losses through building envelopes. Building energy efficiency standards, establish minimal standards for newly constructed and refurbished buildings. Depending on the building applications and regions, different minimum efficiency standards apply. These regulations also demand that buildings be airtight, which goes along with the requirements to reduce energy losses caused by the heat transmission via building envelopes.

Thermal insulation is used to minimise heat through the walls of a building. Due to the larger surface area, walls tend to lose more energy than any other part of the building exterior. Thermal insulation can be added to walls to retrofit existing buildings. The thermal performance of insulation can be defined by its R-value (RSI value in SI units) which is the resistance to heat transfer (larger value more thermal resistance, better insulation) or U-value which is the opposite ($U\text{-value} = 1/R$). According to UK Building regulations (Revised 2022 Part L Target Thermal U-Values), new commercial wall fabric shall have a U-value of no more than 0.26 W/m²K (RSI value of 3.85).

To meet the demands of the upcoming zero energy and zero emission buildings, thicker building envelopes are needed when applying standard thermal insulation materials. In Europe, targeting to an average U-value close to 0.2 W/m²·K is optimal (Johansson, 2020). Using traditional insulation materials this means an insulation thickness of about 20 cm. There is a need to develop high performance thermal insulation because very thick building envelopes are not desirable (Jelle, et al., 2012).

The following is a discussion of several high-performance thermal insulation materials, dynamic insulation materials, novel building envelope designs to redirect thermal energy, and high thermal mass building envelopes.

a) Vacuum insulation panels

Typically, vacuum insulation panels (VIPs) are made of a laminated metalised polymer laminate film covering an open porous core of fumed silica or fibrous material. Non-aged centre-of-panel thermal conductivity value for a VIP can be as low as 2 to 4 mW/(m·K) depending on the core material (Adl-Zarrabi, 2020). Commercially available products (Kingspan OPTIM-R) quote an aged design value thermal conductivity of 0.007 W/m·K.

According to Simões (2021) to achieve a U-value (takes into account thermal bridging) of $0.24 \text{ W/m}^2\text{K}$ would require an encapsulated VIP of thickness 40 mm and to achieve a U value of $0.12 \text{ W/m}^2\text{K}$ would require 75 mm. The equivalent thickness of Expanded Polystyrene (EPS) thickness would be 127 and 272 mm respectively. The insulation cost of VIP is 3000 €/m^3 , with an installation cost of 62.5 Euro per m^2 and a service life of 25 years. Compared to 120 €/m^3 , 50 €/m^2 , and 25 years respectively for EPS.

b) Aerogel

Aerogel is a synthetic, porous, extremely light substance. Without the gel's structure significantly collapsing, the liquid component is replaced with gas. This results in a solid with an incredibly low density and thermal conductivity (Berardi, 2019). Aerogels have a large specific surface area, a very low apparent density (Meliță et al., 2019). Thermal conductivities of the aerogel board were reported as $15\text{--}17 \text{ mW/(m}\cdot\text{K)}$ (Adl-Zarrabi, 2020).

Aerogel-based blankets, where aerogel is coupled with a fibrous matrix, have been used in buildings for both internal and external insulation of the walls since the early 2000s (Adl-Zarrabi, 2020). Case studies showed that aerogel blankets are possible to install in up to five layers (50 mm) without too much difficulty.

When used as a retrofit solution 35 mm of aerogel has the same insulating effect as 82 mm of polyurethane. The cost of retrofitting aerogel is 45% higher than the average of other types of insulation (Orsini, 2020).

c) Active and thermally anisotropic insulation

The capabilities of the building envelope can be increased by controllable active insulation systems (AISs), which allow the thermal resistance of the insulation material to be dynamically regulated within a defined range. With AISs, the building envelope may be used to manage heat transfer rather than acting as a passive barrier between indoors and outside. Additionally, AISs can function as thermal batteries that can be loaded and discharged on demand when paired with the thermal mass in the envelope system (Antretter, et al., 2019). Cooling during peak load hours in Los Angeles could be reduced by more than 80% without a negative impact on thermal comfort conditions.

Kisilewicz (2019) present results from a thermal barrier or active thermal insulation system of pipes placed inside the structure of an external building envelope in which a heating and cooling medium circulates, supplied with low temperature energy from the ground. The effective operation of active thermal insulation is possible due to the energy from the building partitions that is stored in the ground. During the summer, thermal energy received from the partitions is stored in the ground, and during the heating season, it is then returned to the interior of the partitions, creating a layer of elevated temperature, or a 'thermal barrier'. In the analysed periods, the reduction of the total amount of heat loss through external walls was from 53% in February to 81% in November.

(Biswas, et al., 2019) carried out numerical simulations of thermally anisotropic building envelope (TABE). These add thin conductive layers between the insulation (shown in Figure 69). The conductive layers are linked to a thermal loop that sends thermal energy (heat or coolness) to a system for energy storage or other applications. The indoor environment is then heated or cooled using the stored energy. Sensors and controllers are used to maximise energy savings or peak load reductions.

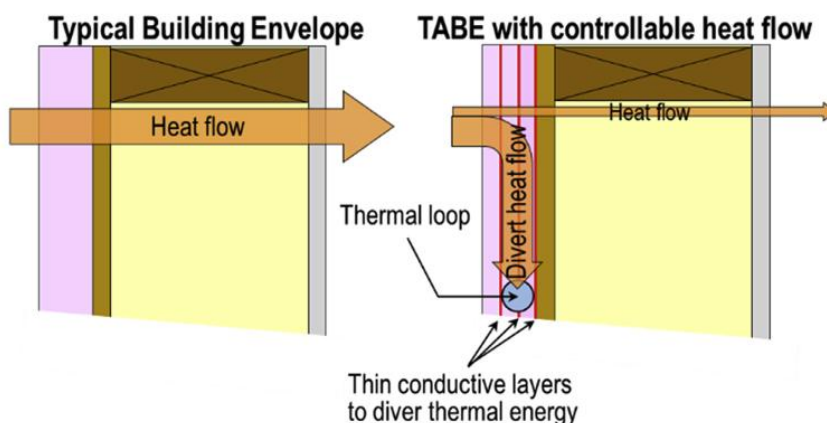


Figure 69. Thermally anisotropic building envelope.

Combined FEA and EnergyPlus simulations of a typical two-story, single-family residential building, predicted annual savings of 19-26% in cooling energy use and 13-26% in heating energy use under Phoenix and Baltimore weather conditions.

e) Phase change materials

Phase change materials (PCMs) can be integrated into building envelopes. PCMs react to temperature changes by passively charging and discharging. They can move peak cooling or heating to off-peak hours depending on the PCM formulation, but they cannot regulate the timing of charging or discharging (Harris, C., 2019).

Konstantinidou (2019) carried out life cycle cost implications of integrated phase change materials in office buildings. They found that the energy saving achieved (18%) during the use stage cannot compensate the high cost of construction (80% higher). Based on the results, a price reduction of 30% in PCM would be required to bring their use up to parity with conventional materials.

Scope 1 emissions savings (% or another quantifiable metric)	No information available
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	A reduction in U value from 0.25 (similar to current maximum value allowed) to 0.125 W/(m² K) would deliver a saving of 3% in the energy demand. If thickness of insulation was the limiting factor, then advanced building insulation would save emissions. However, it is more likely that the buildings are constructed to building codes and minimal cost. In which case advanced insulation is more expensive for equivalent insulation effectiveness
Quality of scope 2 emissions information	High
TRL level	7-9 for increasing U-value by conventional means
Maintainability issues	No issue
Legislative concerns	No concern
Payback time (years)	Payback is generally negative

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12.4.2 Building lighting efficiency

Improving energy-efficiency in buildings has been major focus area for retailers over time, as one of the cheapest ways of reducing both costs and carbon emissions (European Parliament, 2010).

The efficacy of LED products has steadily improved since their introduction as a source for general illumination. This trend is expected to continue, thanks to new materials, better manufacturing processes, and new configurations. However, the variability in LED products is greater than for the more mature technologies and the products are changing rapidly. Importantly, efficacy should not be the only factor when comparing products. Other performance characteristics, such as colour quality, luminous intensity distribution, and dimmability must be included in a holistic decision.

LEDs are the most efficient lighting option (bar natural light) with a typical luminous efficacy up to 150.5 lm/W, compared to metal halide (99.2 lm/W), fluorescent T-5 (81.6 lm/W) and halogen (25.6 lm/W) (DIAL, 2025a). In the future, it may be possible to achieve system luminous efficacy in the range of 200 to 250 lm/W (DIAL, 2025b).

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	LED lighting systems saving energy by 45% compared to fluorescent T-5 lighting.
Quality of scope 2 emissions information	Good.
TRL level	8-9
Maintainability issues	LEDs have long life compared to fluorescent.
Legislative concerns	Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings
Payback time (years)	Variable.

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