FOOD PROCESSING ROADMAP

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The **Zero Emission Cold-Chain (ZECC)** project brings together experts from across several UK Universities to build a series of roadmaps to reach the UK's 2050 net-zero carbon emissions target for the cold chain. This four-year project challenged decarbonisation issues by exploring the techno-economic and behavioural aspects of the cold-chain system and the integration of sectors.

Much of UK's food is dependent on the cold food chain, which is also a significant contributor to the country's energy demand. This project is about thinking thermally and analysing engineering, energy resources, food quality and safety, finance and business aspects to crack the conundrum of sustainable decarbonisation of cooling and the cold chain.

ZECC brings together world-leading researchers, industry, technology innovators and customers such as farmers and retailers to look at the whole system and map the opportunities and challenges to ensure that the chain can support UK-wide Net Zero goals and decarbonise while also meeting demand and being resilient.

Project partners took a whole systems approach toward a sustainable cold-chain by exploring the reduction of cooling within food cold-chain, investigating sustainable technologies and the optimisation of cooling equipment and operations as well as integrating cooling demands into a single efficient system. The approach aligns with the Sustainable Development Goals of the United Nations (12.3).

The ZECC project roadmaps aim to:

- Reduce carbon emissions and reach the UK's 2050 net-zero target
- Provide information on energy usage and the future of cooling energy consumption demands, taking a systems approach to demands and their impact on the UK
- Reduce costs as well as identifying economic opportunities for the food cold chain

This roadmap in particular focuses on the UK food processing sector.

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Acknowledgements

The ZECC project was led by the University of Birmingham, with London South Bank University, Heriot-Watt University, and Cranfield University as partners in the consortium. The project acknowledges support from the Engineering and Physical Sciences Research Council (EPSRC) under research grant EP/V042548/1.
ZECC also acknowledges the ENOUGH project (EU Horizon 2020 grant agreement No. 101036588) for supporting the Roadmap.

ZECC Food Processing Roadmap

http://epapers.bham.ac.uk//id/eprint/4457/

10.25500/epapers.bham.00004457

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Nomenclature

AD	Anaerobic Digestion
AHDB	Agriculture and Horticulture Development Board
AI	Artificial Intelligence
AIS	Active insulation system
AMF	Alternating magnetic field
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BAT	Best available technology
BBC	British Broadcast Corporation
$CaCl_2$	Calcium chloride
CAGR	Compound annual growth rate
CAS	Cell alive system
CCA	Climate Change Agreements
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
DEFRA	Department for Environment, Food & Rural Affairs
DfT	Department for Transport
DM	Dry matter
DSR	Demand side response
DESNZ	Department for Energy Security and Net Zero
DUKES	Digest of UK Energy Statistics

DX	Direct expansion
ECA	European Chemicals Agency
ECL	European Climate Law
EF	Electrostatic field
EFSA	European Food Safety Authority
ENOUGH	Horizon project 'European Food Chain Supply to Reduce Greenhouse Gas Emissions by 2050'
EPBT	Energy payback time
EPS	Expanded Polystyrene
EPSRC	Engineering and Physical Sciences Research Council
ESOS	Energy Savings Opportunity Scheme
ETS	Emissions Trading System
EU	European Union
EUROSAT	Statistical office of the 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
IIR	International Institute of Refrigeration
INP	Ice nucleation proteins
ImechE	Institution of Mechanical Engineers
IoT	Internet of Things
IQF	Individual quick freezers
IR	Infrared
IRENA	International Renewable Energy Agency
ISO	International Standards Organisation
JSRAE	Japanese Society for Refrigeration and Air Conditioning Engineering
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
PFAS	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
QA	Quality Assurance
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
UNEP	United Nations Environment Programme
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
WHR	Waste heat recovery
WNA	World Nuclear Association
WRAP	Waste and Resources Action Programme
ZECC	Zero Emission Cold-Chain

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.

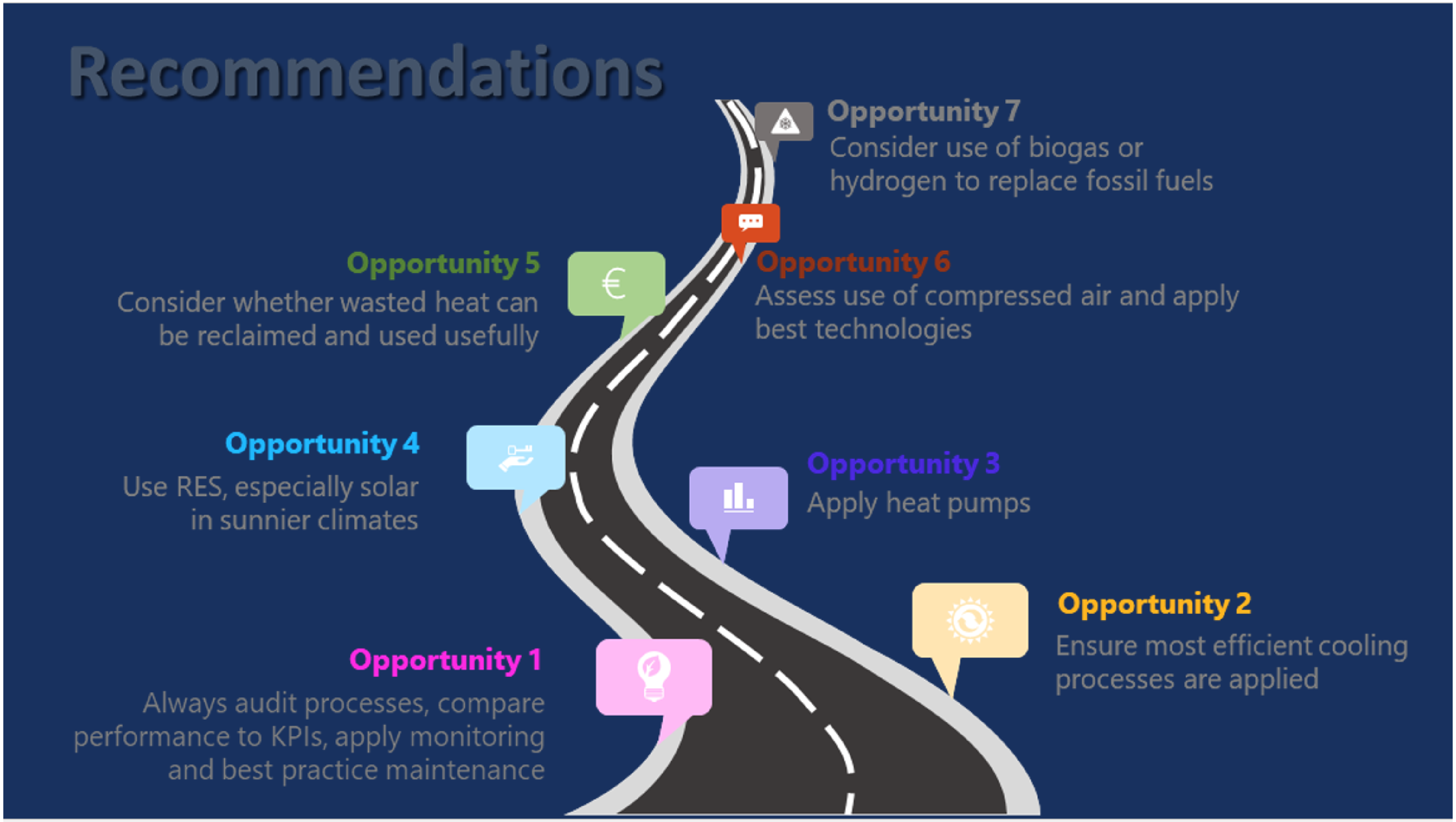
The potential to reduce emissions in the meat, fish, dairy and further processing food sectors are assessed through identifying the best technologies/strategies and modelling the impact on typical processing operations for the meat sector. The most appropriate technologies/strategies with the most potential 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 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. 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 sourced from low-carbon production.
6. Use of solar photovoltaic (PV) to provide low carbon electricity (potentially integrated with energy storage).

In all cases it is recommended to compare process performance to key KPIs and metrics. 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
Opportunity 7
Consider use of biogas or hydrogen to replace fossil fuels
Opportunity 6
Assess use of compressed air and apply best technologies
Opportunity 5
Consider whether wasted heat can be reclaimed and used usefully
Opportunity 4
Use RES, especially solar in sunnier climates
Opportunity 3
Apply heat pumps
Opportunity 2
Ensure most efficient cooling processes are applied
Opportunity 1
Always audit processes, compare performance to KPIs, apply monitoring and best practice maintenance

About this road map

Globally, GHG emissions from the food chain are estimated to account for 33% of the total GHG emissions [1]. Emissions from the food chain can emanate from direct or indirect sources and emissions related to post farm gate (post-harvest/slaughter) are thought to account for around 20% of total emissions [2].

This road map focuses on the UK food processing sector. Almost all food undergoes some form of primary processing to cool or heat 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 food processing sector is feasible.

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

- **Meat processing**

This sector covers large slaughterhouses and companies who further process meat products. Many of these are owned by international conglomerates and there are also a large number of small to medium sized enterprises (SME) 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. 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. While these traditional products represent lower volumes, they are high-value commodities in international trade.

- **Dairy processing – milk and cheese**

The UK 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

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[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.

[2] ENOUGH Project, 2025. *Food production, processing and packaging road map*. Available at: https://enough-emissions.eu/wp-content/uploads/2025/08/Food-production-processing-packaging-road-map.pdf

a growing range of value-added products. In this roadmap we focus on pasteurised drinking milk as well as secondary processing into cheese such as the iconic Cheddar.

- **Secondary processing to produce composite products**

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.

1 Introduction

1.1 The market

1.1.1 Meat processing

The 2024 UK market for meat products is dominated by poultry (44%), pork (23%) and beef (22%) meats according to Food and Agriculture Organisation Corporate Statistical Database (FAOSTAT [3]) (

Figure 1).

Almost 68% of meat products consumed are produced within the UK. Approximately 16% (by mass) of meat is imported into and 16% exported out of the UK (Figure 2).

[3] Food and Agriculture Organization of the United Nations (FAO) 2026, *FAOSTAT: Food Balance Sheets*, FAO, Rome, https://www.fao.org/faostat/en/#data/FBS.

Figure 1. Net mass of meat products in the UK markets in 2024 (from FAOSTAT).

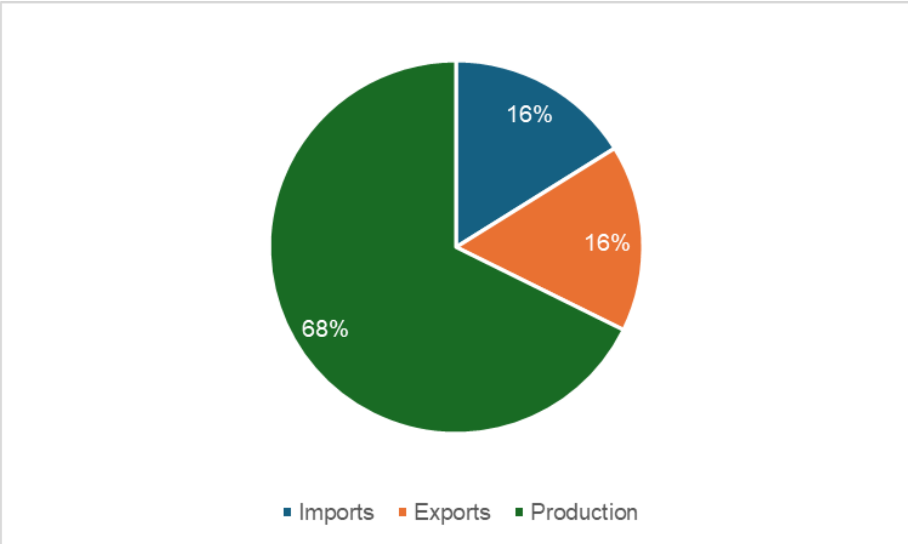


Figure 2. Percentage of exports, imports and home production for meat products in the UK market in 2024 (from FAOSTAT).

Figure 3 presents the mass of meat available per capita per year in the UK [4]. The per capita mass of poultry available for consumption has increased since 2010, whereas at the same time the per capita mass of pork has decreased. Overall, the total mass of meat available for consumption per capita increased between the 2010 and 2023. In 2023 poultry and pork were

[4] 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].

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.

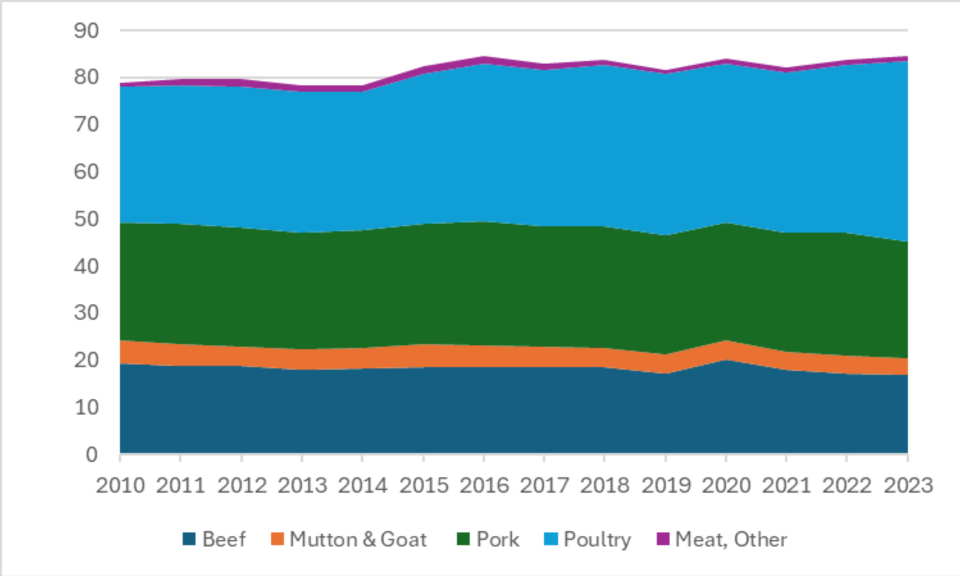
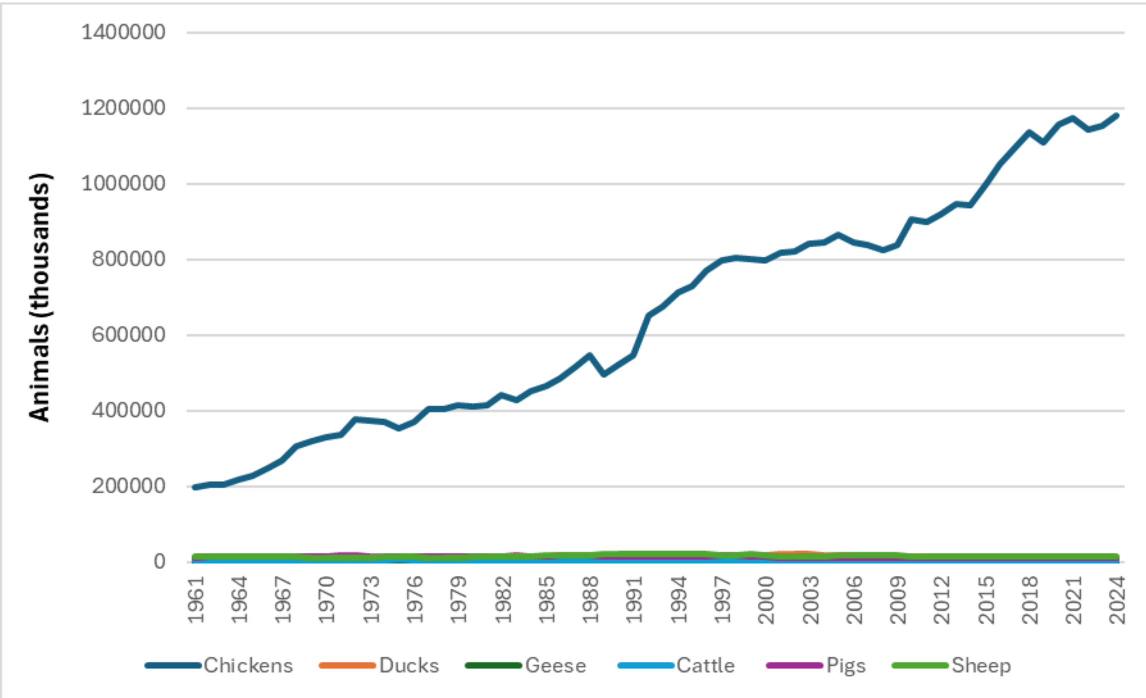


Figure 3. Meat available for consumption per capita in the UK (from FAOSTAT).

In terms of total number of animals slaughtered for meat production in the UK (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) [5].



[5] 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].

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

1.1.2 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% [6].

The UK is an important participant in the global seafood trade and processing industry. The sector handles substantial volumes of both domestically caught and imported fish and shellfish. However, the UK is a net importer of seafood, reflecting the mismatch between domestic production and consumer demand. According to the UK Sea Fisheries Statistics report published by the Department for Environment, Food and Rural Affairs (DEFRA), the UK imported approximately 647 thousand tonnes of fish and seafood products in 2022, valued at around £3.7 billion, while exports totalled 330 thousand tonnes valued at £1.7 billion [7]. This resulted in a trade deficit of roughly 316 thousand tonnes, illustrating the country's reliance on international seafood supply chains.

In 2022 the UK fishing fleet landed approximately 618,759 tonnes of fish and shellfish, with a value exceeding £1 billion [8]. In addition to wild capture fisheries, aquaculture, particularly Atlantic salmon farming in Scotland (£1.25 billion in value and 185,883 tonnes in 2024) plays a significant role in national seafood production and exports.

Figure 3 presents the mass of fish available for consumption per capita per year in the UK [6]. These categories include freshwater fish (such as salmon and trout); demersal fish (bottom-dwelling species such as cod, haddock, and plaice); pelagic fish (open-water species such as mackerel, herring, and sardines); other marine fish; and seafood such as crustaceans (e.g. crab, lobster, and prawns), cephalopods (e.g. squid and octopus), and other molluscs (e.g. mussels, oysters, and scallops). Overall, the total mass of fish available for consumption per capita decreased between the 2010 and 2023. In 2023 demersal fish represents 43% of the total fish consumption.

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[6] FAO (2024) *The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*. Rome: Food and Agriculture Organization of the United Nations.

[7] Defra, 2023. *UK Sea Fisheries Annual Statistics Report 2022*. London: Department for Environment, Food and Rural Affairs. Available at: https://www.gov.uk/government/statistics/uk-sea-fisheries-annual-statistics-report-2022

[8] Seafish (2023) *Seafood in Numbers 2022: Landings*. Edinburgh: Seafish. Available at: Seafish Seafood in Numbers 2022 – Landings

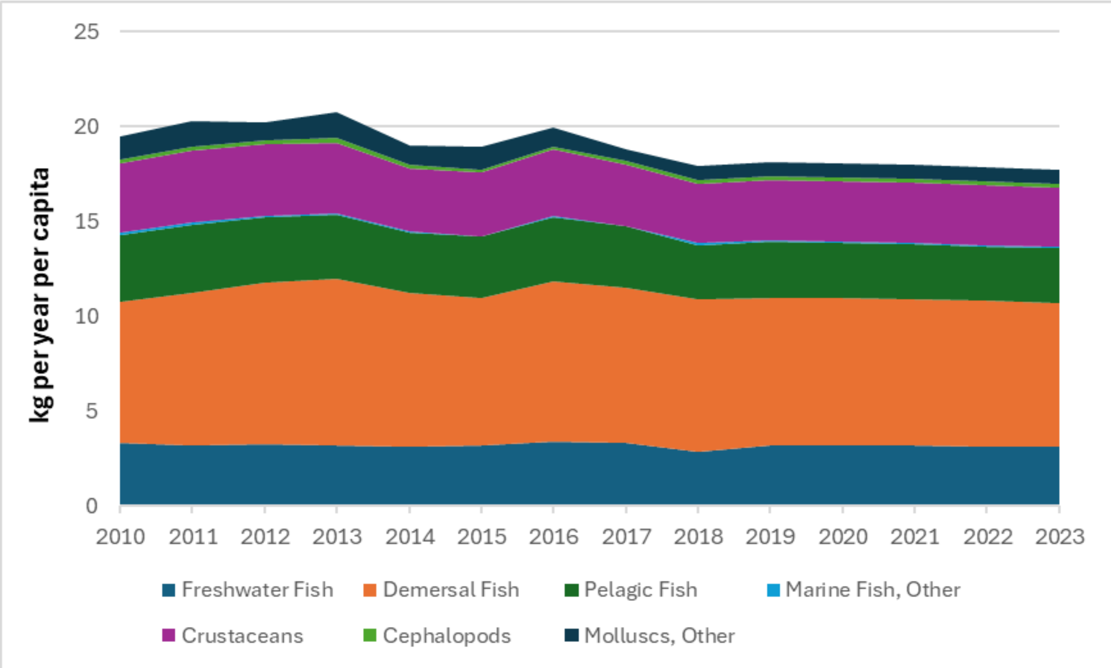

Figure 5: Fish available for consumption per capita in the UK (from FAOSTAT).

Household expenditure data in the UK indicates a clear preference for fresh or chilled fishery products (around 60–63% of seafood spending), compared to frozen products (around 23–25%), with the remainder (around 14%) accounted for by ambient products such as canned, smoked, and preserved seafood [9].

The fish processing industry in the UK is closely integrated with wider European and global supply chains, with many products undergoing multiple stages of handling before reaching consumers. For example, cod caught in the North Atlantic, often by vessels operating in Norwegian or Icelandic waters, is frequently exported to countries such as Poland or China for filleting and portioning, before being re-imported into the UK as consumer-ready products. This reflects a combination of economic factors and supply chain specialisation. While the UK remains an important hub for seafood consumption and some processing, particularly in ports such as Grimsby and Peterhead, labour-intensive processing activities have increasingly shifted overseas to locations with lower labour costs. Despite ongoing automation, many stages, such as filleting, trimming, and preparation, still require manual precision, making labour costs a key driver in how seafood processing is distributed internationally.

1.1.3 Dairy processing to produce milk and cheese

The UK has a well-developed dairy sector, producing around 15 – 16 billion litres of milk annually, from approximately 7,000 dairy producers in Great Britain [10,11]. While smaller than

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[9] Seafish, 2025. *Seafood retail data and market insights*. Available at: <Seafood retail data and insight> (Accessed: 20 April 2026).

[10] AHDB, 2025b. *GB producer numbers*. Available at: https://ahdb.org.uk/dairy/GB-producer-numbers

[11] CLAL, 2026. *United Kingdom: Dairy sector*. Available at: https://www.clal.it/en/?section=quadro_uk

leading EU producers such as Germany and France, the UK plays a distinctive role within the European dairy system, particularly due to its strong domestic market for liquid milk.

Despite structural similarities with the wider European dairy industry, including the dominance of cow's milk in total production, the UK differs in its stronger emphasis on fresh dairy products and its reliance on trade to balance supply and demand. As in the wider European context, production levels have remained relatively stable in recent years (although currently experiencing a period of high growth and record-breaking volumes in 2025/26), with monthly processing volumes typically exceeding 1.1 billion litres of milk [12].

The UK dairy processing sector is relatively concentrated, with around 70% of milk intake processed by a small number of large companies [13]. Milk collected by dairies in the UK is processed into a wide range of fresh and manufactured dairy products, including liquid drinking milk, cheese, butter, cream and milk powders. Historically, a significant proportion of UK milk has been used for liquid consumption, reflecting strong domestic demand for fresh milk.

Recent data indicates that this pattern largely continues, although there has been a gradual structural shift in how milk is utilised. According to the Agriculture and Horticulture Development Board (AHDB), approximately 44% of UK milk is used for liquid consumption, while around 33% is processed into cheese, with the remainder used for products such as cream, butter and milk powders [14] (see Figure 6).

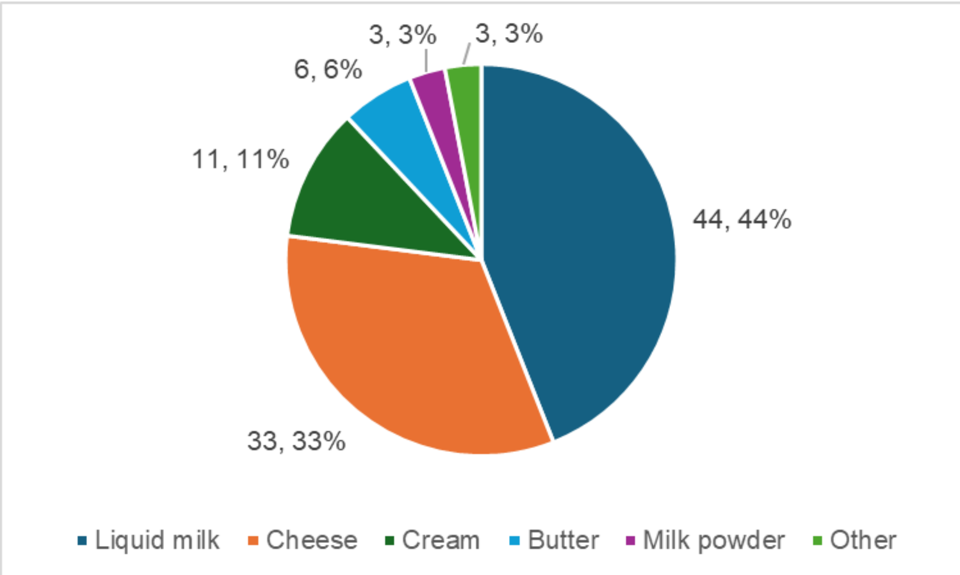

Figure 6: Utilisation of whole milk in the UK

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[12] Defra, 2025b. *Milk utilisation by dairies in the United Kingdom*. Available at: https://www.gov.uk/government/statistics/milk-utilisation-by-dairies-in-england-and-wales

[13] AHDB, 2019. *UK processors data*. Available at: https://ahdb.org.uk/dairy/uk-processors-data

[14] Agriculture and Horticulture Development Board (AHDB), 2025a. *Dairy market summary 2024/25*. Available at: https://ahdb.org.uk

Data from the Department for Environment, Food & Rural Affairs (Defra) confirms that cheese remains the largest manufactured dairy product in the UK, while liquid milk continues to represent the single largest end use overall [15]. However, long-term trends show that the share of milk used for liquid consumption has gradually declined from around 46% in 2015 to approximately 42 – 44% in recent years, reflecting changing consumer preferences and increased demand for higher-value dairy products [16].

At the same time, there has been a growing strategic emphasis on cheese production. Cheese offers higher returns compared to bulk commodities such as milk powder and is supported by both domestic consumption and export opportunities. In contrast, production of butter and milk powders in the UK remains relatively smaller in scale compared to major EU producers, where these products historically accounted for a larger share of processed milk.

The industry is shifting toward higher-value products, particularly cheese, while maintaining a strong liquid milk market. This shift reflects declining liquid milk demand, narrowing profit margins and emerging health-focused consumer trends

1.1.4 Secondary processing to produce composite products

Prepared and semi-prepared products, such as pre-marinated meats and pre-cut vegetables, are becoming increasingly popular in the UK due to their convenience. The semi-finished food market is experiencing steady growth, driven by changing consumer lifestyles, including busier working patterns and demand for quick meal solutions, alongside technological advancements in food processing. These products appeal to both households and food service providers by offering time savings, consistency in taste, and ease of preparation [17, 18].

In the UK, the secondary processing of meat, fish, and dairy products encompasses a broad range of activities, including the production of ready meals, prepared foods, and semi-prepared ingredients for retail and catering sectors. The UK food and drink manufacturing sector is the largest manufacturing sector in the country, with a turnover exceeding £140 billion, of which processed meat products form a significant share (20 to 25%) [19]. The meat processing industry remains substantial, although it faces pressures from rising input costs, labour shortages, and shifting consumer preferences towards healthier and more sustainable diets.

The UK fish processing industry is also an important contributor, particularly in regions such as Grimsby, which is a major seafood processing hub. The sector supports thousands of jobs

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[15] Department for Environment, Food & Rural Affairs (Defra), 2026. *Milk utilisation by dairies in England and Wales*. Available at: https://www.gov.uk

[16] Agriculture and Horticulture Development Board (AHDB), 2024b. *How is milk utilisation trending in the UK?* Available at: https://ahdb.org.uk

[17] Agriculture and Horticulture Development Board (AHDB), 2024a. *Consumer insight and market trends in UK meat and dairy*. Available at: https://ahdb.org.uk

[18] Food and Drink Federation, 2025. *UK Food and Drink Industry Report*. Available at: https://www.fdf.org.uk

[19] Department for Environment, Food & Rural Affairs (Defra) (2026) *Food statistics in your pocket*.

and continues to grow, driven by demand for convenient seafood products such as breaded and ready-to-cook fish. Growth is supported by innovation in freezing, packaging, and cold chain logistics [20]. However, the industry faces challenges related to supply chain disruptions, trade changes following Brexit, and sustainability concerns around fish stocks.

The dairy processing sector in the UK is equally significant. The overall UK dairy market continues to grow steadily, supported by demand for cheese, yoghurt, and convenience dairy products. Cheese in particular has seen strong growth as a higher-value product, while liquid milk consumption has gradually declined [16]. In addition, retail trends show that convenience stores and online grocery platforms are increasingly important distribution channels, reflecting wider changes in consumer purchasing behaviour [21].

Sustainability and responsible sourcing are becoming central to the UK secondary processing industry. Government policy, including the UK's net-zero commitments, alongside pressure from non-governmental organisations, is encouraging producers to reduce GHG emissions, minimise waste, and improve energy efficiency. Industry bodies highlight the importance of sustainable sourcing of raw materials, particularly in meat and dairy supply chains [23,22].

The growth of secondary processing in the UK has several important implications. Firstly, increasing demand for convenience foods is driving innovation in product development, packaging, and preservation technologies, resulting in a more diverse and higher-quality product range. Secondly, sustainability pressures are accelerating the adoption of environmentally friendly practices, enhancing both environmental performance and brand reputation.

Finally, the continued shift towards online retail is transforming how consumers purchase processed foods. Online grocery sales have grown significantly in the UK, particularly since the COVID-19 pandemic, and remain a key growth channel. However, the distribution of chilled and processed foods presents logistical challenges, particularly in maintaining cold chain integrity during last-mile delivery. Efficient cold chain systems and advanced logistics planning are therefore critical to ensuring product quality and safety.

1.2 Market drivers

In June 2019, the UK became the first major economy to legislate a legally binding net zero GHG emissions target for 2050. It has also committed to reducing emissions by 68% by 2030 (compared to 1990 levels) under its Nationally Determined Contribution (NDC) to the Paris

[20] Seafish, 2024a. *UK Seafood Industry Overview*. Available at: https://www.seafish.org

[21] Department for Environment, Food & Rural Affairs (Defra), 2026. *Food statistics and retail trends*. Available at: https://www.gov.uk

[22] Department for Environment, Food & Rural Affairs (Defra), 2023a. *Environmental improvement plan*. Available at: https://www.gov.uk

Agreement, and by 78% by 2035 in line with the Climate Change Committee's Sixth Carbon Budget [23].

To achieve these targets, the UK Government has introduced a range of cross-sector policies, including:

- **Net Zero Strategy (Build Back Greener)** – outlining actions across energy, transport, buildings and industry to deliver emissions reductions [24].
- **British Energy Security Strategy (2022)** and **Powering Up Britain (2023)** – accelerating renewable and nuclear deployment, including a target of 50 GW of offshore wind by 2030, alongside investment in solar, hydrogen and carbon capture technologies [25,26].
- **Transport Decarbonisation Plan (2021)** – phasing out the sale of new petrol and diesel cars and vans by 2035 and expanding electric vehicle infrastructure [27].
- **Clean Maritime Plan** – reducing greenhouse gas emissions from shipping and promoting low-carbon fuels at UK ports [28].
- **Jet Zero Strategy (2022)** – increasing the use of Sustainable Aviation Fuels (SAFs) and supporting zero-emission flight technologies [29].
- **Environmental Land Management (ELM) scheme** – incentivising landowners to enhance carbon sequestration, biodiversity and sustainable land use [30].

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[23] Climate Change Committee, 2021. *The Sixth Carbon Budget: The UK's Path to Net Zero.* London: CCC. Available at: https://www.theccc.org.uk/publication/sixth-carbon-budget/

[24] Department for Energy Security and Net Zero & Department for Business, Energy & Industrial Strategy, 2021. *Net Zero Strategy: Build Back Greener*. GOV.UK, published 19 October, updated 5 April 2022. Available at: https://www.gov.uk/government/publications/net-zero-strategy

[25] Department for Energy Security and Net Zero; Prime Minister's Office; Department for Business, Energy & Industrial Strategy, 2022. *British energy security strategy*. GOV.UK, published 7 April. Available at: https://www.gov.uk/government/publications/british-energy-security-strategy

[26] Department for Energy Security and Net Zero, 2023c. *Powering Up Britain.* London: DESNZ. Available at: https://www.gov.uk/government/publications/powering-up-britain

[27] DfT (Department for Transport), 2021. *Transport Decarbonisation Plan.* London. Available at: https://www.gov.uk/government/publications/transport-decarbonisation-plan

[28] DfT, 2019. *Clean Maritime Plan.* London. Available at: https://assets.publishing.service.gov.uk/media/5d24a96fe5274a2f9d175693/clean-maritime-plan.pdf

[29] DfT, 2022. *Jet Zero Strategy: Delivering Net Zero Aviation by 2050.* London. Available at: https://www.gov.uk/government/publications/jet-zero-strategy-delivering-net-zero-aviation-by-2050

[30] Department for Environment, Food and Rural Affairs (DEFRA), 2023. *Environmental Land Management schemes: overview*. London: DEFRA. Available at: https://consult.defra.gov.uk/elm/elmpolicyconsultation/supporting_documents/ELM%20Policy%20Discussion%20Document%20230620.pdf

- **England Trees Action Plan (2021–2024)** – supporting the planting of at least 30,000 hectares of new trees annually by 2025 to contribute to carbon removal and nature recovery [31].

The whole UK food system generated approximately 145 $MtCO_2e$ in 2023, representing around 38% of total UK greenhouse gas (GHG) emissions (385 $MtCO_2e$) [32]. This estimate includes emissions across the entire supply chain, including agriculture, fertiliser production, food manufacturing, imports, transport, retail, hospitality, household consumption, and waste disposal, and therefore extends beyond the food cold chain alone [33].

2 Current trends

2.1 Energy costs

Food processing facilities consume considerable amounts of energy. **Error! Reference source not found.** presents the final energy consumption in 2018 per industrial sector at in the UK [34]. The only sector to use more energy than the food and drink sector was the chemical sector. More recent data from ECUK, 2023, show this was still the case in 2020 [35]. The food and drink sectors stands out from the other sectors, in that most of its energy, are from low temperature processes and this sector is one of the highest users of energy (see Figure 8). As food and drink do not use high temperature processes, as chemical, mineral and metals do, this should lend to easier decarbonisation by electrification.

[31] DEFRA, 2021. *England Trees Action Plan 2021 to 2024.* London: DEFRA. Available at: https://www.gov.uk/government/publications/england-trees-action-plan-2021-to-2024

[32] Department for Energy Security and Net Zero (DESNZ), 2024a. *UK greenhouse gas emissions: 2023 final figures*. Available at: UK greenhouse gas emissions: 2023 final figures

[33] WRAP, 2026. *UK Food System Greenhouse Gas Emissions Update: Technical Report 2025*. Available at: https://www.wrap.ngo/sites/default/files/2026-01/WRAP-2026-01-GHG-Emissions-Update-Technical-Report-2025.pdf

[34] Griffin et al, 2018. Griffin, P.W., Hammond, G.P. and Norman, J.B., 2018. Industrial decarbonisation of the pulp and paper sector: A UK perspective. *Applied Thermal Engineering*, *134*, pp.152-162.

[35] ECUK, 2023. Final energy consumption in industry - detailed statistics. ECUK_2023_Consumption_tables.xlsx.

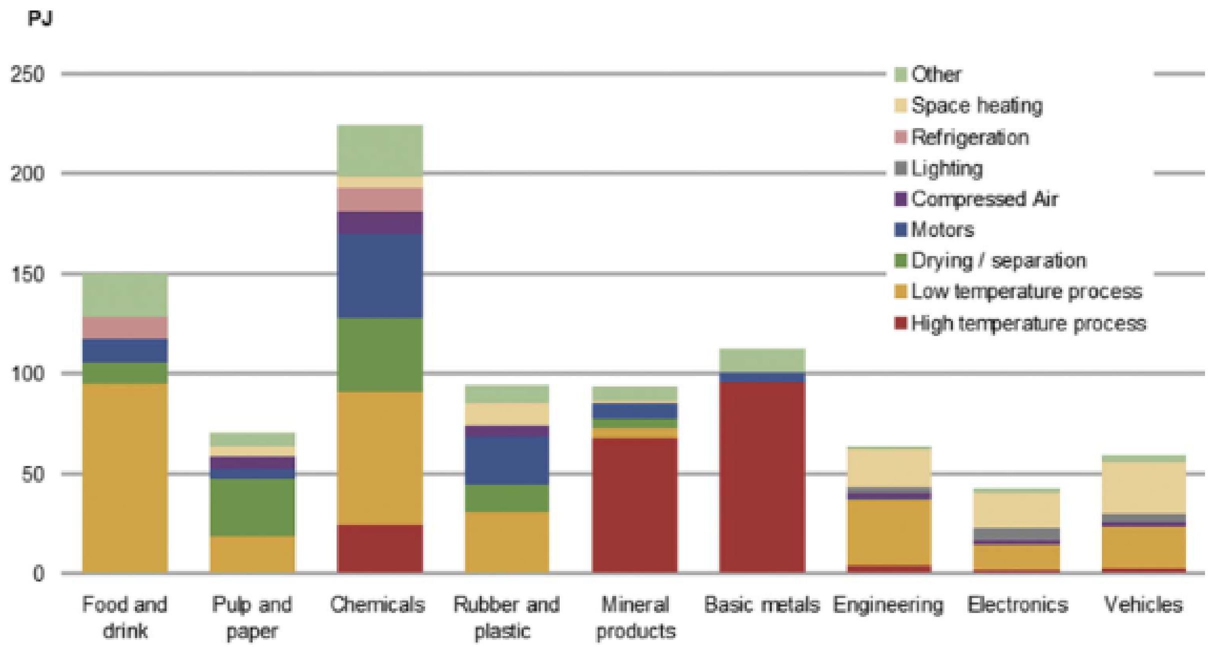

Figure 7: Industrial consumption by sub-sector, Griffin et al, 2018.

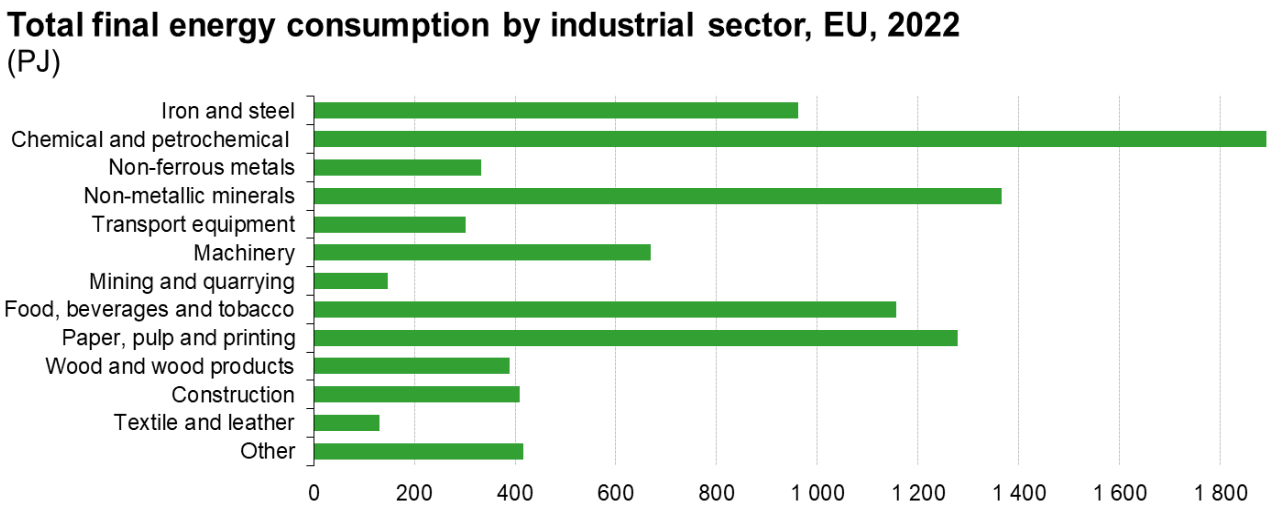

Figure 8: Total final energy consumption by industrial sector, EU, 2022

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 [36]. In the UK, these effects were amplified by reliance on natural gas for

[36] International Energy Agency (IEA) (no date) *Global energy crisis*. Available at: https://www.iea.org/topics/global-energy-crisis?language=en

industrial energy, leading to significant increases in energy costs for food manufacturers and other energy-intensive industries.

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. In the UK context, this has accelerated investment in energy efficiency, electrification, and low-carbon technologies within the food processing sector, although uncertainty in long-term energy prices remains a key challenge.

2.1.1 Electricity

The development of the electricity prices for non-household consumers within the European Union and in the UK is shown in Figure 9 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. This increase was more pronounced in the UK, largely due to its higher reliance on natural gas for electricity generation and exposure to wholesale energy price volatility [37]. Since then, prices have dropped, but only to the level they were at the beginning of 2022. Governmental measures were introduced to reduce prices. In the UK, these included the Energy Bill Relief Scheme (EBRS) and the Energy Bills Discount Scheme (EBDS), which provided direct support to non-domestic consumers. In 2022, the share of taxes had reached a minimum[38], however, in the UK context, price changes were driven more by wholesale energy costs and policy interventions than by tax adjustments alone.

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[37] DESNZ, 2024b. *Energy Prices and Trends*. Available at: https://www.gov.uk

[38] Eurostat, 2025. *Electricity price statistics*. Data extracted October 2025. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_non-household_consumers

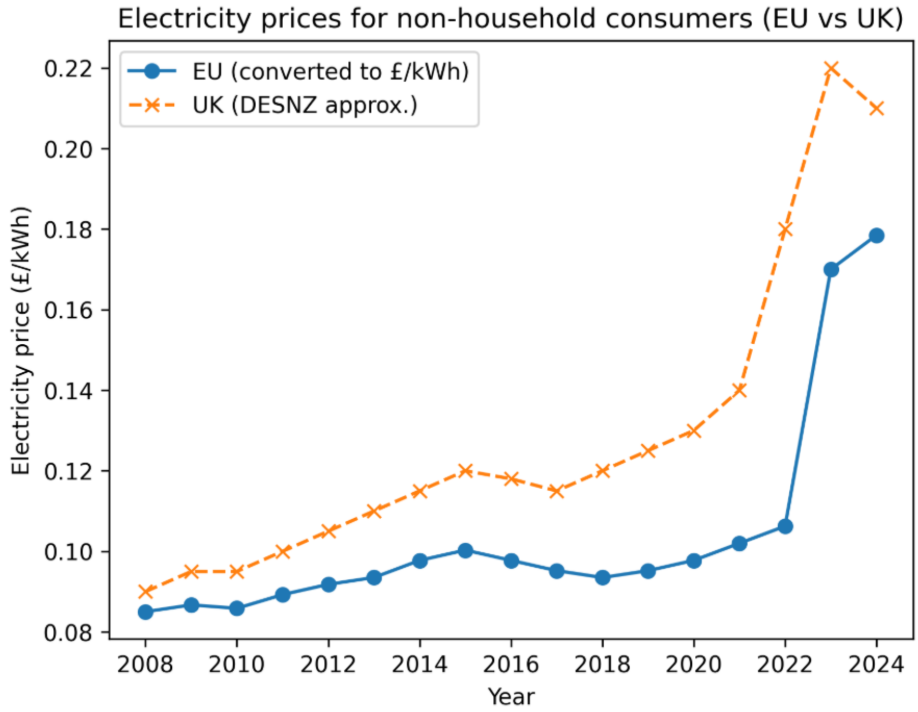

Figure 9: Development of electricity prices for non-household consumers (EU[142] and UK[175]), 2008–2024 (£/kWh). EU values converted from € using €1 = £0.85

2.1.2 Natural gas

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

According to UK decarbonisation analyses, there is significant uncertainty on the role of gas in the long term with unabated emissions from natural gas become increasingly incompatible with the UK's net zero 2050 targets [39]. In the UK, natural gas currently plays a dominant role in industrial heat generation, including in the food and drink sector, which is highly dependent on gas for steam and process heating. However, UK energy scenarios project a substantial reduction in natural gas consumption by 2050, particularly in pathways aligned with deep decarbonisation, driven by electrification, energy efficiency, and fuel switching [39].

Regardless of the overall gas demand evolution, the role of renewable and low-carbon gases is expected to increase in the coming decades. In the UK context, this includes the development of biomethane from anaerobic digestion, hydrogen (particularly green and blue hydrogen), and synthetic fuels as part of national decarbonisation strategies. In this context, several studies have been conducted on the potential development of low-carbon and carbon-neutral gases in the UK and its impact on the energy infrastructure[40] . Despite methodological

[39] Department for Energy Security and Net Zero (DESNZ), 2023b. *UK Net Zero Strategy and energy scenarios*. Available at: https://www.gov.uk

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

differences and diverging study outcomes, a consensus is emerging that low-carbon gases will play a major role in decarbonising the UK economy, supported by existing gas infrastructure and new hydrogen networks.

2.2 Economic pressures

The financial crisis has impacted both operators and customers. Brexit has significantly impacted the UK food industry by introducing long-term trade barriers, labour shortages, and higher operational costs. 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.

2.3 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 international 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 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 (CCA) is a voluntary scheme applied in the UK since the early 2000s. It provides a discount on the climate change levy (CCL) (a tax on energy bills) in return for meeting energy efficiency targets. The scheme has achieved notable reductions, with a reported 17% reduction in emissions during the fourth target period (2019-2020). The scheme has been extended to 2027 and a new 6-year scheme for 2026–2030 has been confirmed, indicating continued government confidence in its effectiveness.

2.4 The labour market

The food industry is reported to have significant challenges in recruitment, retention and upskilling of employees. Potential employees often hold outdated or negative stereotypes that don't match the modern reality of the sector. Improved pay and conditions (e.g. financial "joining bonuses") as well as career and development opportunities (e.g. apprenticeships) are being used to encourage new entrants into the labour market.

The UK food manufacturing industry has been impacted by Brexit, which ended the automatic right to live and work in the UK for EU nationals, who previously made up a massive portion of the workforce, which has led to labour shortages There is also an imbalance in the ratio of men to women in the industry (women make up 28.4 to 36%), particularly in the meat industry (33.5%) [41].

2.5 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. In the UK, temperatures have also risen significantly, with the most recent decade being around 1°C warmer than the 1961–1990 average, reflecting the broader warming trend observed across Europe [42]. 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 [43]. The UK has experienced record-breaking temperatures in recent years, including the first recorded temperature above 40°C in 2022, highlighting the increasing intensity of heat extremes [44].

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[41] Food Standards Agency (2023) *Impact of labour shortages: Labour shortages in UK food systems*.

[42] Met Office, 2024. *UK climate trends*. Available at: https://www.metoffice.gov.uk

[43] European Environment Agency (EEA). 2025. Global and European temperatures. Published 16 June 2025. Available at: https://www.eea.europa.eu/ims/global-and-european-temperatures.

[44] Met Office, 2023. *UK climate extremes and temperature records*. Available at: https://www.metoffice.gov.uk

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 [45]. In the UK, heatwaves are becoming more frequent, longer, and more intense, with projections indicating that extreme heat events could become commonplace by mid-century under current emissions scenarios [46].

Increasing temperatures also bear a challenge to food processors. In some cases, larger refrigeration plants may be better able to cope with warmer ambient conditions because they are often designed with greater redundancy, larger heat-exchange surfaces, and more sophisticated control systems. However, performance ultimately depends on the specific design and operating conditions rather than plant size alone. 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% [47]. The same report also found greater levels of break down in hotter weather increasing maintenance bills. All of this is bad news for food manufacturers 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 2050 [5]. The United Kingdom remains a signatory to the Paris Agreement and has committed to achieving net zero greenhouse gas emissions by 2050 under the Climate Change Act (amended in 2019) [48].

In line with its Nationally Determined Contribution (NDC), the UK has committed to reducing greenhouse gas emissions by at least 68% by 2030 compared to 1990 levels, which is more ambitious than the EU target [49]. Transitioning to renewable energy and implementing energy efficiency measures are important contributions to the reduction of GHG emissions. In the UK, this transition includes significant expansion of offshore wind, electrification of industry, and improvements in energy efficiency across sectors such as food processing and food manufacturing [192].

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[45] United States Environmental Protection Agency (EPA). no date. Climate Change Indicators: Weather & Climate. Available at: https://www.epa.gov/climate-indicators/weather-climate.

[46] Climate Change Committee (CCC), 2023. *UK climate risk assessment*. Available at: https://www.theccc.org.uk

[47] Imperial College London. 2020. Warmer summers risk chilling energy bill. Published 3 July 2020. Available at: https://www.imperial.ac.uk/news/198934/warmer-summers-risk-chilling-energy-bill/.

[48] UK Government, 2019. *The Climate Change Act 2008 (2050 Target Amendment) Order 2019*. Available at: https://www.legislation.gov.uk

[49] Department for Energy Security and Net Zero (DESNZ), 2023b. *UK Net Zero Strategy*. Available at: https://www.gov.uk

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. Hydrofluoroolefins (HFOs) also offer zero ODP and low GWP, however, have other environmental impacts. The topic of natural and HFO refrigerants will be discussed in detail in the following section.

2.6 The move to low GWP refrigerants

The move to low GWP refrigerants has been driven primarily by legislative pressure from F-Gas Regulations, which aim to reduce the GWP of refrigerants used in all refrigeration sectors. Although Great Britain (GB) is no longer part of the EU, it retained and incorporated Regulation 517/2014 into domestic law following Brexit. The UK currently operates its own F-Gas regime, based on the 2014 Regulation but amended through UK legislation, and it does not automatically adopt subsequent EU revisions.

In March 2024, the EU replaced this regulation with Regulation (EU) 2024/573 [50], introducing stricter phase-down schedules and controls. There was initially uncertainty regarding whether GB would align with this updated F-Gas Regulation, the UK Government has since launched a consultation on proposed reforms to the domestic F-Gas regime. As part of any new legislation the UK Government must ensure that the UK is able to achieve the Montreal Protocol (Kigali Amendment) phase down of HFC consumption by 85% by 2036 and also achieve the net zero carbon budget by 2050. The Department for Environment Food and Rural Affairs (DEFRA) are responsible for the proposed changes to the regulation in GB. They are proposing that the current HFC phase down is amended from 1 January 2027 with a move from a target of 79% cut to a target of 98.6% cut by 2048. No changes to the placing on the market prohibitions already applied in Annex III of the GB regulation are proposed.

Additionally, the EU regulation references Per- and Polyfluorinated Substances (PFAS). The regulation 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’. Most HFOs and some HFCs are PFAS and PFAS regulation is currently being considered by the European Chemicals Agency.

[50] European Commission., 2025. *EU legislation to control fluorinated greenhouse gases (F-gases)*. Climate Action – European Commission. Available at: https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/eu-legislation-control-f-gases_en

3 Future issues and trends

3.1 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.

4.2 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 (approximately 3 times less for industrial users) than electricity in the UK. This means that to have parity in operational costs electrical systems must be very efficient. Therefore, an electrically driven heat pump would have to have a Coefficient of Potential (COP) of greater than 3 to compete with a gas system on running costs.

3.2 Availability of new technologies to replace fossil fuels

To decarbonise the UK food industry, there is a need to move away from fossil fuels, which are still widely used for process heating. Most fossil fuels in the food industry are used for heating. Electrically driven heat pumps are a promising technology for increasing system efficiencies and decreasing GHG emissions [51].

The HTHP market is dominated by vapour compression technology, but few equipment of this type is capable of delivering heat at temperature levels (over 90°C) compatible with the needs of the food industry [52]. However, there is a need for systems to provide heat at higher temperatures. The brewing, dairy and sugar industry requires process heat temperature ranges of 60-120, 80-150 and 80-160°C respectively. 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 22). This predicts that heat

[51] Heat Pumping Technologies (HPT). no date. Annex 58: High-Temperature Heat Pumps. Available at: https://heatpumpingtechnologies.org/annex58/.

[52] Ayou, D.S., Corberán, J.M. and Coronas, A. (2021) *High-temperature Heat Pumps for Industrial Applications. 45th Informatory Note on Refrigeration Technologies*. Paris: International Institute of Refrigeration (IIR).

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.

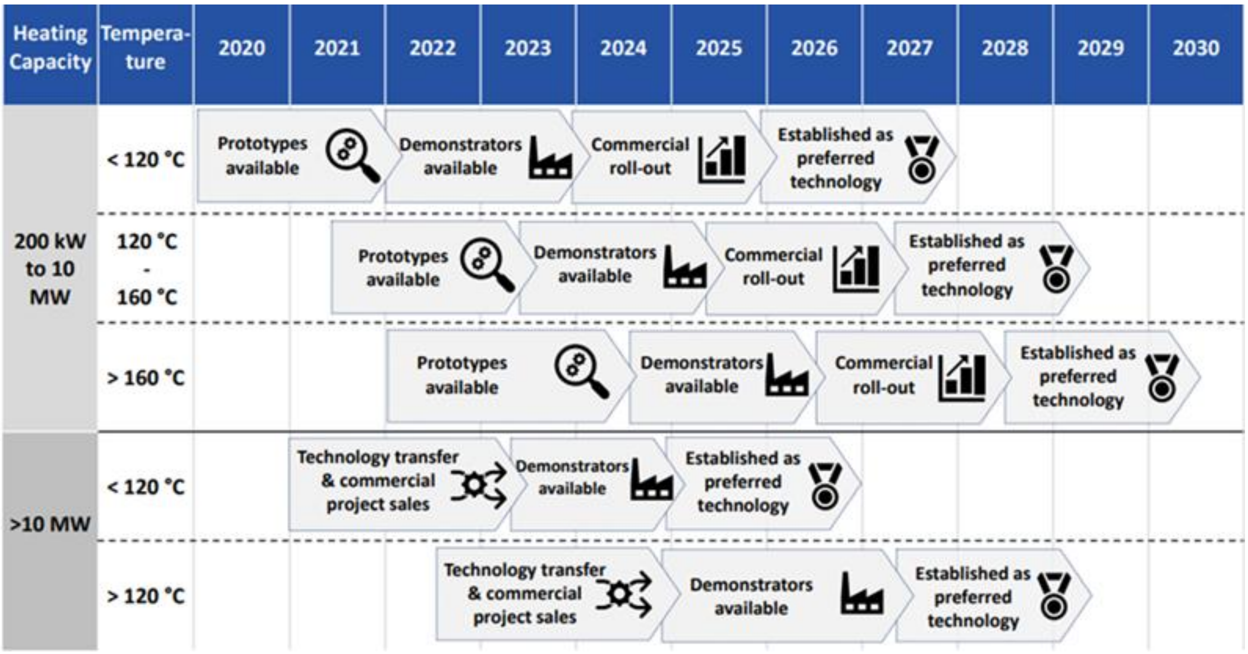

Figure 10: Timescale for development of HTHPs

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 CH_4 (45-75% by volume) and CO_2 and can be used for heating and cooking. This gas can be further refined into biomethane (CH_4 >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.[53] 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

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[53] 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.

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.[54] 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. 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 [55].

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 [56] 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.

The other solution is to develop a new pure hydrogen infrastructure. According to International Renewable Energy Agency (IRENA),[57] 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. Typical costs are £9.50 (based on weighted average strike price) compared to grey hydrogen at just over £2 to per kg in 2026 [58], [59].

The cost will also depend on the electrolysers which split water into hydrogen and oxygen. These must also be scaled up and improved to make green hydrogen cost competitive. According to IRENA,[57] this could bring green hydrogen costs below the 1.44£/kg mark – a crucial milestone for cost competitiveness – before 2030.

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[54] 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.

[55] DESNZ, 2023a. 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.

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

[57] IRENA, 2021). Making the breakthrough: Green hydrogen policies and technology costs, International Renewable Energy Agency, Abu Dhabi.

[58] Burgess, J. (2024) ‘UK offers first green hydrogen production contracts to HAR1 projects’, *S&P Global Commodity Insights*, 12 December.

[59] Quantum Commodity Intelligence (2026) ‘UK, NW Europe hydrogen cost assessments hold firm at start of 2026’, *Quantum Commodity Intelligence*, 7 January.

3.3 Integration (of heating and cooling)

Currently there is limited consideration of thermal integration within some food processing facilities. However, this is an area that installers and operators are beginning to investigate. For example, feasibility 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 the retail sectors where heat is reclaimed from CO_2 refrigeration systems. Integration is not simple in existing outlets that 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 Dearnsdale Fruit in the UK [60]. They installed a heat recovery system 2 years ago that is saving the business £20k 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.

3.4 Automation, robotics and process control

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 and robotics can also contribute to reducing GHG emissions by improving process efficiency and reducing material losses. In addition, process control systems can optimise the use of energy and other resources throughout production. Key benefits include:

- **Reduced waste**

Automated sorting and packaging systems can minimise food waste during processing and packaging. Additionally, automated inventory tracking and production scheduling can help in better inventory management, reducing the amount of food that spoils before reaching consumers.

- **Improved resource and energy efficiency**

Process monitoring and control technologies, such as sensors, data analytics, and process control systems, can optimise production processes, leading to more efficient use of energy.

[60] Cold Chain News. 2023. Heat recovery system saves fruit business £20,000. Published 26 June 2023. Available at: https://www.coldchainnews.com/heat-recovery-system-saves-fruit-business-20000/.

For example, automated control of lighting, refrigeration, ventilation, and process temperatures 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.

- **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.

3.5 Advanced controls

An increasing focus has been on measurement and analysis to assess efficiency and identify where maintenance issues may be beginning to develop. This may require energy sub metering and additional sensors 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.

3.6 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 and carbon emissions are likely to be valued more in the future.

3.7 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 for 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.

3.8 Waste processing

3.8.1 The issues

According to Food Waste Statistics (2024) [61] 16% of food waste comes from food manufactures. Although this is lower than the 70% from households, it is still the second highest above hospitality and food services with 12%. 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 [62].

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 cycles [63]. 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 [64].

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

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[61] Food Waste – 2025 Facts & Statistics. https://www.wastemanaged.co.uk/our-news/food-waste/food-waste-facts-statistics/#:~:text=WRAP%20estimates%20that%2070%25%20of,2%25%20from%20the%20retail%20industry.

[62] 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.

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rich in nutrients such as nitrogen (N), potassium (K) and phosphorus (P). These elements, which are collectively referred to as NPK soil nutrients,[65] are very vital for the growth and reproduction of plants.

3.8.2 The trends

Since March 2025, strict "Simpler Recycling" legislation requires all manufacturers in England with 10 or more employees to separate food waste from general waste. Most factories use the following disposal routes; anaerobic digestion, conversion into animal feed and redistribution of surplus. Landfill and discharge to the sewer system are no longer allowed.

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 [66].

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 22). This figure depicts the vital points concerning policy implications toward advanced food waste recycling [67].

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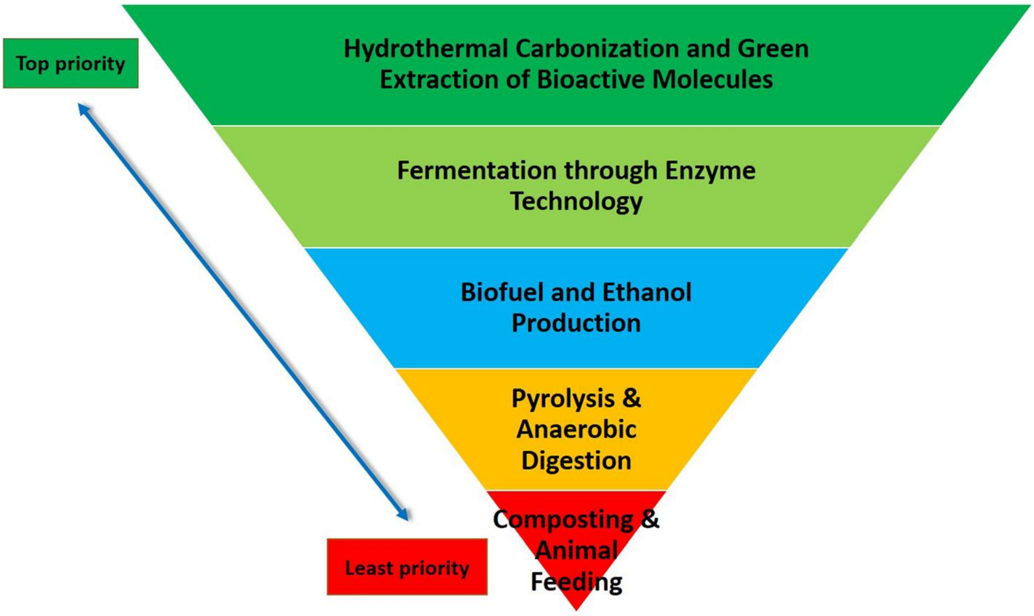

Figure 11: A hypothetical hierarchy pyramid of food waste management and valorisation.

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.

3.9 Circular economy and food loss/waste

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 should 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. 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.

3.10 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 energy [68]. 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 food [69].

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% [70]. 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 healthy [71].

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 choices [72].

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[68] BBC. 2023. *Business article*. Available at: https://www.bbc.co.uk/news/business-65954252.

[69] Food Manufacture. 2022. Consumers making 'extensive' changes to eating habits in face of cost-of-living crisis. Published 23 September 2022. Available at: https://www.foodmanufacture.co.uk/Article/2022/09/23/How-are-consumers-changing-their-eating-habits.

[70] Toluna. 2022. Dietary trends and plant-based perceptions in the UK. Posted 8 June 2022. Available at: https://tolunacorporate.com/dietary-trends-and-plant-based-perceptions-in-the-uk/.

[71] Food Manufacture. 2022. How are consumers' diets changing? Published 30 May 2022. Available at: https://www.foodmanufacture.co.uk/Article/2022/05/30/how-are-consumers-diets-changing.

[72] SIAL America. 2022. The 4 biggest consumer food trends shaping 2022. Available at: https://sialamerica.com/white-papers/the-4-biggest-consumer-food-trends-shaping-2022/.

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.

4 Performance of food processing sectors

4.1 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.

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). Food Drink Europe provide KPIs for a range of food types as MWh/tonne [Error! Bookmark not defined.]. Together with information collated by the ZECC team, this provides a broad range of KPIs across a range of products (Figure 12). Even within one food category, the range in KPIs collected across often a large number of facilities ranges widely, as shown by the error bars. 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 processers use less energy per tonne of food processed, due to economies of scale. Figure 12 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.

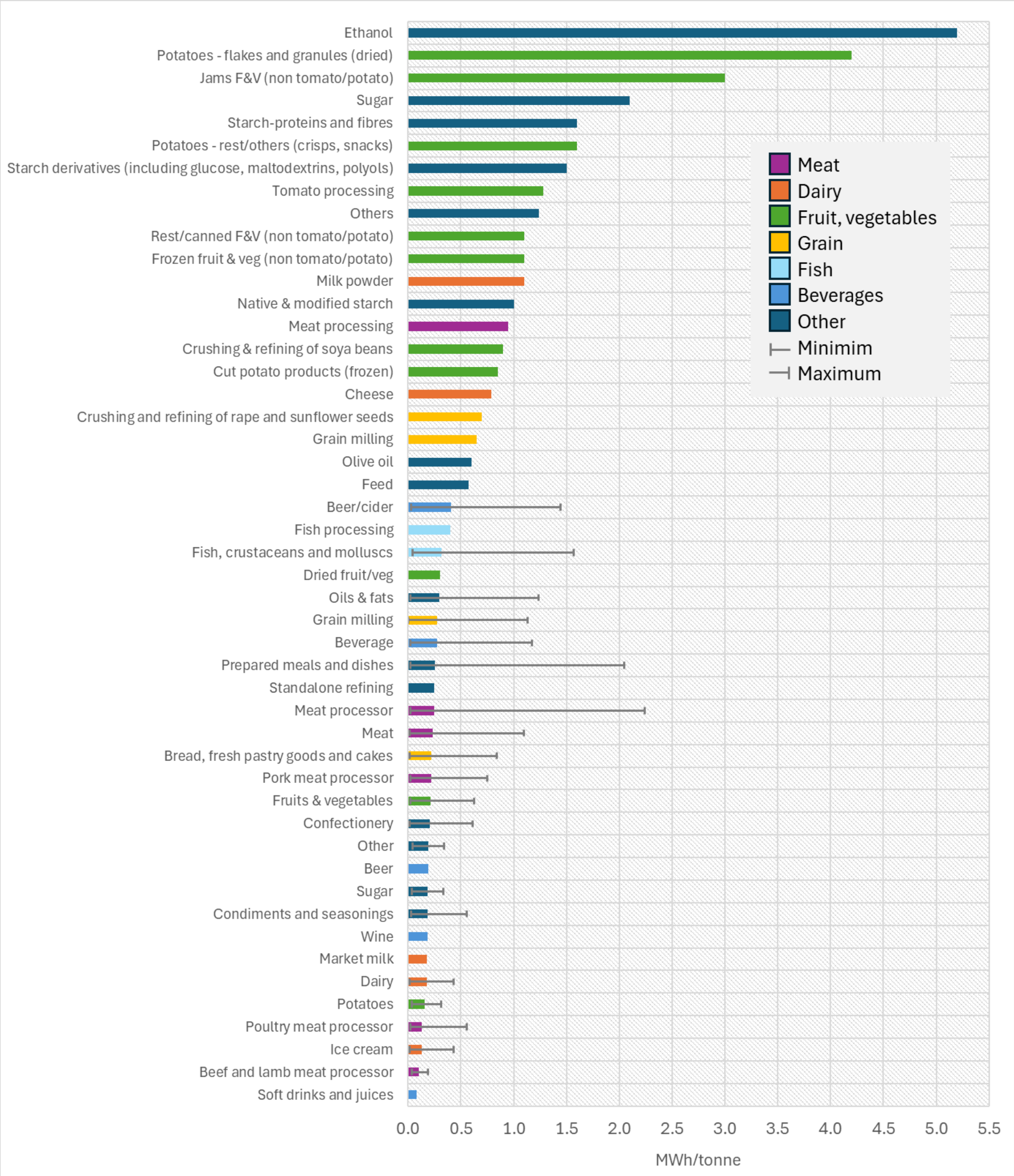

Figure 12: Energy use per tonne of food processed for a range of products.

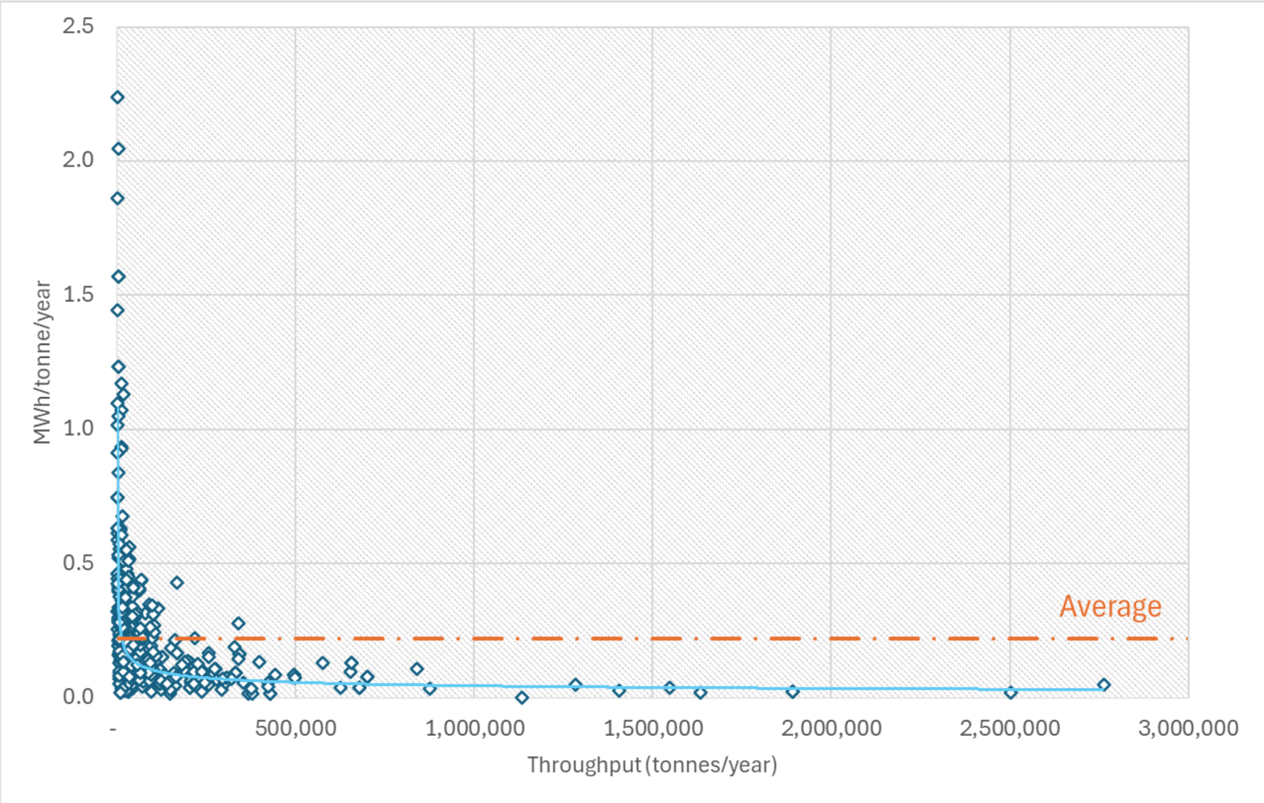

Figure 13: Energy use per tonne of food processed.

4.1.1 Meat processing

4.1.1.1 Metrics

Over time there has been gradual closure of smaller abattoirs and consolidation into larger entities.

Detailed performance metrics for meat processing are relatively scarce and are complicated by whether they include just chilling of carcasses or also include cutting and deboning and, in some cases, also freezing. In addition, metrics may be presented in different formats. Reported metrics are listed in Table 1. The majority of metrics are reported as kWh/tonne or MJ/tonne. Data compared for MJ/tonne and kWh/tonne are presented in Figure 14 and Figure 15 respectively.

Table 1: Published metrics for meat processing plants

Sector	Metric	Value	Range	Notes	Reference
Beef	kWh/head	70	300	Packing plant	Hansen, P., Christiansen, K., and Hummelmose, 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	Beef packing (Denmark)	Hansen, P., Christiansen, K., and Hummelmose, 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).

Sector	Metric	Value	Range	Notes	Reference
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	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		Packing (Poland)	Wojdalski, J., Drózdz, 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		Packing plant(Australia)	Pagan, R., Renouf, M., and Prasad, P., 2002. Eco-Efficiency Manual for Meat Processing. Queensland: Meat and Livestock Australia.
Beef	MJ/tonne	626	666	Packing plant(Poland)	Kowalczyk, R., and Netter, J., 2008. A new look at the energetic factors consumption in food industry. Postępy Techniki Przetwórstwa Spożywczego, 45–47.
Beef	MJ/tonne	1723		Packing plant	Wojdalski, J., Drózdz, 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:10.100711947-012-0924-4.
Beef and sheep	MJ/tonne	878		Dress carcass weight	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. Energy Efficiency; p. 791–810.

Sector	Metric	Value	Range	Notes	Reference
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. Energy Procedia, 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., Drózdz, 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:10.100711947-012-0924-4.
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. Energy, 31(12), pp.2047-2063.
Beef, veal, sheep	MJ/tonne	2110		Dress carcass weight for whole and frozen	Wojdalski, J., Drózdz, 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:10.100711947-012-0924-4.
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. Energy, 31(12), pp.2047-2063.
Beef, veal, sheep	MJ/tonne	2146		Dress carcass weight for whole and chilled	Wojdalski, J., Drózdz, 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:10.100711947-012-0924-4.

Sector	Metric	Value	Range	Notes	Reference
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. Energy, 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. Energy Procedia, 123, pp.353-360. Ramírez, C.A., Patel, M., and Blok, K., 2004.
Beef, veal, sheep	MJ/tonne	2866		Dress carcass weight for whole and frozen	Wojdalski, J., Drózdz, 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:10.100711947-012-0924-4.
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	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., Drózdz, 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:10.100711947-012-0924-4.
Pork	MJ/tonne	1397		Dress carcass weight	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. Energy Efficiency; p. 791–810.

Sector	Metric	Value	Range	Notes	Reference
Pork	MJ/tonne	1570		Slaughtering	Wojdalski, J., Drózdz, 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:10.100711947-012-0924-4.
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. Ramírez, C.A., Patel, M., and Blok, K., 2004
Pork	MJ/tonne	2097		Dress carcass weight for whole and frozen	Wojdalski, J., Drózdz, 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:10.100711947-012-0924-4.
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. Ramírez, C.A., Patel, M., and Blok, K., 2004
Pork	MJ/tonne	2849		Dress carcass weight for whole and frozen	Wojdalski, J., Drózdz, 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:10.100711947-012-0924-4.

Sector	Metric	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. Energy, 31(12), pp.2047-2063.
Pork	MJ/tonne	3128		Dress carcass weight for whole and chilled	Wojdalski, J., Dróżdz, 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:10.100711947-012-0924-4.
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. Energy, 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. Energy, 31(12), pp.2047-2063.
Pork	MJ/tonne	3884		Dress carcass weight for whole and frozen	Wojdalski, J., Dróżdz, 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:10.100711947-012-0924-4.
Poultry	MJ/tonne	1584		Dress carcass weight, electricity and fuels and heat consumption	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. Energy Efficiency; 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. Energy Procedia, 123, pp.353-360. Ramírez, C.A., Patel, M., and Blok, K., 2004

Sector	Metric	Value	Range	Notes	Reference
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. Energy, 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. Energy Procedia, 123, pp.353-360. Ramírez, 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. Energy, 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. Energy, 31(12), pp.2047-2063.
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. Energy, 31(12), pp.2047-2063.
Processed meat	MJ/tonne	750		Embodied energy use	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. Energy Efficiency; 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. Energy Efficiency; 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

Sector	Metric	Value	Range	Notes	Reference
Rendering	MJ/tonne	234		Raw material	Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. Energy Efficiency; p. 791–810.
Rendering	MJ/tonne	1276			Lijun, W., 2014. Energy efficiency technologies for sustainable food processing. Energy Efficiency; 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. Innovative Food Science and Emerging Technologies 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. Innovative Food Science and Emerging Technologies 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. Innovative Food Science and Emerging Technologies 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. Innovative Food Science and Emerging Technologies 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. Innovative Food Science and Emerging Technologies 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. Innovative Food Science and Emerging Technologies 47:371–83.

Sector	Metric	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. Innovative Food Science and Emerging Technologies 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. Energy 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

Sector	Metric	Value	Range	Notes	Reference
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. Energy 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. Postępy Techniki Przetwórstwa Spożywczego, 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
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

Sector	Metric	Value	Range	Notes	Reference
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.

Sector	Metric	Value	Range	Notes	Reference
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.

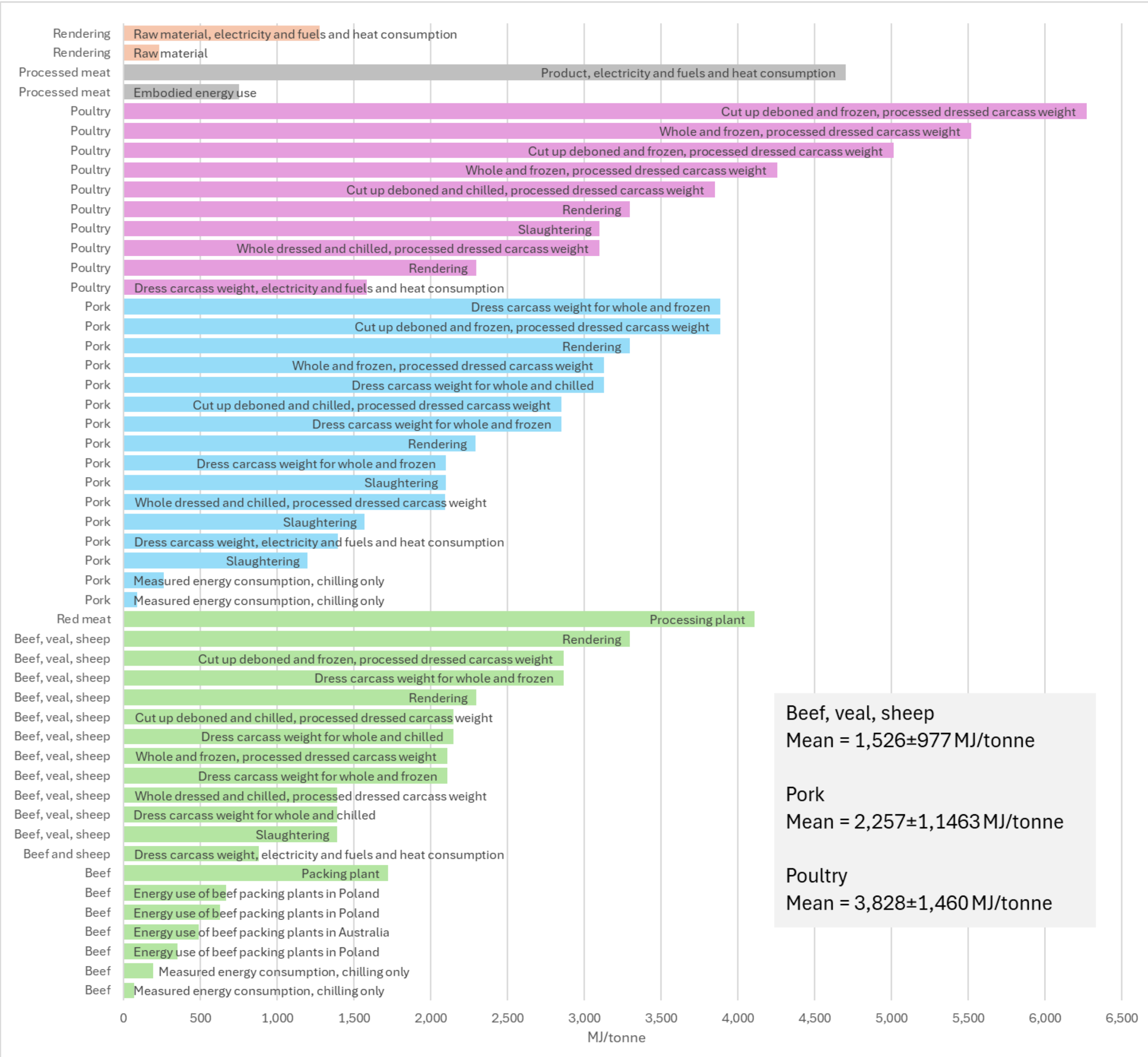

Figure 14: Metrics for meat processing in MJ/tonne.

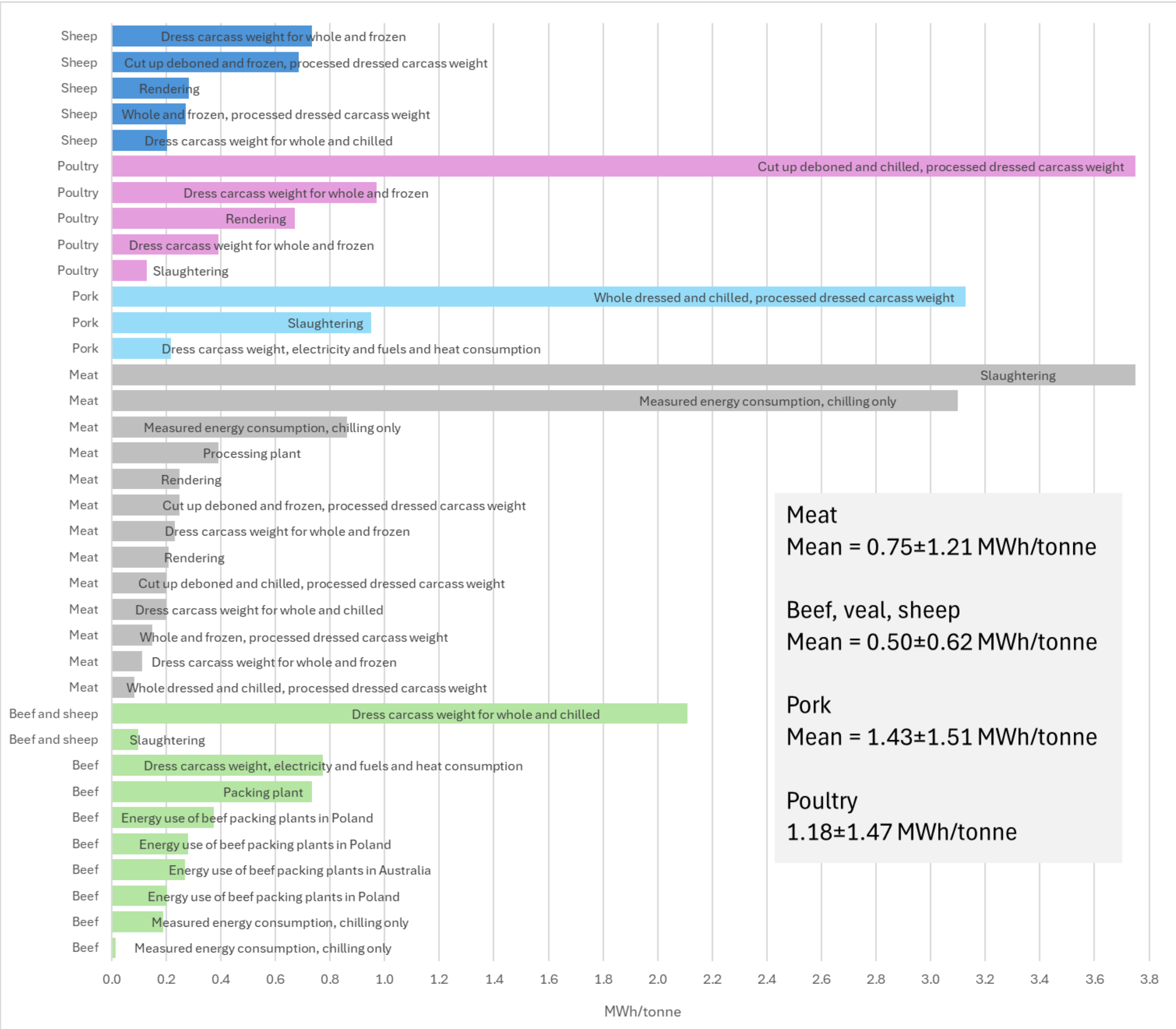

Figure 15: Metrics for meat processing in kWh/tonne.

4.1.1.2 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 in on-site boilers (traditionally provided by gas, LPG or oil). Thermal energy is used to heat water for cleaning, knife sterilisation, washing tripe, heating and blood drying. Rendering sometimes also occurs in abattoirs and cutting plant facilities (to typically provide edible oils or biodiesel raw materials) and also requires 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.

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 their total energy consumption 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 for cooling per kg due to smaller carcasses 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) [73]. Poultry abattoirs are reported to use the greatest energy per tonne [74].

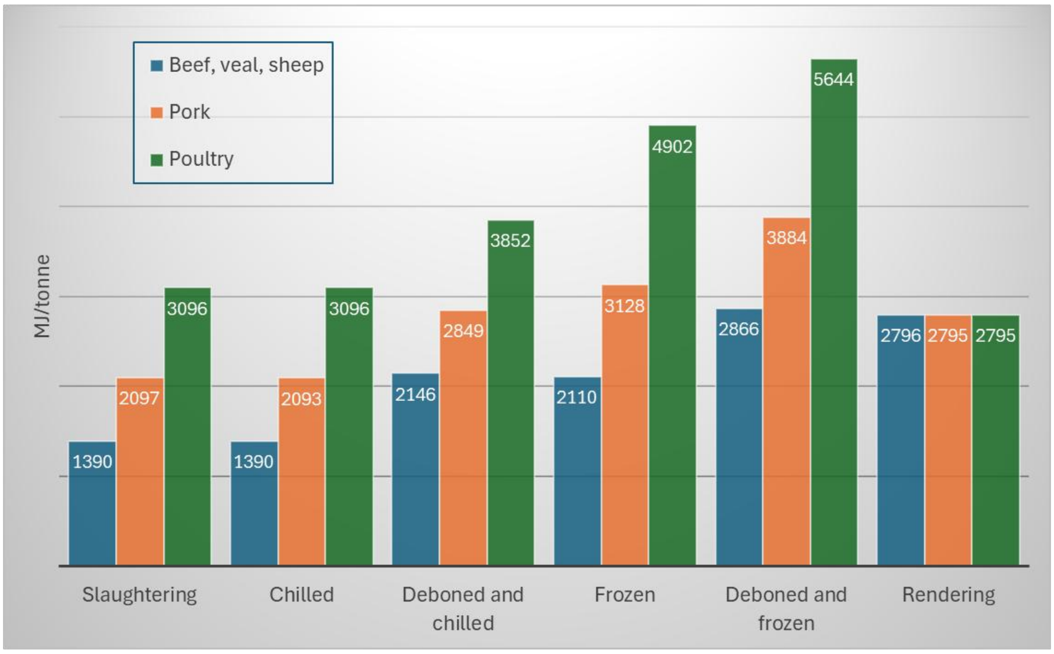

Figure 16: Energy used various processes in beef/veal/sheep, pork and poultry abattoirs

Limited detailed information on how energy is divided between the various thermal processes in a meat processing plant are available. Colley [75] identified that in Australia, 59% of the energy was associated with steam, 33% with electricity and 8% with hot water in a slaughterhouse (Figure 17).

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[73] Walsh, C. 2010. *Resource use in the British beef and lamb processing sector*. MLCS Consulting.

[74] 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.

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

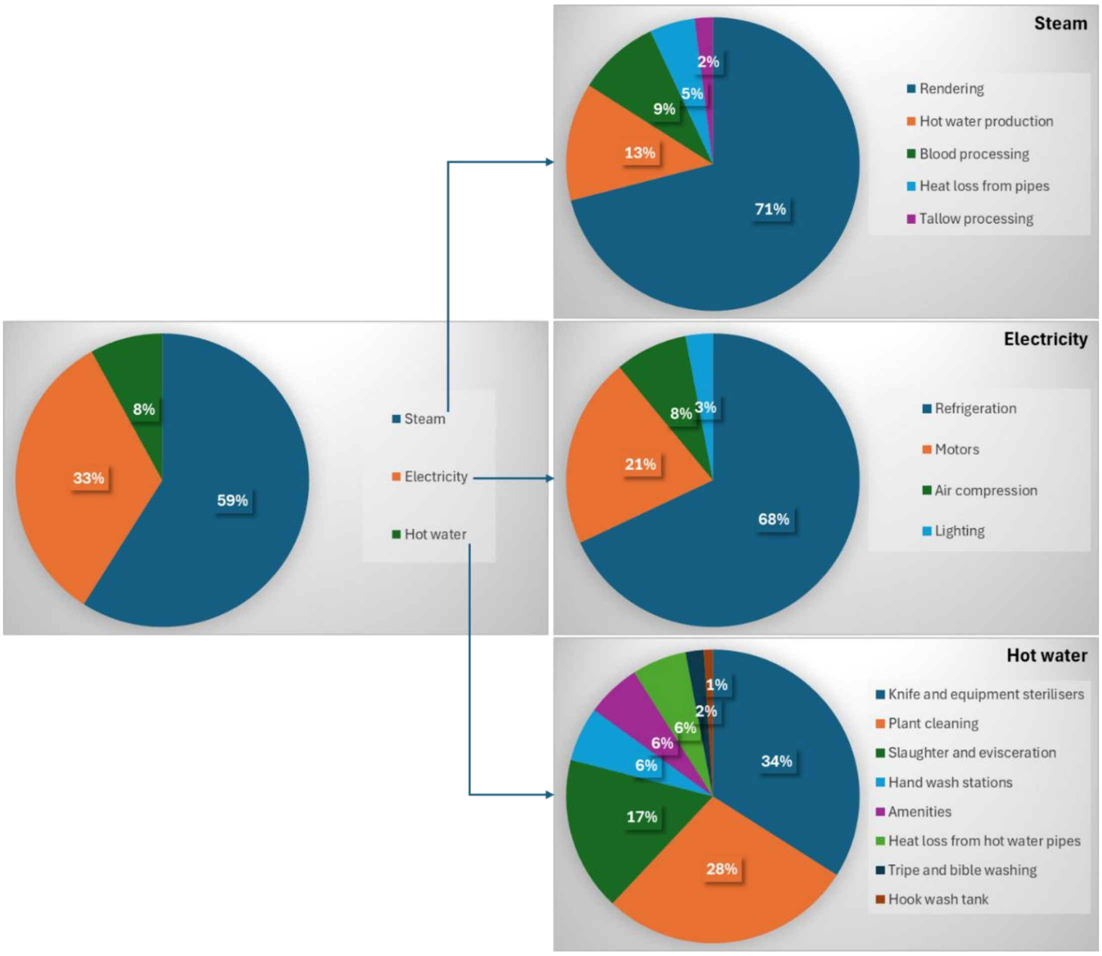

Figure 17: Division of energy in a slaughterhouse in Australia

4.1.2 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 UK/EU fisheries management regulations, including quotas and post-Brexit trade arrangements. Additionally, market dynamics and shifts in consumer preferences also impact the outputs from the different product groups.

In the UK, seafood processing is concentrated in key hubs such as Grimsby, which is one of the largest seafood processing centres in Europe, and the sector is characterised by a strong reliance on imported raw materials, particularly whitefish [76].

In the UK, electricity represents the dominant energy source in fish processing, although natural gas is widely used for thermal processes such as steam generation and drying.

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[76] Seafish, 2024b. *Seafood processing sector overview*. Available at: https://www.seafish.org

Fishmeal processing has a high demand for heat, typically supplied as steam, for raw materials, evaporation, and drying processes. This heat has traditionally used heavy fuel oil (HFO) -fuelled boilers. The UK has heavily restricted the use of high-sulphur HFOs due to strict air quality standards governed by the Environment Agency and the Medium Combustion Plant Directive (MCPD). UK plants have largely phased out HFO in favour of cleaner fuels. As the UK has a highly developed national gas grid, onshore UK fishmeal plants (such as major processing hubs in Scotland and northeastern ports) predominantly use mains natural gas to fire their steam boilers. Rather than exporting all byproduct oils, UK processors frequently utilise a closed-loop system. Low-grade or excess fish oil generated during the processing run is blended directly into the plant's boiler fuel supply. This reduces the factory's reliance on the national grid and lowers carbon tax liabilities under the UK Emissions Trading Scheme (UK ETS). Due to high energy costs in the UK, plants focus extensively on waste heat recovery (WHR). Evaporator vapours are captured to pre-heat the raw fish. 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 most sectors of the fish processing industry, refrigeration systems are 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. Refrigeration is also the dominant energy use in facilities handling frozen imports and ready-to-eat seafood products.

In the processing of pelagic species, i.e. Atlantic mackerel which are typically frozen, refrigeration systems can account for as much as 77% of a plant’s total energy consumption [77]. While pelagic processing is less dominant in the UK compared to Norway, similar energy profiles are observed in freezing-intensive operations. This is primarily driven by the intensive use of tunnel freezers during production.

[77] Svendsen, E.S., Bengsch, J., Widell, K.N., Selvnes, H., Sevault, A.G.E., Hafner, A. and Nordtvedt, T.S. (2023). *Integration of Cold Thermal Energy Storage at a Pelagic Fish Processing Plant: A Modelling Approach*. Proceedings of the 26th IIR International Congress of Refrigeration, Paris, France. https://doi.org/10.18462/iir.icr.2023.0422

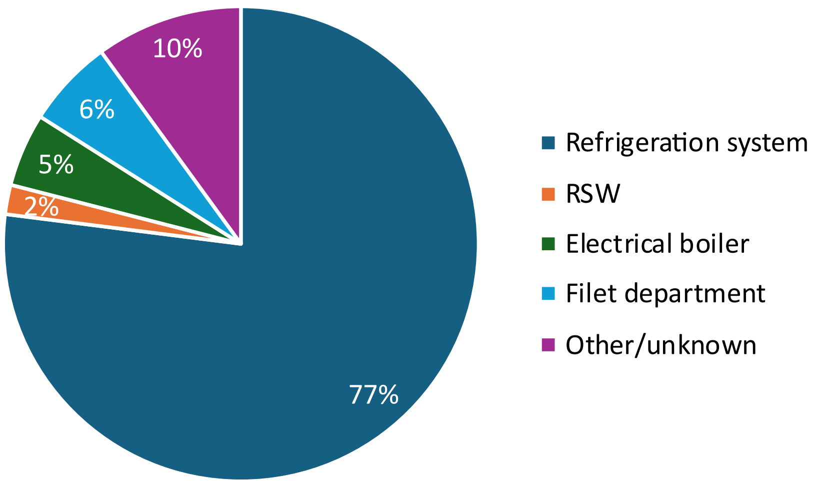

Figure 18: Division of energy in a typical pelagic production plant (Norwegian data). Similar energy distribution is observed in UK freezing-intensive seafood processing facilities. Reproduced from Widell et al. (2022) [78]

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. This is particularly relevant in the UK, where facilities often process imported frozen whitefish into a wide range of value-added products. Figure 19 presents energy division of a whitefish processing plant producing both fresh and frozen, consumer ready products.

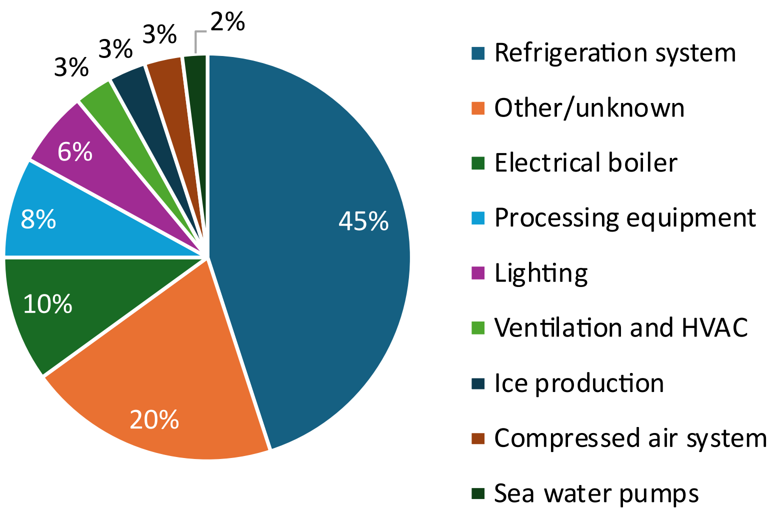

Figure 19: Division of energy in a whitefish processing plant (Norwegian data), representative of mixed-product facilities similar to those found in the UK seafood processing sector[79]

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[78] Widell, K.N., Svendsen, E.S., Selvnes, 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

[79] 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.

4.1.3 Dairy processing to 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.[80], 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. Table 2 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.

4.2 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.

[80] Giner Santonja, G., Karlis, P., Raunkjær Stubdrup, K., Brinkmann, T. and Roudier, S. 2019. *Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries*. JRC Science for Policy Report, EUR 29978 EN. European Commission.

Table 2: Current energy usage in dairy processing.

Sector		Energy use (kWh/tonne)	Share of total milk-processing energy	References
Milk processing	Reception Storage Pasteurisation	700-970	2% 7% 17-26%	Giner et al 2019 [80]
	Centrifugation and homogenisation		12%	
	Cooling		19%	
	Cleaning in place		9.5%	
Milk powder	Drying	831-2077	45-51%	Xu and Flapper [81]
Cheese	Reception Cheese processing Treatment/storage Ripening Cooling/refrigeration Compressed air Cleaning in place	1080-1191	7-19% 14% 12-32% 9-65% 8-19% 5% 19%	Xu and Flapper [82] Ramirez et al [83]
Butter	Cooling Compressed air Cleaning in place	277-1495.8	66% 8% 26%	Ramirez et al.[83]
Ice cream		249	n/a	International Dairy Federation [84]
Yoghurt		1319	n/a	

[81] 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.

[82] T. Xu, J. Flapper., 2019. Energy use and implications for efficiency strategies in global fluid-milk processing industry. Energy Policy, 37 (12) (2009), pp. 5334-5341.

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

[84] International Dairy Federation (2005) *Energy Use in Dairy Processing*. Bulletin of the International Dairy Federation No. 401. Brussels: International Dairy Federation.

5 Selected products/locations/fuels

5.1 Why products/processes were selected

5.1.1 Meat Processing

Beef, pork and poultry were selected as the case study products due to their high levels of consumption in the UK. Additionally, each product has slightly different slaughtering and processing characteristics as described in section 6.1.1.

5.1.2 Fish processing

Mackerel was selected as the focus species due to its significant share of total fish production in the United Kingdom and the North-East Atlantic region. In 2021, mackerel accounted for nearly 6% of the total global production volume. In the UK, mackerel is one of the most important pelagic species by landing value and volume, particularly in Scotland, where it represents a major component of the fishing industry [85].

UK mackerel landings have fluctuated in recent years due to quota allocations, stock management, and international agreements, but the species remains one of the most valuable fisheries for the UK fleet [86].

A significant proportion of UK-caught mackerel is exported, particularly to markets in Asia and Africa, with relatively lower domestic consumption. In the UK, mackerel consumption is comparatively modest compared to the EU (33-35,000 tonnes per annum) [84], with consumer demand concentrated in processed and smoked products rather than fresh whole fish.

Key markets for UK mackerel exports include countries such as the Netherlands, Nigeria, Egypt, and Japan, reflecting the global nature of the UK pelagic sector [85].

6.1.3 Dairy processing

According to a recent US Department of Agriculture World Markets and Trade report, UK cheese production is expected to remain stable or show modest growth in 2024, supported by steady domestic demand and export opportunities [87]. Total UK cheese production is estimated at around 0.5–0.55 million tonnes annually, with key producing regions including England, Wales, and Northern Ireland [88].

Unlike the EU, where production is dominated by several large member states, the UK dairy sector is more consolidated, with a strong focus on value-added products such as cheddar,

[85] Seafish, 2024b. *UK seafood industry overview and trade data*. Available at: https://www.seafish.org

[86] Department for Environment, Food & Rural Affairs (Defra), 2024c. *UK sea fisheries statistics 2023*. Available at: https://www.gov.uk

[87] US Department of Agriculture (USDA), 2024. *Dairy: World Markets and Trade*. Available at: https://www.usda.gov

[88] Department for Environment, Food & Rural Affairs (Defra), 2024a. *Agriculture in the United Kingdom statistics*. Available at: https://www.gov.uk

which accounts for a significant share of total production. As a reliable source of revenue and a product of high market demand, cheese production remains a pivotal focus for the UK dairy sector.

Concurrent with production trends, UK cheese exports are projected to recover gradually following post-Brexit trade disruptions, with key export markets including Ireland, the United States, and countries in the Middle East and Asia [89]. At the same time, the UK continues to be a net importer of cheese, particularly from the EU, reflecting strong domestic demand and established trade links.

Furthermore, domestic cheese consumption within the UK is expected to remain stable or increase slightly, supported by the continued recovery of the hospitality and foodservice sectors. After a temporary decline in 2022 due to decreased consumer purchasing power, consumption stabilised in 2023 and is now projected to strengthen in 2024, driven by rising real incomes, and the continued recovery of out-of-home consumption following the COVID-19 pandemic [89].

6.1.4 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.

5.2 Fuels used and their carbon intensities

The food and drink industry's scope 1 emissions are largely attributable to fossil fuels used by manufacturing facilities and offices [90]. The use of solid fossil fuels (e.g. coal) in the food industry is now almost negligible in the UK; however, the industry is still reliant on natural gas for cooking and heating and petroleum for transport [91]. 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 (**Error! Reference source not found.**) [92].

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[89] Agriculture and Horticulture Development Board (AHDB), 2024c. *UK dairy market outlook*. Available at: https://ahdb.org.uk

[90] FoodDrinkEurope. 2015. *A Time to Act: Climate Action and the Food and Drink Industry*. June 2015.

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

[92] Department for Energy Security and Net Zero (DESNZ), 2025. *Digest of UK Energy Statistics (DUKES) 1.1: Aggregate energy commodity balance: gross calorific values basis* [Excel spreadsheet]. Available at:

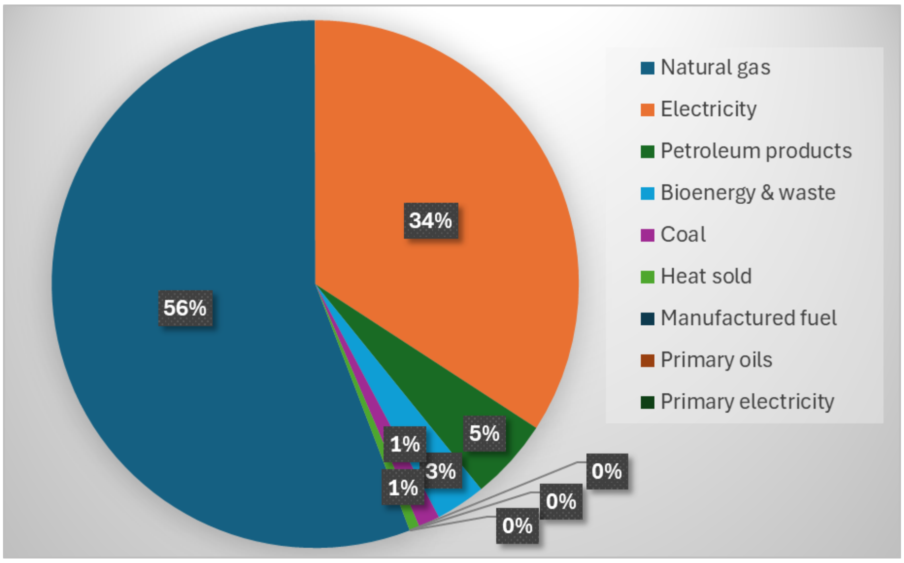

Figure 20: Breakdown of fuel from DUKES for food and beverage manufacturing in the UK (2023)

Food processes that already use electricity, will decarbonise naturally with the electricity grid. The UK electricity grid carbon intensity is projected to fall to near-zero levels by 2050, driven by the large-scale deployment of renewable energy, nuclear power, and low-carbon technologies [93]. This will significantly reduce carbon emissions without effort from the food processer. However, efficiency options cannot be ignored as these will aid more rapid decarbonisation and reduce running costs. 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. The share of electricity and heating used by different food processing sectors varies considerably. In the absence of detailed UK-specific data at sub-sector level, European averages are used here as an indicative benchmark; while overall patterns are likely to be similar, differences may arise due to the UK's specific industrial structure, technologies and fuel mix. 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

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

[93] Climate Change Committee (CCC), 2020. *The Sixth Carbon Budget: The UK's path to Net Zero*. Available at: https://www.theccc.org.uk/publication/sixth-carbon-budget/

to decarbonising the UK food and drink sector. Other industries with low levels of electricity use include dried potato products and frozen and canned fruit and vegetables.

Table 3: Share of energy use in the European food and drink sector.

Sub-sector	Share of energy	
	Electricity (%)	Heating (%)
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

Sub-sector	Share of energy	
	Electricity (%)	Heating (%)
Average	38	62

6 Typical (standard) processes investigated

6.1.1 Meat processing

Typical slaughterhouse processes for poultry, beef and pork are shown in Figures 21 to 23.

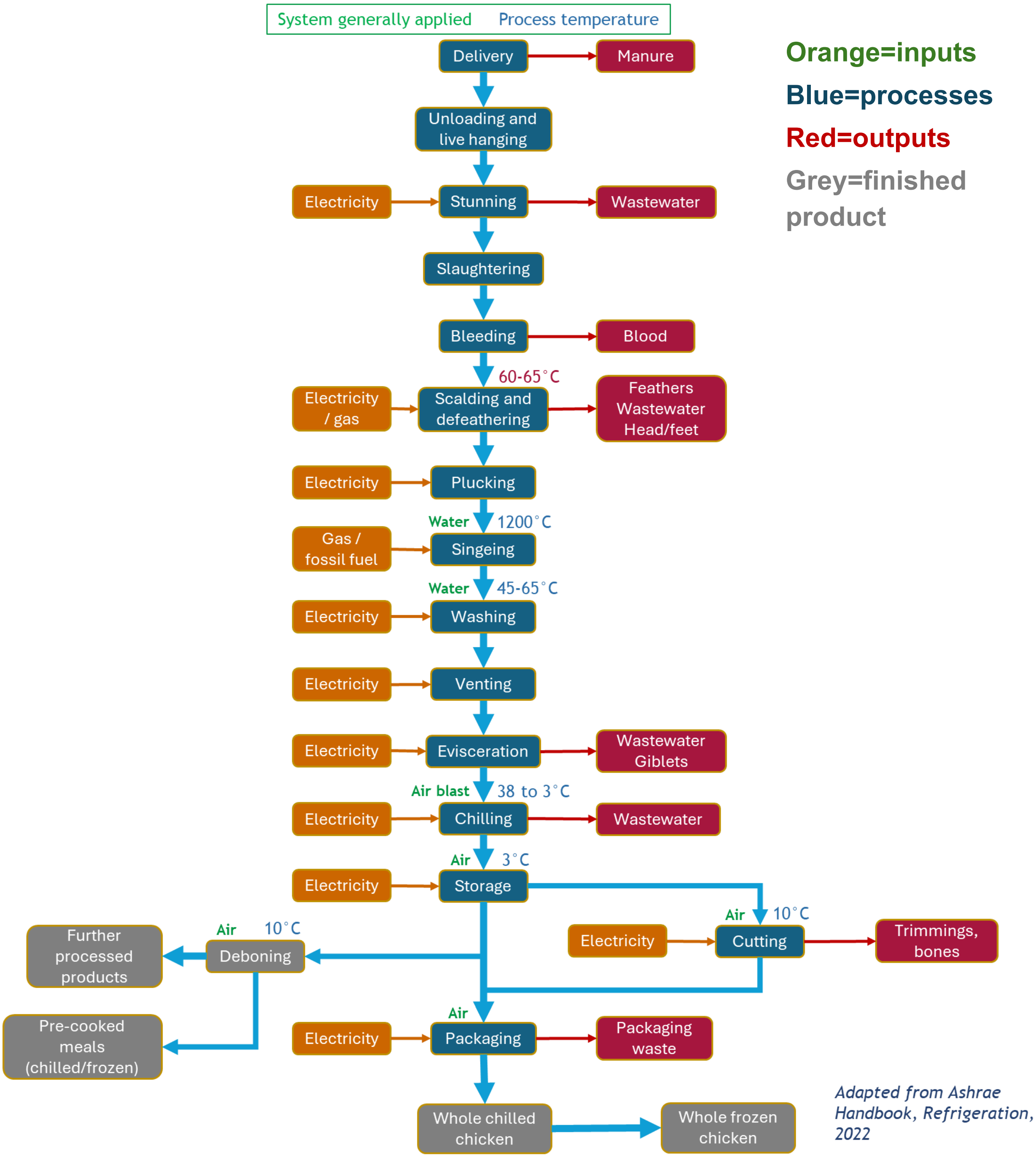

Figure 21: Typical poultry primary processing steps

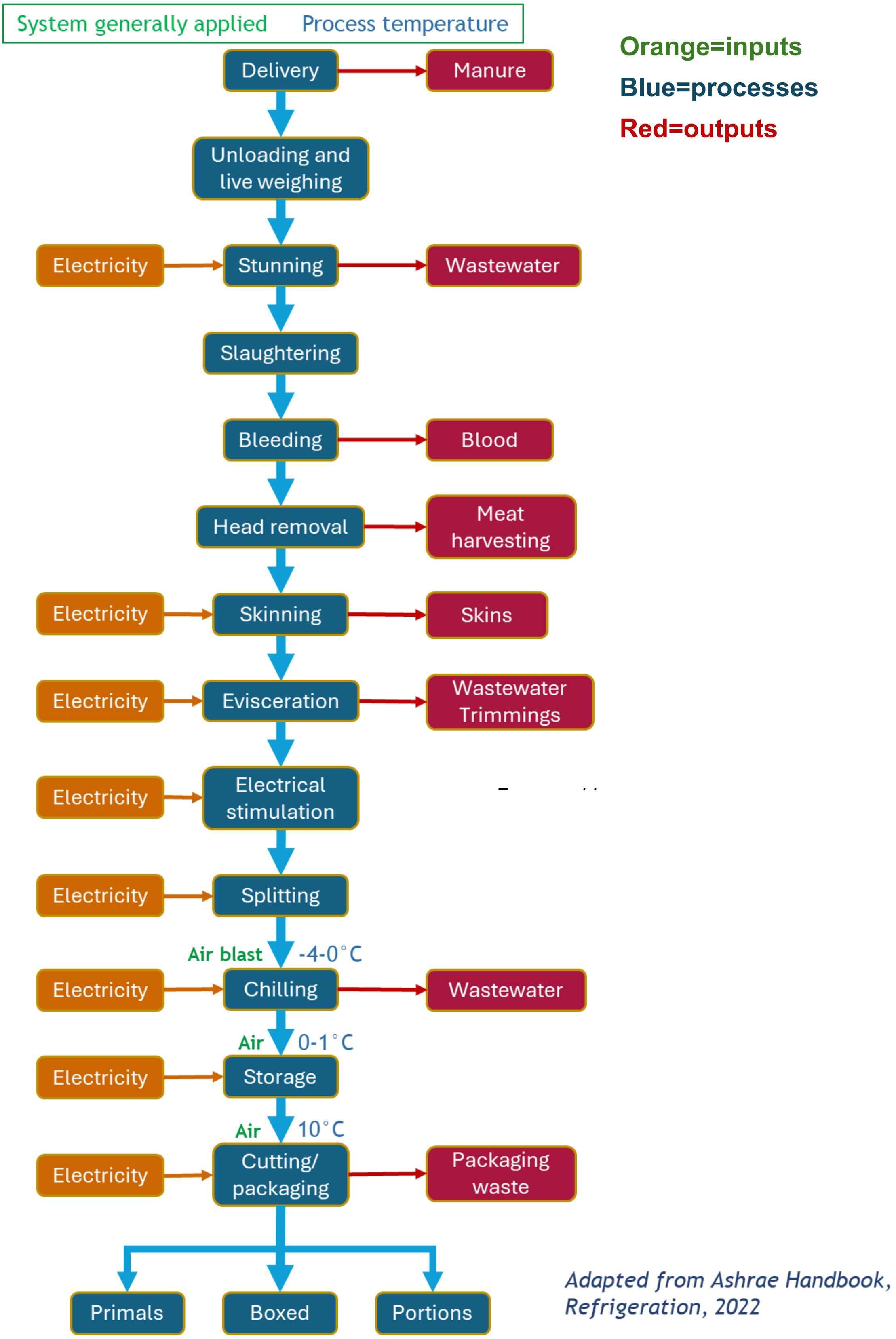

Figure 22: Typical beef primary processing steps.

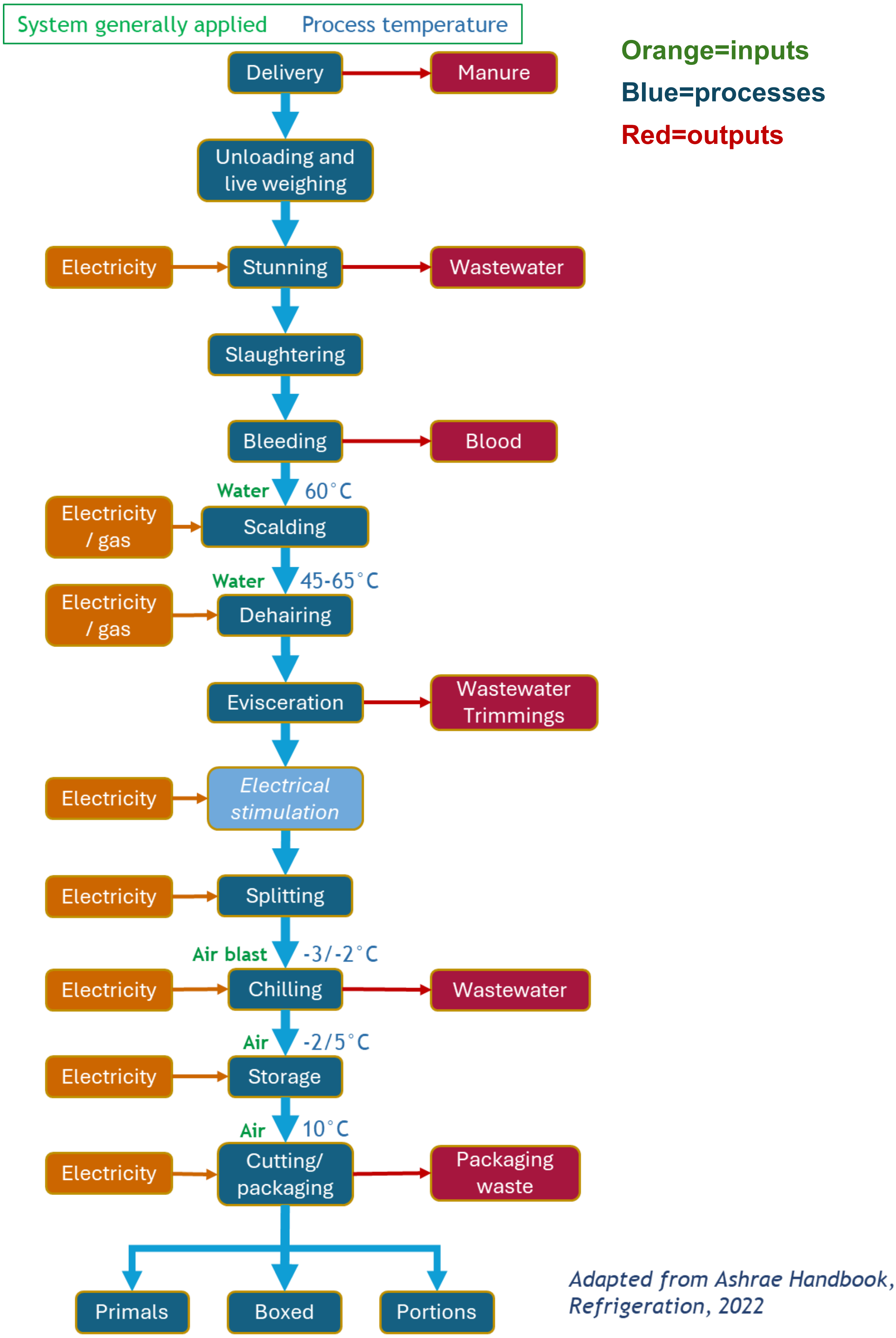

Figure 23: Typical pork primary processing steps.

6.1.2 Fish processing

The typical primary processing steps for Atlantic mackerel are illustrated in Figure 24. 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.

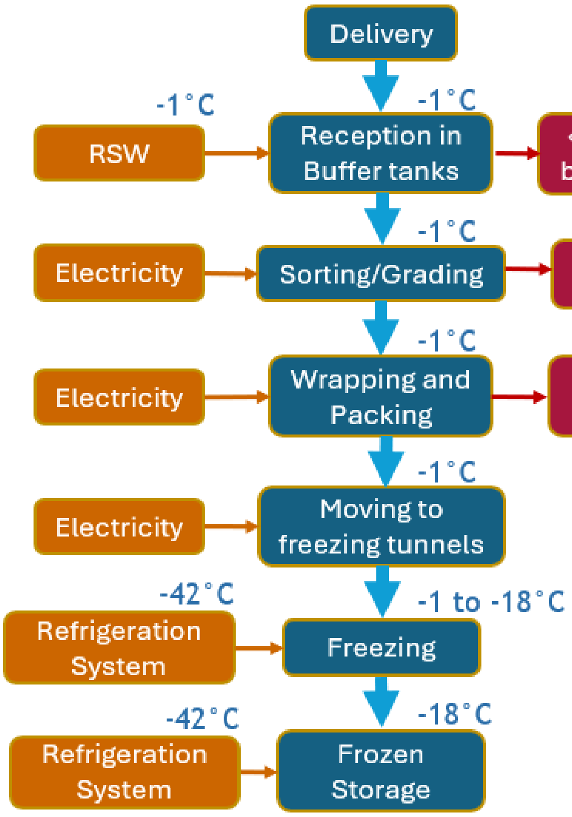

Figure 24: Typical primary processing of Atlantic mackerel.

6.1.3 Dairy processing to produce cheese

Generally raw milk is received in the dairy and transferred to bulk storage. The milk is 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: HTST, UHT, pasteurised etc. Homogenisation is the next unit operation, where the fat globules need to be reduced to a size < 0.7µm. For pasteurised milk the process is presented in Figure 25.

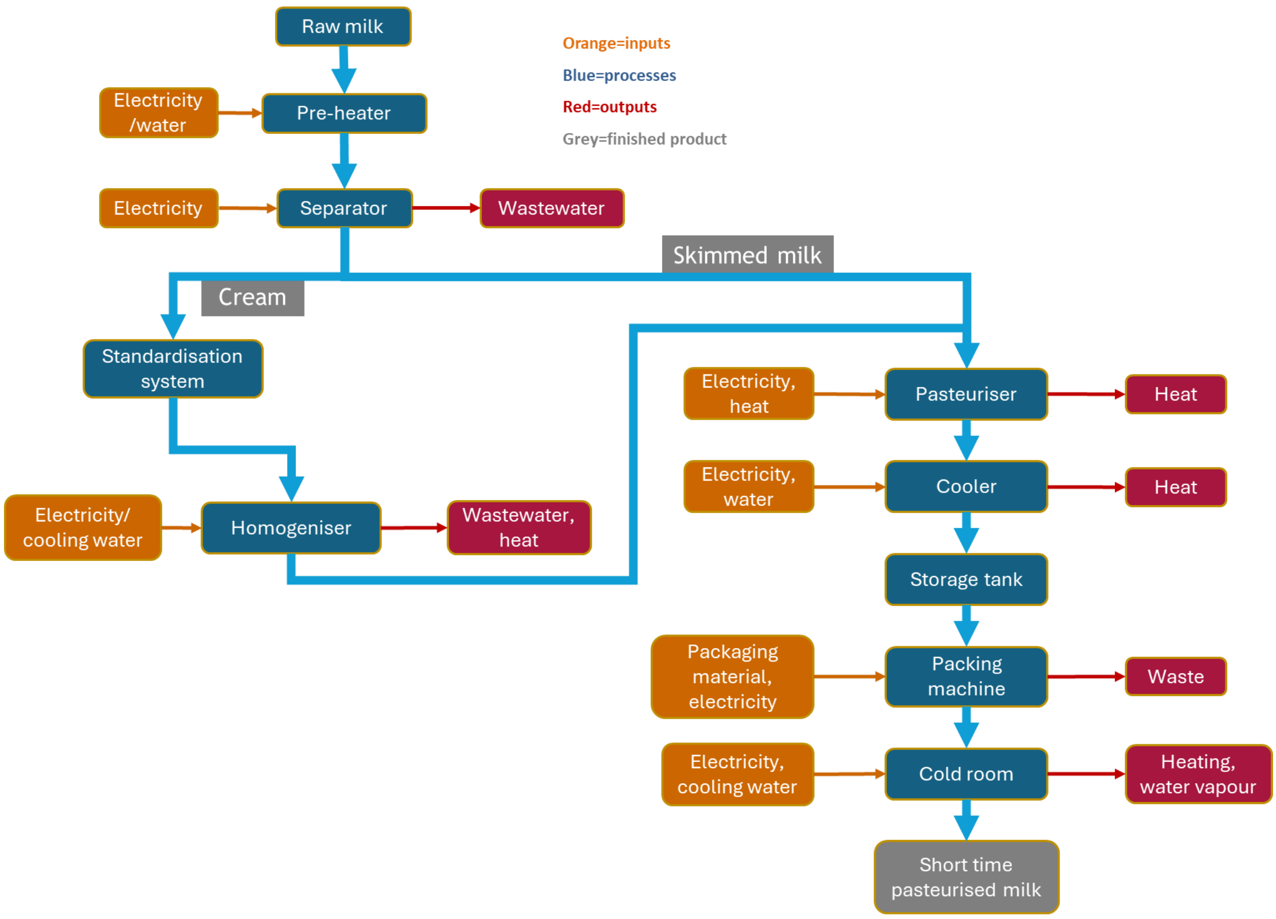

Figure 25: Short-time pasteurised milk process.

There are a very wide range of processes according to the type of cheese being manufactured (see Figure 26). Typically, the process entails production of a coagulum, due to the action of rennet and lactic acid, separation of the resulting curds from the whey, manipulation of the curds to produce the desired characteristics of the type of cheese). Traditionally cheese manufacture was a manual process but now is much more automated. 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 vat 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 tastes and flavours.

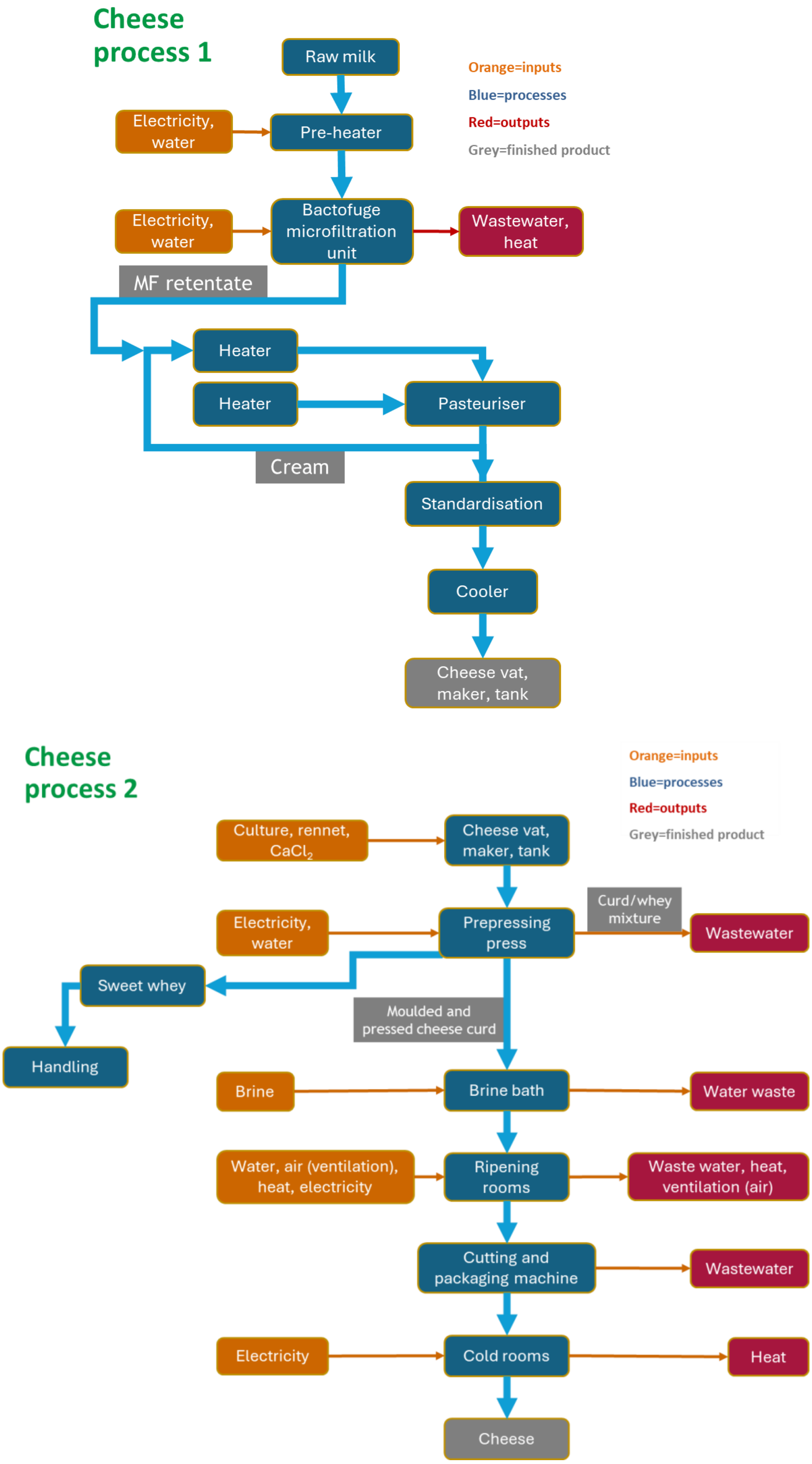

Figure 26: Manufacture of Cheese part 1 and part 2.

6.1.4 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 the UK. 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.

6.1.4.1 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.

The flow diagram shown in Figure 27 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 spiral freezer.

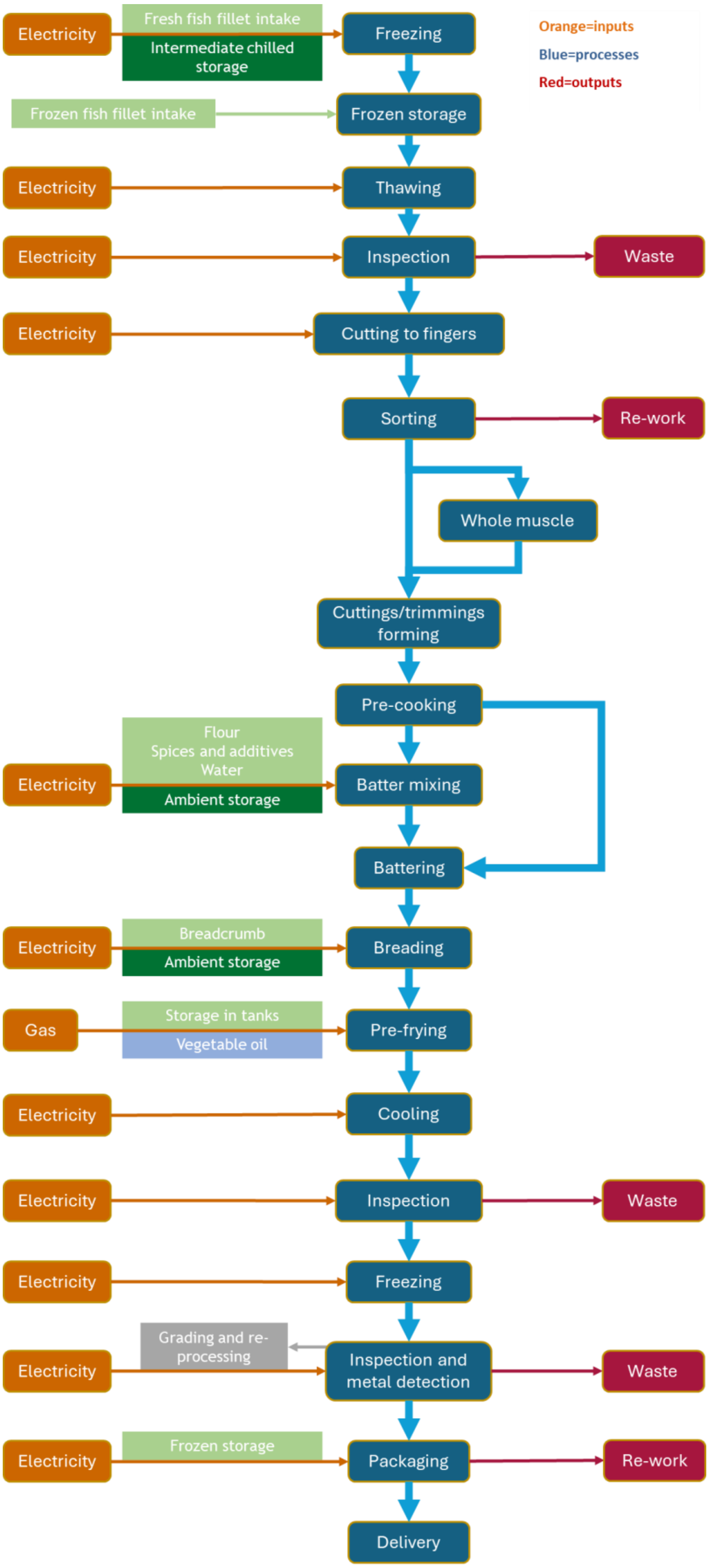

Figure 27: Flow diagram for the manufacturing of quick-frozen breaded fish fingers.

6.1.4.2 Beef casserole ready meal

The industrial manufacturing process of a chilled beef casserole ready meal (Figure 28) 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 whilst still under aseptic conditions. After seal inspection, metal detection and labelling, the product is cooled rapidly to below 5°C to minimise the growth of pathogenic and spoilage microorganisms and ensure microbiological safety, stored chilled or frozen and distributed via the cold chain.

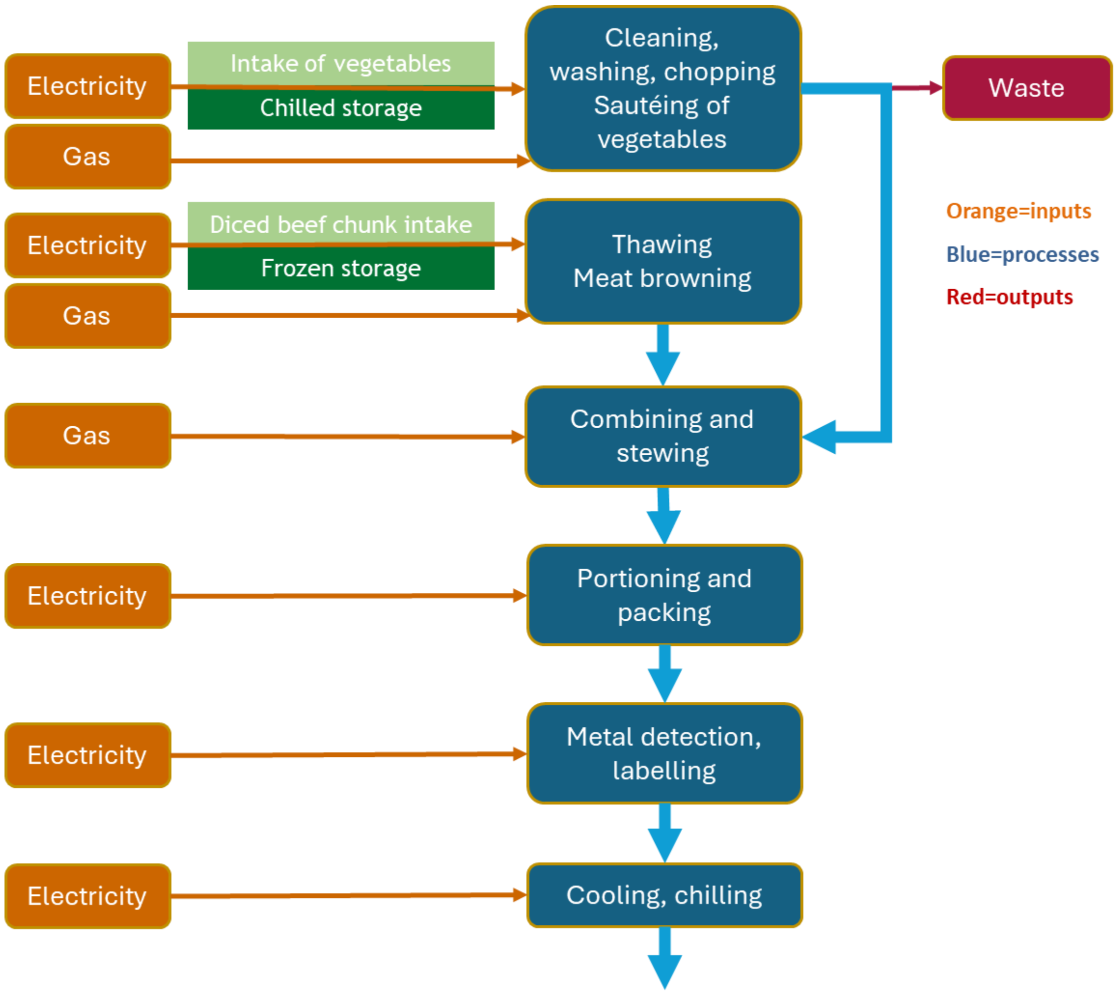

Figure 28: Flow diagram for the industrial manufacturing of chilled, ready to eat beef casserole.

7 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 4: 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.
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

Information	Comments
	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 5: 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												
10.1.1	Air cycle (reverse Brayton cycle) refrigeration (low temperature only)	7		ü		ü		ü		ü	ü	ü	
10.1.2	Ambient cooling	9							ü	ü	ü(only if remove refrig equip)	ü	
10.1.3	Antifreeze proteins	4-5						ü(ice cream)				ü	
10.1.4	Cold recovery on LNG driven fishing vessels (fish)	8-9				ü					ü	ü	
10.1.5	Dehydrofreezing	9								ü		ü	
10.1.6	Electrostatic field freezing	5-6		ü		ü		ü		ü		ü	
10.1.7	Heat pipes	4		ü		ü		ü		ü		ü	
10.1.8	Hydrofluidisation	9		ü		ü				ü		ü	
10.1.9	Ice bank chilling	9						ü				ü	
10.1.10	Ice nucleation proteins (INPs)	7-8						üice cream)				ü	

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
10.1.11	Impingement cooling/freezing	9		ü		ü		ü		ü		ü	
10.1.12	Localised cooling	9		ü		ü		ü		ü		ü	
10.1.13	Magnetic field freezing/ Cell Alive System (CAS)	5-6		ü		ü		ü		ü		ü	
10.1.14	Superchilling	7-9		ü		ü		ü		ü		ü	
10.1.15	Supercooling	3-5		ü		ü		ü		ü		ü	
10.1.16	Ultrasound assisted freezing	6-7		ü		ü				ü		ü	
10.1.17	Vascular perfusion / infusion	7-8		ü								ü	
	Heating												
10.2.1	Automatic shutdown	8-9								ü	ü	ü	
10.2.2	Drying – novel systems	7-9						ü			ü	ü	
	Efficient oven design	1-4								ü	ü	ü	
10.2.3	Frying - efficiency improvements, novel options	6								ü	ü	ü	
10.2.4	High-pressure freezing and thawing	1-3								ü	ü	ü	
10.2.5	High-temperature heat pumps	Up to 9	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü	

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
10.2.6	HPP (High Pressure Processing)	8		ü		ü		ü		ü	ü	ü	
10.2.7	High-Temperature Short-Time (HTST)	7-9								ü	ü	ü	
10.2.8	Impingement of air jets	5-9		ü		ü		ü		ü	ü	ü	
10.2.9	Improve combustion efficiency (gas/oil)	8-9	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü	
10.2.10	Improved oven control e.g. active exhaust control	4-9							ü	ü	ü	ü	
10.2.11	Keeping oven loaded	8-9							ü	ü	ü	ü	
10.2.12	Microwave/ultrasonic combination cooking	8-9							ü	ü	ü	ü	
10.2.13	Motor efficiency (fans and conveyors)	8-9	ü	ü	ü	ü	ü	ü	ü	ü		ü	
10.2.14	Ohmic heating	6-7							ü	ü	ü	ü	
10.2.15	Recovery of exhaust heat	8-9							ü	ü	ü	ü	
10.2.16	Reduce heating up time	8-9							ü	ü	ü	ü	
10.2.17	Reduce thermal mass of tins	5-7							ü	ü	ü	ü	

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
10.2.18	Retorts (variable temperature control)	6							ü	ü	ü	ü	
10.2.19	Roasting - efficiency and innovative methods	9							ü	ü	ü	ü	
10.2.20	Steaming - efficiency improvements, novel options	9							ü	ü	ü	ü	
	Other												
10.3.1	Advanced evaporation technologies	8-9								ü	ü	ü	
10.3.2	Alternative fuels for fishing vessels (fish)	4-7			ü	ü					ü	ü	
10.3.3	Centrifugation	9								ü	ü	ü	
10.3.4	Compressed air optimisation	9	ü	ü	ü	ü	ü	ü	ü	ü		ü	
10.3.5	Efficient conching	7-9							ü	ü	ü	ü	
10.3.6	Efficient grinding	7-9							ü	ü	ü	ü	
10.3.7	Hot boning (meat)	8-9		ü								ü	
10.3.8	Internet of Things (IoT) and Artificial Intelligence (AI)	4-9	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü
10.3.9	Milling	7-9							ü	ü	ü	ü	

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
10.3.10	Polygeneration	8		ü		ü		ü		ü	ü	ü	
10.3.11	Refining and extraction	8-9								ü	ü	ü	
10.3.12	Reverse osmosis	9						ü		ü	ü	ü	
10.3.13	Smoking	8-9		ü		ü		ü		ü	ü	ü	
10.3.14	Solar power	8-9	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü
10.3.151 0.3.15.1	Thermal energy systems (TES):												
10.3.15.1	TES integration at processing plants; low, medium and high temperature	4-9		ü		ü		ü		ü	ü	ü	ü
10.3.15.2	TES integration on fishing vessels (fish)	4-9		ü		ü		ü		ü	ü	ü	ü
10.3.16	Utilisation of processing wastes	3-9		ü		ü		ü		ü	ü	ü	ü
	Ancillaries												
10.4.1	Building fabric optimisation	7-9		ü		ü		ü		ü	ü	ü	ü
10.4.2	Building lighting efficiency	8-9	ü	ü	ü	ü	ü	ü	ü	ü		ü	

8 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 ZECC Cold storage road map. Therefore, readers should refer to this road map for general information on how to optimise refrigeration plant performance.

8.1 Meat processing

A number of technologies were modelled to evaluate the GHG emissions reduction potential from primary meat processing. These include:

- More efficient chilling – improving overall efficiency of refrigeration systems though optimised components, better maintenance and operation practices and also alternative chilling operations such as 2-stage chilling, hot boning and rapid chilling.
- Heat pumps to provide hot water for space heating, cleaning and washing that replace fossil fuels. There is potential to use the waste heat from 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.
- Slaughterhouses use air compressors and there is considerable potential to apply strategies to reduce energy and carbon emissions as shown in section
- 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.
- Solar power generated on site has potential to provide heat or electricity to meat processing plants

The technologies/strategies shown above were simulated for pork, beef and poultry slaughterhouses (excluding any rendering) to assess the potential to reduce emissions from meat processing in the UK. The methods by which the GHG emissions were attributed and the justifications for the technologies applied are listed below. It should be noted that the results from the modelling provide a general overview of the potential savings achievable across a sector of the primary meat processing industry and that individual facilities will vary in their baseline fuels used, their current processes and proportion of energy attributed to each individual process.

8.1.1 Assumptions for the carbon reduction model

The overall emissions for the UK food processing sector (Table 6) were obtained based on data from FoodDrinkEurope [94] and ENOUGH project [95]. An assumption was made that the meat industry is responsible for 4.3% of the total food processing emissions [94].

Table 6. Carbon emissions of food processing sector from the ENOUGH top-down model.

	UK ($MtCO_2e$)
Scope 1 (exc. fugitive)	6.05
Scope 1 fugitive	0.51
Scope 2	2.5

Ramírez et al. [96] stated 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 al [97] 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 Infomil [98], European Commission [99] and Pontoppidan et al. [100] 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 29).

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[94] FoodDrinkEurope. 2021. *Decarbonisation road map for the European food and drink manufacturing sector*. A report for FoodDrinkEurope, ED14569, Issue number 1, dated 07/07/2021.

[95] ENOUGH (2025) *Food production, processing and packaging road map*. Available at: Food production processing packaging road map PDF

[96] 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.

[97] 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.

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

[99] 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.

[100] Pontoppidan, O., Hansen, P., 2001. Cleaner technology in the poultry and cattle slaughtering branch. Project report (renere teknologi pa˚ 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/.

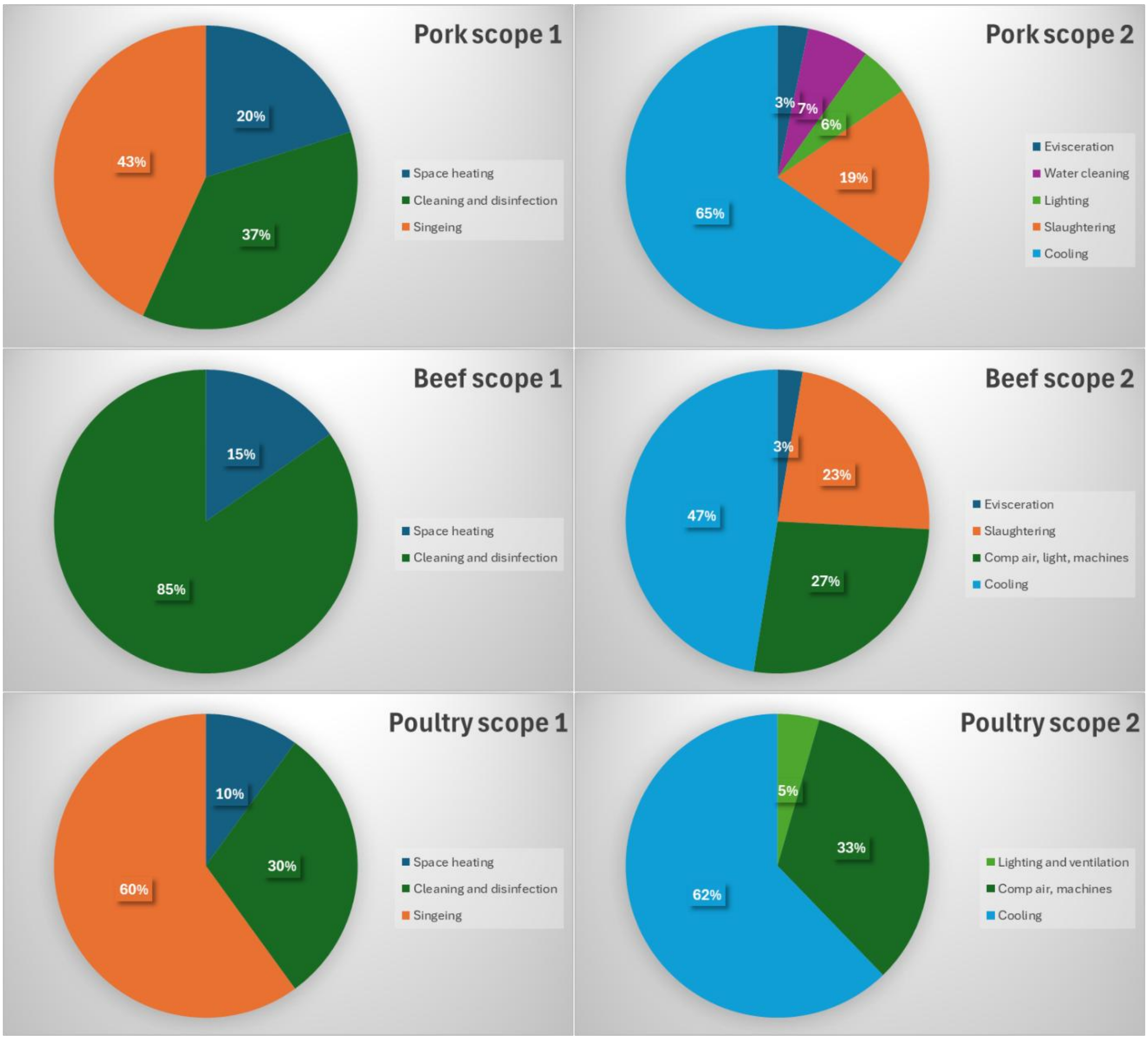

Figure 29: Proportion of greenhouse gas emissions attributed across each process for each meat type

A carbon intensity of 0.184 $kgCO_2e/kWh$ was assumed for LPG [101] and electrical grid carbon intensities for the UK were projected through to 2050 using the projections from Enerdata (EnerBlue scenario) [102]. Fugitive emissions were calculated by applying the 2024 European F-gas phase down requirements.

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

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101 Department for Energy Security and Net Zero (DESNZ) (2024) *UK Government greenhouse gas conversion factors for company reporting 2024*. London: DESNZ.

102 Enerdata (2025) *Global Energy & Climate Outlook 2050 (EnerBlue scenario)*. Available at: https://eneroutlook.enerdata.net/ (Accessed: 4 June 2026).

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

Predicted grid carbon reductions were compared to a 1990 baseline. This was generated from UNFCCC data [103] using all industrial GHG emissions, for scope 1 and Public Electricity and Heat Production (Section 1.A.1.a) for scope 2 emissions (see Figure 30).

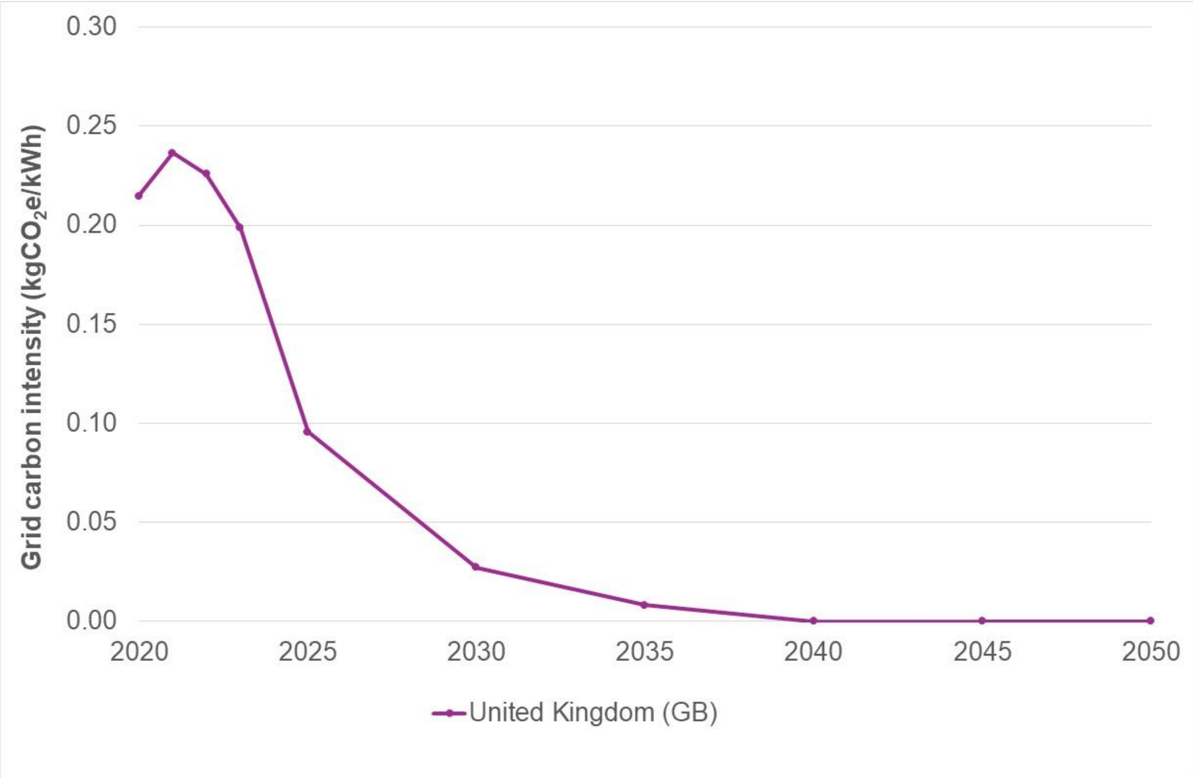

Figure 30: Grid carbon intensity for the UK (Enerdata projections).

103 UNFCCC (United Nations Framework Convention on Climate Change). no date. *Greenhouse Gas Inventory Data – Detailed data by Party*. Available at: https://di.unfccc.int/detailed_data_by_party.

Table 7: Assumptions applied to each meat process in model.

Process	Where applied	Fuel baseline/replacement	Assumptions*
More efficient chilling	Pork, poultry and beef	Electricity	2% compound annual savings 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 [104]) LPG boiler 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 [249]) 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 [249]) 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[105] Green hydrogen emissions of 0.011 kg CO_2e/kWh[106]

[104] Pedersen, S.V. (2024) *Annex 57: Flexibility by Implementation of Heat Pumps in Multi-Vector Energy Systems and Thermal Networks – Final Report*. Heat Pumping Technologies TCP (HPT TCP), International Energy Agency. Available at: HPT Annex 57 Final Report

[105] 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.

[106] 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.

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 Marconi[107]. The following maximums were applied: FR 15%, IT 15%, NO 8%, POL 35%, UK 10%, LITH 20% Biomethane emissions (generation from AD) of 0.012 kg CO_2e/kWh applied [108]
PV to mitigate electricity use	Pork, poultry and beef	Electricity	PV panel generation for the six locations from RETscreen, based on a 15° slope, 0° azimuth, and 15% efficiency. The following figures were used: London (UK) 144.8 kWh/year.m² Number of abattoirs estimated from Passantino[109] 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)

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

---

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

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

[109] Passantino, A. 2009. *Welfare of animals at slaughter and killing: a new regulation on the protection of animals at the time of killing*. Journal of Consumer Protection and Food Safety, 4, pp. 273–285. Available at: 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.

8.1.2 Potential carbon reductions

Overall carbon savings for pork, poultry and beef processing between 2019 and 2050 are presented in Figure 31. Compared to 1990 [110], the overall potential carbon reductions in 2050 are at least 84%. Each individual process was assessed and applied cumulatively. Results for pork are shown in Figure 32, poultry in Figure 33 and beef in Figure 34.

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

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[110] 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)

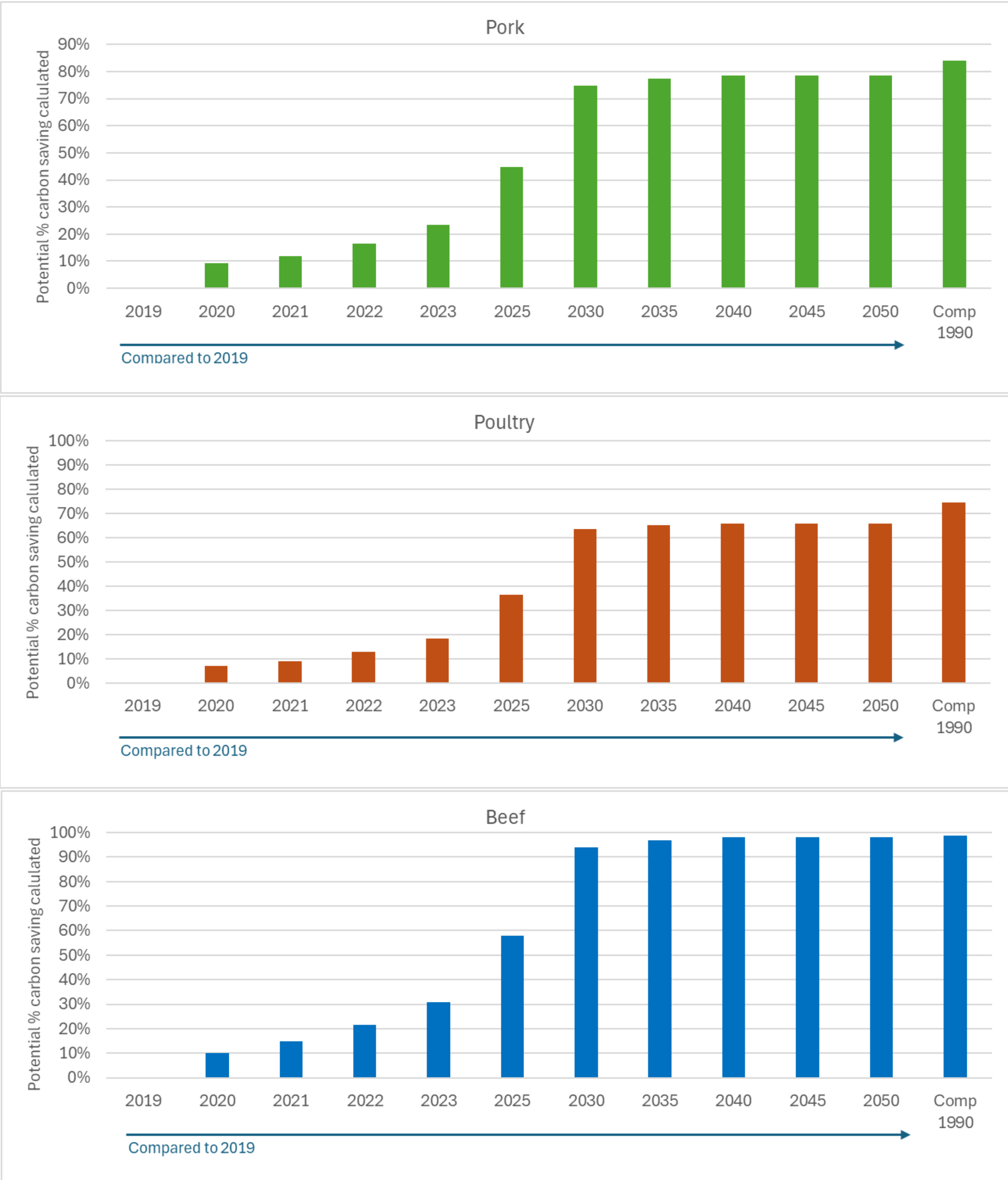

Figure 31: Carbon reduction potential for meat processing (Note: solar contribution is not included).

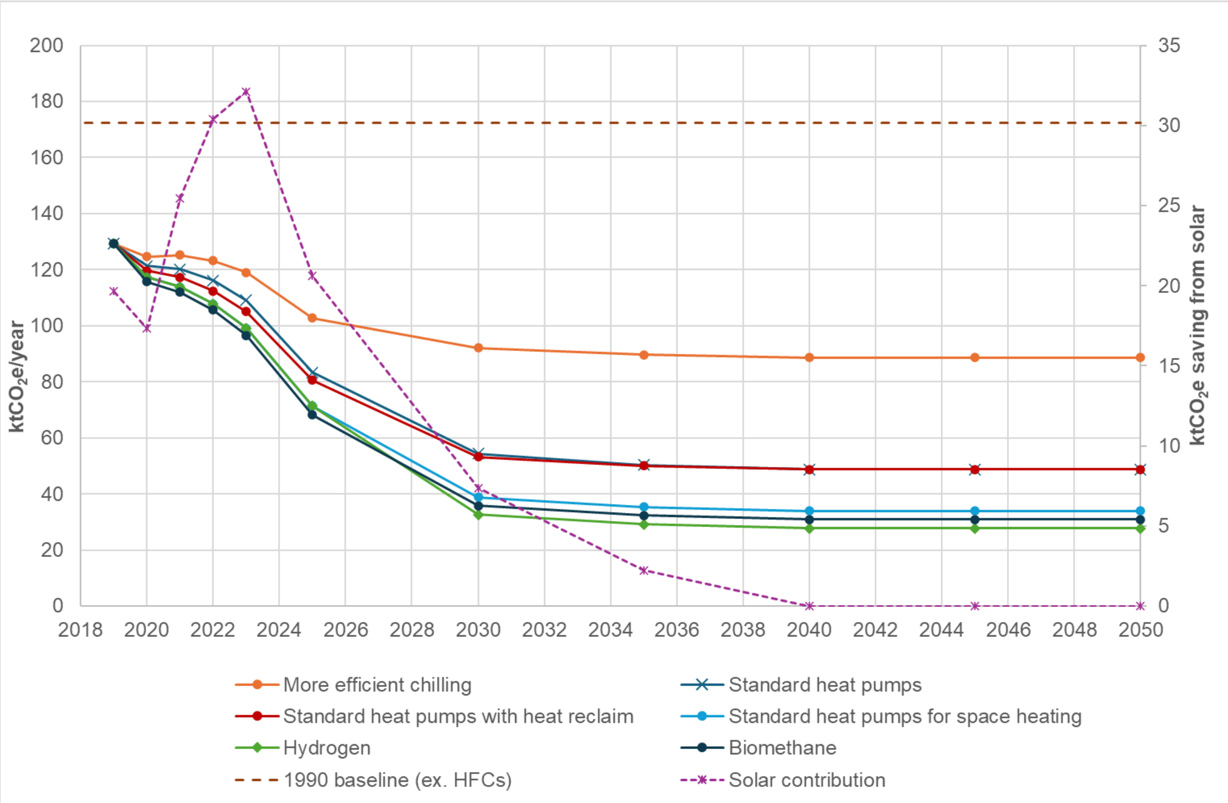

Figure 32: Potential carbon reduction for pork processing (2019 baseline).

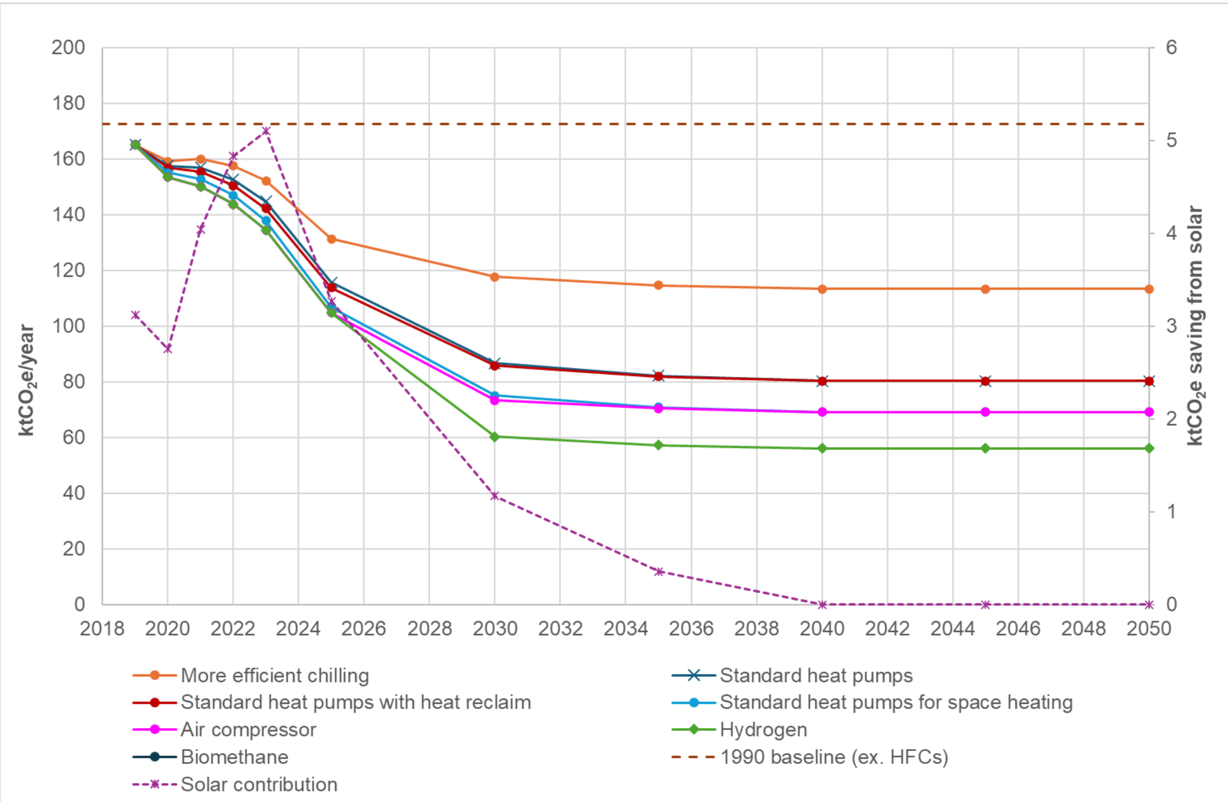

Figure 33: Potential carbon reduction for poultry processing (2019 baseline).

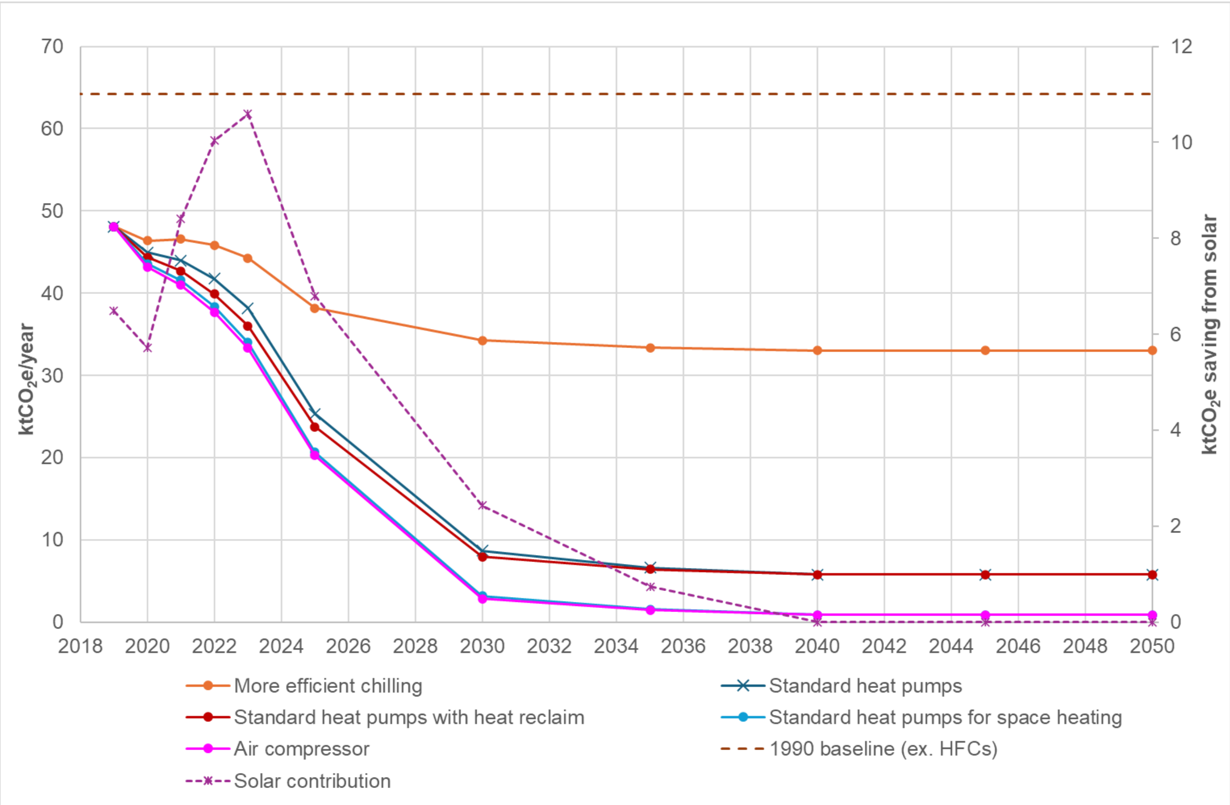

Figure 34: Potential carbon reduction for beef processing (2019 baseline).

9 Recommendations

9.1 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 4.1.1.1), 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 of the electrical grid decreases over time. 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.**

10 Appendix: Detailed technology/strategy options

10.1 Refrigeration

10.1.1 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.[111] "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.[112] 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)[113] 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

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[111] 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.

[112] 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.

[113] Pelsoci, T. and Bond, P.J., 2001. Closed-Cycle Air Refrigeration Technology. In Economic Case Study of an ATP-funded Project.

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.[114] 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.[115]) was used as the basis for a theoretical study of a spiral freezer presented by Pearson.[116] Based on performance figures published by Andou and Okuda[117], 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.[118] 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.[119] used both the cooling and heating in a combined system for cooking burgers and then rapidly freezing them.

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[114] 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.

[115] 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.

[116] Pearson S.F., 2006. Air cycle refrigerating system for continuous freezer, IIR Conference, Palmerston North, New Zealand.

[117] Andou K. and Okuda S., 2004. Development of air refrigerating system, In 6th IIR Gustav Lorentzen Conference on Natural Working Fluids, Glasgow.

[118] 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.

[119] 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.

Interest in air cycle has continued (for example Shuo et al.[120] 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.

10.1.2 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.

[120] 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).

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[121], 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 Figures 35 and 36. Reduction in active (refrigerated) cooling times are shown in Figure 37.

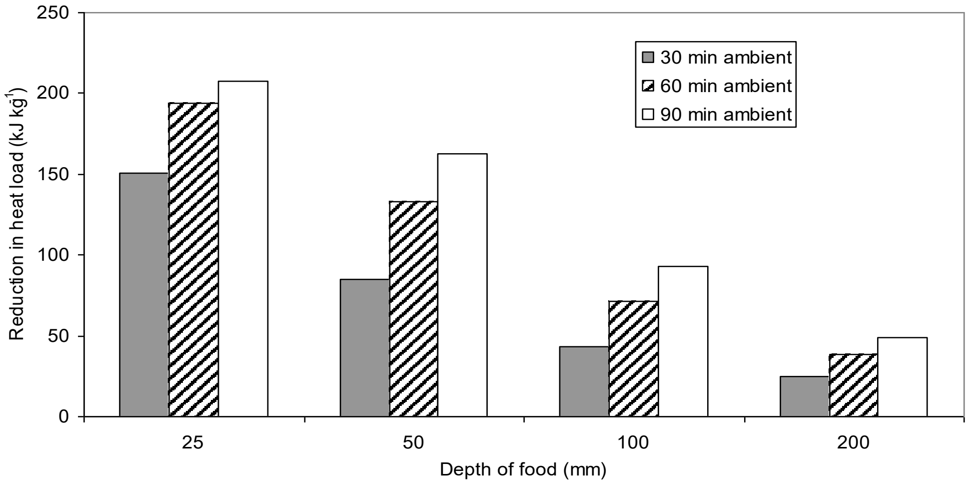

Figure 35: Reduction in heat load during active (refrigerated) cooling for Bolognese sauce cooled to a mean temperature of 5°C in air with a heat transfer coefficient of 40 W m-2.K.

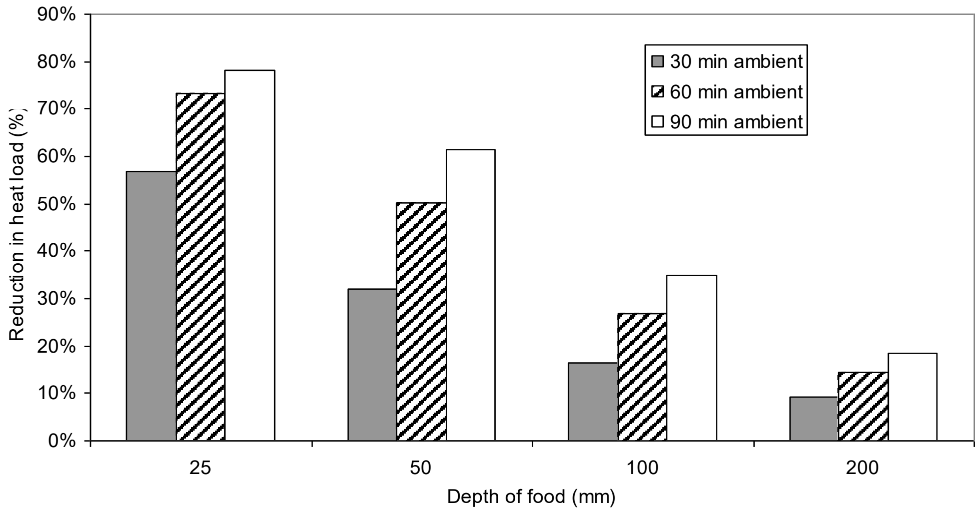

Figure 36: Percentage reduction in heat load during active (refrigerated) cooling for Bolognese sauce cooled to a mean temperature of 5°C in air with a heat transfer coefficient of 40 W m-2.K.

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[121] 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.

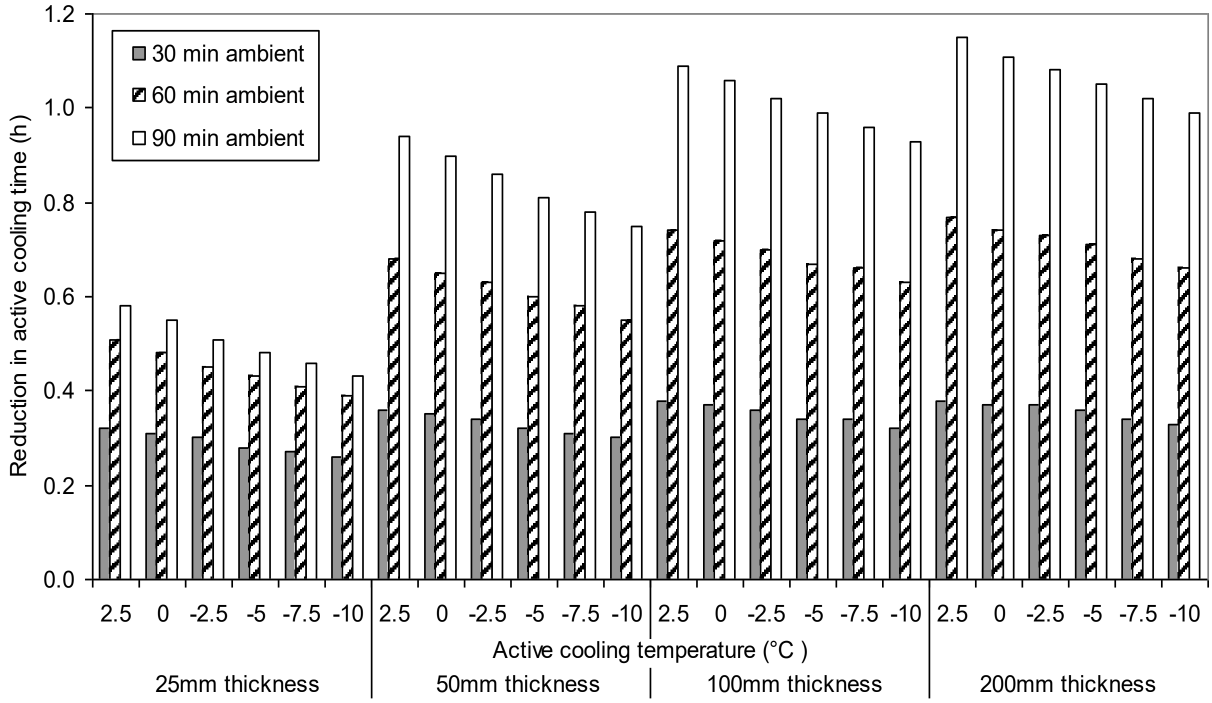

Figure 37: Reduction in active (refrigerated) cooling time (excluding ambient cooling period) for Bolognese sauce cooled to a mean temperature of 5°C in air with a heat transfer coefficient of 40 W m-2.K

Evans[122] reported that the heat removed during a 1-hour ambient colling period was 134 kJ/kg, equivalent to 49% of the total heat load needing to be removed. Evans[122] 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. [123]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

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[122] 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.

[123] 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.

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.

10.1.3 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.[124] [125] Ustun and Turhan[126] and Venketesh

[124] 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.

[125] 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.

[126] 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.

and Dayananda[127] 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

10.1.4 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

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[127] 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.

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[128], refrigerated vehicles[129] and marine vessels.[130] [131] [132] Baldasso et al.[130] 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 -.44%). Both Xiao et al.[131] and Yao et al.[132] 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.[133]

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.

[128] 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 SystemsSeptember 13-15th 2017POLITECNICO DI MILANOBOVISA CAMPUSMILANO, ITALY 129, 42–49. https://doi.org/10.1016/j.egypro.2017.09.177

[129] 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

[130] 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

[131] 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

[132] 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

[133] Grensesprengerne [WWW Document], 2023. URL https://www.innovasjonnorge.no/artikkel/grensesprengerne (accessed 9.27.24).

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	TRL 8-9
Maintainability issues	One system is in use, no performance data available
Legislative concerns	N/A
Payback time (years)	N/A

10.1.5 Dehydrofreezing

Dehydrofreezing involves the partial dehydration of foodstuffs, using either air or more commonly osmotic solutions such as 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.[134] 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[135] and by Mascheroni[136]).

[134] 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.

[135] Huxsoll, C. C., 1982. Reducing the refrigeration load by partial concentration of foods prior to freezing. Food Technology, 36(5), 98–102.

[136] 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.

Crivelli et al.[137] 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 [136], who presented freezing curves for products which had been dehydrated to various different extents (see Figure 38).

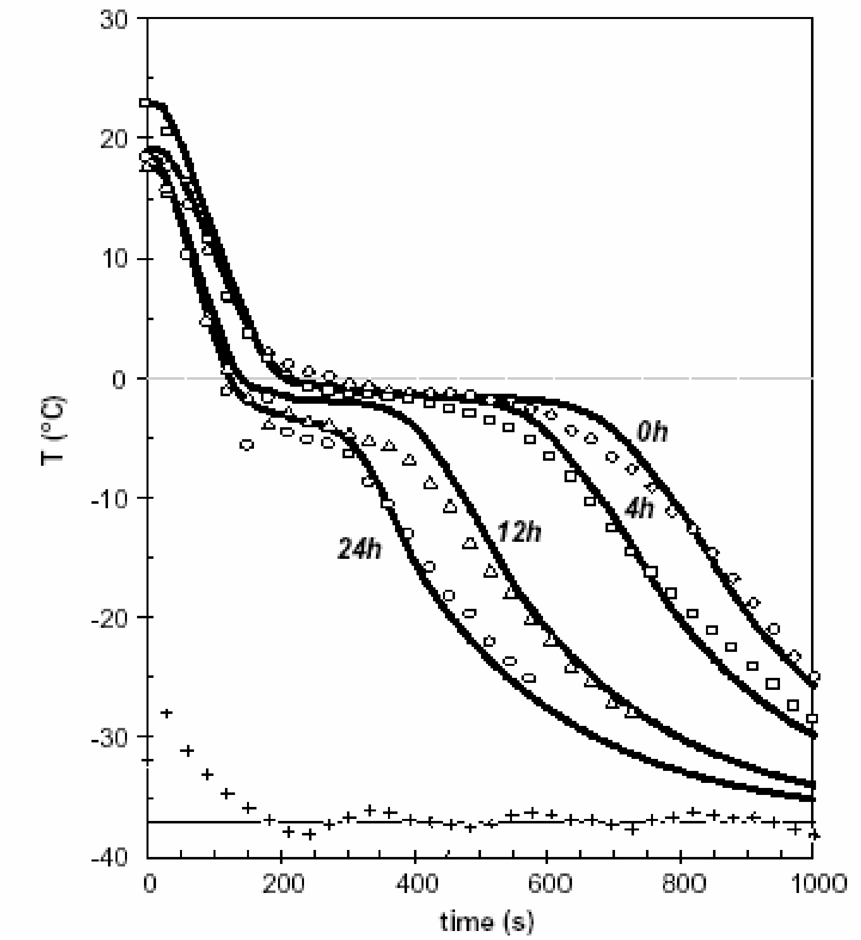

Figure 38. Figure 38: Product being frozen after dehydration for various times (from Mascheroni, 2007).

Despite the potential advantages, use of dehydrofreezing has not become widespread, possibly due to complication of processing and capital cost. James et al.[138] postulated that the

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[137] 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.

[138] 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.

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	TRL9
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

10.1.6 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.[139] Fallah-Joshagani et al.[140] 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.

[139] Orlowska, M., Havet, M., Le-Bail, A., 2009. Controlled ice nucleation under high voltage DC electrostatic field conditions. Food Research International, 42(7), 879–

[140] 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.

Several types of food have been reported on, with varying intensities and freezing process conditions. Babakin et al.[141] applied EF (in this case termed electroconvection) to meat samples and found reduced freezing times and weight loss, Xanthakis et al.[142] reported reductions in ice crystal size and freezing time of pork at high (microwave) frequencies, while Dalvi-Isfahan et al.[143] 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.[144] Jha et al.[145] 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.

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141 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.

142 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.

143 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.

144 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.

145 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.

Payback time (years)	Unknown.

10.1.7 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 (see Figure 39). 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.

Error! Reference source not found.*Figure 39. Cooling time for different heat pipe sizes*

Investigations showed the benefit of using devices such as 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 [146]. 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.

Use of heat pipes inserted into joints of meat for cooking and subsequent cooling was studied by James et al.[147] 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[148] 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

[146] Ketteringham, L. and James, S.J. 2000. *The use of high thermal conductivity inserts to improve the cooling of cooked foods*. Journal of Food Engineering, 45(1), pp. 49–53. doi: 10.1016/S0260-8774(00)00043-1.

[147] 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.

[148] 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.

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)l, 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.

10.1.8 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.[149] [150] [151] 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 W m^{-2} K^{-1}.[149] [150] 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

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[149] Fikiin, A.G., 1992. New method and fluidized water system for intensive chilling and freezing of fish. Food Control 3 (3), 153–160.

[150] Fikiin, K.A. & Pham, Q.T., 1985. *Individual Quick Freezing of Foods by Hydrofluidisation: heat transfer coefficients for fish and vegetables*. In: Proceedings of the International Institute of Refrigeration Conference, Bulgaria (1985).

[151] 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.

and types of foods, and with different media and equipment.[152] [153] [154] [155] 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.

[152] 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.

[153] 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.

[154] 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.

[155] 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.

10.1.9 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.[156]) and for milk (e.g. Jordan et al.[157]). 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[158], 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

[156] 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.

[157] 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.

[158] 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.

	potentially favourable for bacterial growth (although the studies reviewed did not present any data to this effect).
Legislative concerns	None.
Payback time (years)	Unknown.

10.1.10 Ice nucleation proteins (INPs)

In the air, ice crystals of pure water grow at -38°C[159]. 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.[160] these substances are present in several biological organisms such as bacteria, fungi, insects, and even frogs.

Li and Lee[161] 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 -40C is a very low storage temperature). The use of the proteins is also claimed to improve frozen food quality.[162]

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.[163] [164]

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[159] Hoose C, and Möhler O., 2012. 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

[160] Petzold, G., and Aguilera, J. M., 2009. Ice morphology: Fundamentals and technological applications in foods. *Food Biophysics, 4*(4), 378–396.

[161] 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.

[162] 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.

[163] 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.

[164] Li, J., and Lee, T. C., 1998. Bacterial extracellular ice nucleator effects on freezing of foods. Journal of Food Science, 63(3), 375–381.

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.

10.1.11 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.[165]) and baking (reviewed by Chhanwal et al.[166]), chilling and freezing (Dirita et al.[167], Marazani et al.[168],

[165] 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.

[166] Chhanwal, N., Bhushette, P.R. and Anandharamakrishnan, C., 2019. Current Perspectives on Non-conventional Heating Ovens for Baking Process—a Review. Food Bioprocess Technol 12, 1–15 (2019).

[167] 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.

[168] 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.

Yang et al.,[169] thawing (Anderson and Singh[170], and Bozatto et al.[171]) and drying (Moreira[172]). In addition to application-specific studies, many fundamental and theoretical studies have been published aimed at aspects such as optimisation of flow.[173] [174]

In terms of performance and efficiency, Chhanwal et al.[166] 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[175] (partly based on the results of Sundsten et al.[176]) 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.[177] 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

169 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.

170 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.

171 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.

172 Moreira, R.G., 2001. Impingement drying of foods using hot air and superheated steam. Journal of Food Engineering, 49(4), pp.291-295.

173 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.

174 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.

175 Salvadori, V.O. and Mascheroni, R.H., 2002. Analysis of impingement freezers performance. Journal of Food Engineering, 54(2), pp.133-140.

176 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.

177 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.

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.

10.1.12 Localised cooling

The use of localised air delivery systems to maintain the temperature of food directly was considered by Burfoot et al.[178] 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.[179] 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.

[178] 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, pp. 23–28.

[179] 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.

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.

10.1.13 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[180] and Owada[181]) 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 Belozerov et al.[182], who included a review of publications on a range of products,

[180] Owada N. Kurita S. 2001. Super-quick freezing method and apparatus therefor. Patent US, no. 6250087B1.

[181] Owada N. 2007. Highly-efficient freezing apparatus and highly-efficient freezing method. Patent US, no. 7237400B2.

[182] Belozerov, G.A., Belozerov, 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.

including apple and potato,[183] pork,[184 185] cod,[186] fish and potato,[187] crab sticks,[188] garlic,[189] and other food types.

Reviews by Kaur and Kumar[190] on application to fruits and vegetables and by Otero et al.[191] 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 Belozerov et al.[192], 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

183 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.

184 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.

185 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.

186 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.

187 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.

188 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.

189 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.

190 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.

191 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.

192 Belozerov, G.A., Belozerov, 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.

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.

10.1.14 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.[193] 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[194]: 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.[195], 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 fish enters the market and further stored at traditional refrigeration temperatures, the benefit of increased shelf life is lost.

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193 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

194 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

195 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

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.[196] 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

[196] Iversen, A., Ziegler, F., Rotabakk, B.T., 2022. Økonomiske og miljømessige effekter av superkjøling av laks. Nofima AS.

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

10.1.15 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 -5C 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.[197]).

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.[198] 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.

[197] 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.

[198] 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.

Application of supercooling to a range of food types has been studied, with examples being meat,[199 200 201] fish,[202 203 204 200] fruit and vegetables,[205 206 207 208 209 210 211 212 213 214] and various others, including a literature review with multiple food types.[215]

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.

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199 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.

200 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.

201 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.

202 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.

203 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.

204 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.

205 Cox, D.R.G., Moore, S.R., 1997. A Process for Supercooling, Patent WO 97/18879.

206 Diehl, H.C., Wright, R.C., 1924. Freezing injury of apples. J. Agric. Res. 29, 0099–0127.

207 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.

208 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.

209 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.

210 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.

211 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.

212 Lucas, J.W., 1954. Subcooling and ice nucleation in lemons. J. Plant Physiol. 29, 245–251.

213 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.

214 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.

215 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.

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.

10.1.16 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[216], Zheng and Sun[217], Zhang et al.[218] and included in several reviews of

[216] 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.

[217] 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.

[218] 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.

novel freezing technologies [219] [220] [221]. While the majority of studies assessed ultrasound applied to immersion freezing systems, some applied ultrasound by direct contact [222] [223]. Application to various food types has been reported, including amongst others chicken,[222] [224] pork,[225] fish,[226] [227] strawberries,[228] mushrooms,[229] [223] potatoes,[230] radishes[231] [232] broccoli,[233]

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[219] 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.

[220] 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.

[221] 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.

[222] 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.

[223] 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.

[224] 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.

[225] 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.

[226] 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.

[227] 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.

[228] 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.

[229] 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.

[230] Tian, Y., Zhang, P., Zhu, Z. and Sun, D.W., 2020a. 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.

[231] Tian, Y., Chen, Z., Zhu, Z. and Sun, D.W., 2020b. Effects of tissue pre-degassing followed by ultrasound-assisted freezing on freezing efficiency and quality attributes of radishes. Ultrasonics Sonochemistry, 67, p.105162.

[232] 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.

[233] 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.

and fruits and vegetables more generally.[234] 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.[235] 11% reduction for chicken, Tian et al.[230] up to 42% for potato cylinders, Bian et al.[226] up to approximately 33% for strawberries depending on use of single or multiple frequency ultrasound and Islam et al.[229] 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.

10.1.17 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

[234] 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.

[235] 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.

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 ChillTM’). Studies with this system and with other more laboratory scale systems have been reported for various meat animal species, including beef,[236] [237] [238] [239] [240] [241] [242] lamb, [243] [244] bison,[245] and pork.[246] [247].

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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236 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, pp. 156–166.

237 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.

238 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/articl e/id/8886.

239 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.

240 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.

241 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.

242 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.

243 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.

244 Fowler, S.M., Claus, J.M. and Hopkins, D.L., 2017. The effect of applying a rinse and chill procedure to lamb carcases immediately post-death on meat quality?. Meat science, 134, pp.124-127.

245 Mickelson, M.A. and Claus, J.R., 2020. Carcass chilling method effects on color and tenderness of bison meat. Meat science, 161, p.108002.

246 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.

247 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.

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.

10.2 Heating

10.2.1 Automatic shutdown

Stojceska et al.[248] 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[249] 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.

$$\text{Energy savings in batch ovens} = [\text{avoided overrun time x steady state oven power}] - [\text{preheating time x max. oven power}]$$

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

[248] 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.

[249] 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.

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.
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

10.2.2 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.[250]

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

[250] 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

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 CO_2 emissions.[251] 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)[252].

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.[253]

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.[254]

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%).

[251] 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

[252] Jiang, J., Hu, B., Wang, R.Z., Deng, N., Cao, F. and Wang, C.-C. (2022) 'A review and perspective on industry high-temperature heat pumps', *Renewable and Sustainable Energy Reviews*, 161, 112106.

[253] 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.

[254] 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.

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

10.2.3 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,[255] spray frying,[256] microwave frying,[257] vacuum frying,[258] and ultrasound-assisted frying.[258]

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,[256] 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.

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[255] 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.

[256] Udomkun, Patchimaporn, Janjira Tangsanthatkun, 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.

[257] 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.

[258] Su, Y., Zhang, M., Adhikari, B., Mujumdar, A.S. and Zhang, W., 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, pp. 148–159. https://doi.org/10.1016/j.ifset.2018.10.011.

This method is thus often combined with other technologies to ensure uniform heating and enhance the nutritional and sensory quality of the fried foods.[259]

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.[260]

compared to atmospheric pressure frying, particularly for fruits and vegetables.[261] Su et al.[262] 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 labscale 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 labscale 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.

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[259] 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.

[260] Tian, J., Chen, S., Shi, J., Chen, J., Liu, D., Cai, Y., Ogawa, Y. and Ye, X., 2017, *Microstructure and digestibility of potato strips produced by conventional frying and air-frying: An in vitro study*, Food Structure, 14, pp. 30–35. https://doi.org/10.1016/J.FOOSTR.2017.06.001.

[261] Manzoor, S., Masoodi, F.A., Rashid, R., Wani, S.M., Naqash, F. and Ahmad, M., 2022, *Advances in vacuum frying: recent developments and potential applications*, Journal of Food Process Engineering, 46(2), e14219. https://doi.org/10.1111/jfpe.14219.

[262] Su, Y., Zhang, M., Adhikari, B., Mujumdar, A.S. and Zhang, W., 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, pp. 148–159. https://doi.org/10.1016/j.ifset.2018.10.011.

Zhang et al.[263] 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 CO_2 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)	-

10.2.4 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.[264]

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[263] Zhang, X., Zhang, M. and Adhikari, B., 2020, *Recent developments in frying technologies applied to fresh foods*, Trends in Food Science and Technology, 98, pp. 68–81. https://doi.org/10.1016/j.tifs.2020.02.007.

[264] You, J., Habibi, M., Rattan, N. and Ramaswamy, H.S., 2016, *Pressure shift freezing and thawing*, in: Balasubramaniam, V.M., Barbosa-Cánovas, G.V., Lelieveld, H. and Ramaswamy, H.S. (eds.), High Pressure Processing of Food, Springer, pp. 143–166. https://doi.org/10.1007/978-1-4939-3234-4_8.

Different publications like Köprüalan et al.[265] confirm that "high pressure freezing techniques are more efficient at preserving the microstructure of foods than conventional freezing techniques".[266] 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.[267] However, studies indicate greater protein denaturation compared to conventional air-blast freezing in fish.[268] 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.[266] However, high pressure thawing can cause protein denaturation and texture change for certain products.[266] 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.[269]

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	

[265] Köprüalan Aydın, Ö., Sarıoğlu, H.Y., Dirim, S.N. and Kaymak-Ertekin, F., 2023, *Recent advances for rapid freezing and thawing methods of foods*, Food Engineering Reviews, 15, pp. 667–690. https://doi.org/10.1007/s12393-023-09356-0.

[266] Aydın, Ö. K., Sarıoğlu, 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.

[267] 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.

[268] 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.

[269] Svendsen, E. S., Widell, K. N., Tveit, G. M., Nordtvendt, 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.

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

10.2.5 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[270], 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"[271] carried out within the International

> 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.

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 [272] documents the state of the art, especially regarding supplier

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270 IEA, 2022. The Future of Heat Pumps, International Energy Agency, Paris, https://www.iea.org/reports/the-future-of-heat-pumps (accessed 2023-2-4).

271 IEA Heat Pumping Technologies TCP, 2021. *Project 58: High-Temperature Heat Pumps*. Available at: https://heatpumpingtechnologies.org/project58/

272 Zühlsdorf, 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. and Arpagaus, C., 2023, *IEA HPT Annex 58: High-Temperature Heat Pumps. Task 1 report: Technologies*, available at: https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2023/09/annex-58-task-1-technologies-task-report.pdf.

technologies (including TRL for close-to-market technology) and demonstration cases. 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.

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}.

$$COP_h = \frac{\dot{Q}_h}{P_{el}} \qquad \text{Eq. (1)}$$

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.

$$\nu_{C,h} = \frac{COP_h}{COP_{h,Carnot}} \qquad \text{Eq. (2)}$$

$$COP_{C,h} = \frac{T_{sink}}{T_{sink} - T_{source}} \qquad \text{Eq. (3)}$$

Error! Reference source not found. (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 40 (right), CO_2 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 Agengy Austria.[273]

[273] Umweltbundesamt, 2023. Berechnung von Treibhausgas (THG)-Emissionen verschiedener Energieträger, secure.umweltbundesamt.at/co2mon/co2mon.htm

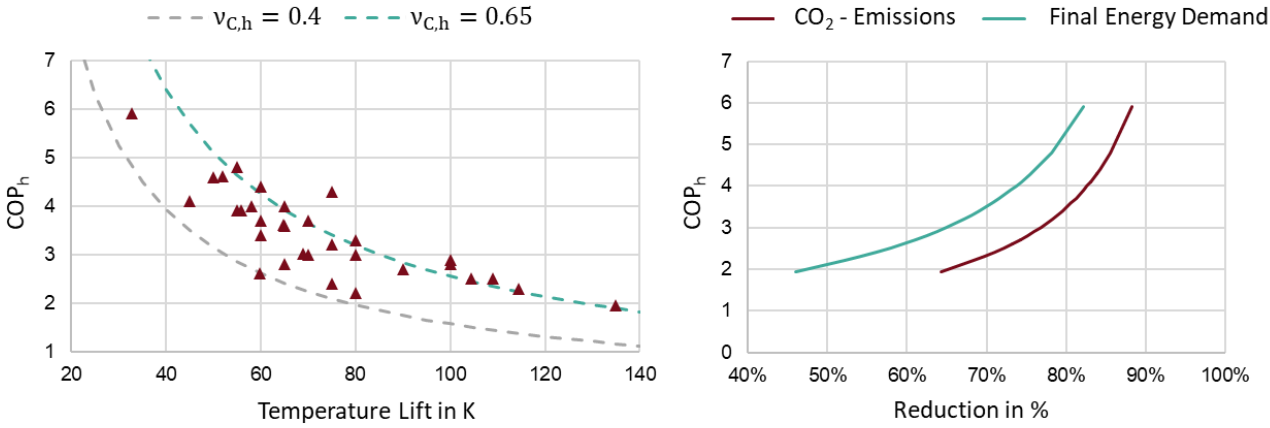

Figure 40. COP as a function of temperature lift for selected HTHPs (left) and CO2 and final energy savings depending on the COP (right), based on Dusek et al. (2024) with data reported in Task 1 of the IEA HPT Annex 58 (https://heatpumpingtechnologies.org/annex5

Figure 41 depicts processes in the food and beverages sector with the corresponding typical supply temperatures and corresponding TRL of the HTHP. According to Arpagaus [274], 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.

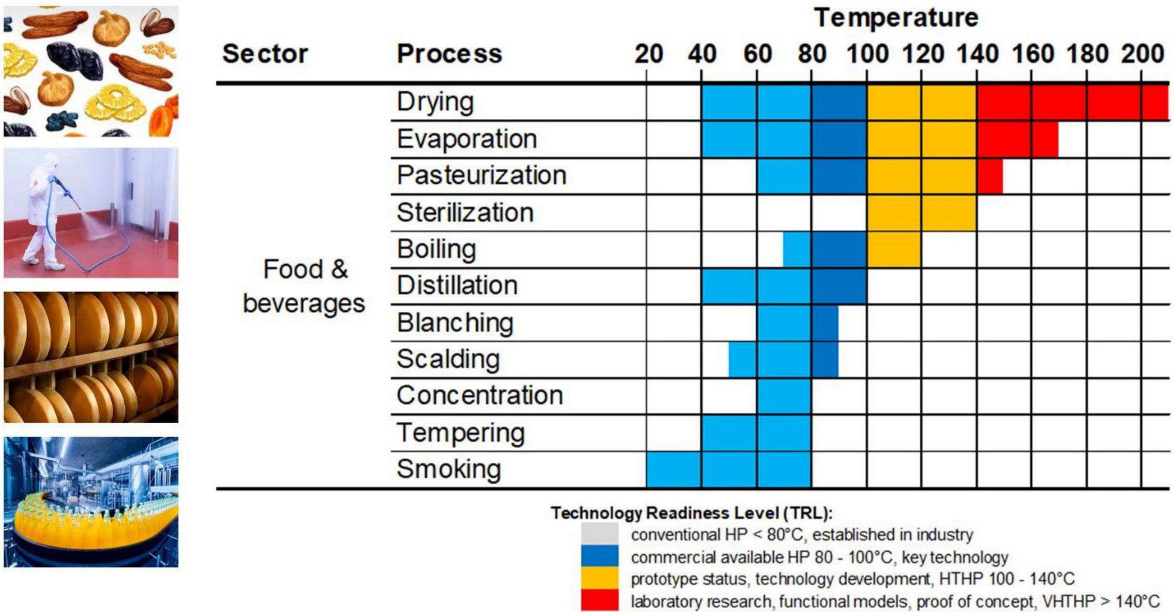

Figure 41: Typical supply temperature ranges of processes in the food and beverage sector. Source: Arpagaus et al. (2023)

[274] 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.

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

10.2.6 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.[275]

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.[276] 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

[275] 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.

[276] 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. https://doi.org/10.1016/j.foodcont.2016.07.019.

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	TRL 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 Listeria monocytogenes 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

10.2.7 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 19.

Table 8: 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)	460.000 kg/year [3].
Quality of scope 1 emissions information	
Scope 2 emissions savings (% or another quantifiable metric)	
Quality of scope 2 emissions information	
Availability barriers	
TRL level	TRL 7-9
Maintainability issues	

Legislative concerns	
Payback time (years)	

10.2.8 Impingement cooking using air jets

Forced convection heat transfer by circulating heated air in ovens is widely used in units for cooking and baking.[277] 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.[278] The impinging jets result in high convective heat transfer rates at the food surface. Li and Walker[279] 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/m^2 K for the top and 17.4–110.9 W/m^2 K for the bottom of the oven, for the two types. Values over 200 W/m^2 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[280]) compared to only about 10–20 W/m^2 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 has pizza where the internal heat transfer resistance is small compared to that at the surface.[281] [282] 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-

[277] Cappelli, A., Lupori, L., and Cini, E., 2021. Baking technology: A systematic review of machines and plants and their effect on final products, including improvement strategies. Trends in Food Science and Technology, 115, 275–284. https://doi.org/10.1016/j.tifs.2021.06.048

[278] Kerry, J. F., 2011. Effects of novel thermal processing technologies on the sensory quality of meat and meat products. Processed Meats: Improving Safety, Nutrition and Quality, 617–665. https://doi.org/10.1533/9780857092946.3.617

[279] Li, A., and Walker, C. E., 1996. Cake Baking in Conventional, Impingement and Hybrid Ovens. Journal of Food Science, 61(1), 188–191. https://doi.org/10.1111/J.1365-2621.1996.TB14756.X

[280] 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

[281] Chhanwal, N., Bhushette, P.R. and Anandharamakrishnan, C., 2019. Current Perspectives on Non-conventional Heating Ovens for Baking Process—a Review. Food Bioprocess Technol 12, 1–15 (2019).

[282] 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

velocity air impingement from slots or nozzles for baking different types of products. High heat transfer rates also mean 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[282], “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.”[282] 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.[283] 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.[284] 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.[285] The analysis indicated that air

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[283] 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

[284] 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

[285] 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

impingement could lead up to 17.9% energy savings. Li et al.[286] 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.[287] 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.[288] 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.[288] Shevade et al.[289] 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.[290] analysed, for continuous pizza baking, the CO_2 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

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[286] Li, X. D., Alamir, M., Witrant, E., Della-Valle, G., Rouaud, O., Boillereaux, L., and Josset, C., 2013. Further investigations on energy saving by jet impingement in bread baking process. IFAC Proceedings Volumes, 46(2), 701–706. https://doi.org/10.3182/20130204-3-FR-2033.00017

[287] Geedipalli, S., Datta, A. K., and Rakesh, V., 2008. Heat transfer in a combination microwave–jet impingement oven. Food and Bioproducts Processing, 86(1), 53–63. https://doi.org/10.1016/J.FBP.2007.10.016

[288] Kerry, J. F., 2011. Effects of novel thermal processing technologies on the sensory quality of meat and meat products. Processed Meats: Improving Safety, Nutrition and Quality, 617–665. https://doi.org/10.1533/9780857092946.3.617

[289] 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

[290] 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

technology. Emissions were calculated using data from the Mexican national electrical system, the value reported for the year 2019 was 0.505 kg CO_2 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) 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

10.2.9 Improve combustion efficiency (gas/oil)

Gas burners are typically 85–95% efficient.[291] 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".[292] It has also been reported that electric ovens are more energy efficient than

[291] 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

[292] 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

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.[293]

Measures for oven combustion control have been adequately described by Therkelsen et al.[291] 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 O_2 greater than 4% in the flue gas, to avoid carbon monoxide (CO) development and soot deposits.[293] 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.[294] 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.[295] 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.[296] 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

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293 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

294 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

295 Anonymous., 2007. Oxygen Trim Control - a disregarded option. Trim System. https://www.scan-tronic.dk/Articles/trim_control_article.pdf

296 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

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.[296] See the respective review on this topic. Mukherjee et al.[297] 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.[298] 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[299] for 89 bakery sites, showed that improved combustion efficiency leads to average reduction of 196 tons of CO_2 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%.

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297 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

298 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

299 Carbon Trust., 2016. Industrial Energy Efficiency Accelerator. Guide to the Industrial Bakery Sector. https://issuu.com/mikeglanfield/docs/ctg034-bakery-industrial-energy-eff

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_2e 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

10.2.10 Improved oven control

Zareifard et al.[300] 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%.

[300] 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

Papasidero et al.[301] 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.[302] 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.[303] 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.[304] applied classical control theory to a heat conduction model with convective boundary conditions to obtain optimal heating strategies. The methodology was applied to two

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[301] 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

[302] 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

[303] 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

[304] Stigter, J. D., Scheerlinck, N., Nicolaï, 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

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.[305] 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[306], 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).

10.2.11 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.[307] Measured throughput (kg/h) and average power (kW) were used to calculate the SEC for direct and

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[305] 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

[306] 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

[307] Carbon Trust., 2016. Industrial Energy Efficiency Accelerator. Guide to the Industrial Bakery Sector. https://issuu.com/mikeglanfield/docs/ctg034-bakery-industrial-energy-eff

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.[308] 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 (Klemes et al.[309] as cited by Ladha-Sabur et al.[310]), 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

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308 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

309 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

310 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

10.2.12 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.[311] reviewed the use of microwaves, primarily is 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 absorbs 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

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[311] 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.

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.[312] 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.[313] 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.[314] 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.[315]

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)

312 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.

313 Jouquand, C., Tessier, F.J., Bernard, J., Marier, D., Woodward, K., Jacolot, P., Gadonna-Widehem, P. and Laguerre, J-C., 2015, *Optimization of microwave cooking of beef burgundy in terms of nutritional and organoleptic properties*, LWT – Food Science and Technology, 60(1), pp. 271–276.

314 Pathare, P.B. and Roskilly, A.P., 2016. Quality and energy evaluation in meat cooking. Food Engineering Reviews, 8(4), pp.435-447.

315 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.

Maintainability issues	None
Legislative concerns	None
Payback time (years)	Very dependent on process and food. Very limited information.

10.2.13 Motor efficiency (fans and conveyors)

In food processing facilities, electrical motors typically run conveyors, combustion air fans and convection fans.[316]

Energy efficiency could be improved by use of the control systems in the ovens to lower the speed of the motor.[317] 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 I 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.[316] 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 conveyer belt motors are relatively low power (0.5 kW), according to Carbon Trust, 2016[318]: 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.

[316] 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

[317] 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

[318] Carbon Trust., 2016. Industrial Energy Efficiency Accelerator. Guide to the Industrial Bakery Sector. https://issuu.com/mikeglanfield/docs/ctg034-bakery-industrial-energy-eff

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.

10.2.14 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 [319]; Mirmoghtadaie et al., 2010 [320]). 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 (Sakr and Liu. 2014 [321]). As a result, thermal damage to food products is minimised in comparison to traditional thermal heating techniques. Despite the benefits of highly uniform heating,

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[319] Barrett, D.M., Beaulieu, J.C. and Shewfelt, R. (2015) 'Color, flavor, texture, and nutritional quality of fresh-cut fruits and vegetables: desirable levels, instrumental and sensory measurement, and the effects of processing', *Critical Reviews in Food Science and Nutrition*, 50(5), pp. 369–389.

[320] Mirmoghtadaie, L., Kadivar, M. and Shahedi, M. (2010) 'Effects of succinic acid and Ohmic heating on the physicochemical properties of sugar beet pulp', *Food Chemistry*, 124(1), pp. 1–5.

[321] Sakr, M. and Liu, S. (2014) 'A comprehensive review on applications of Ohmic heating (OH)', *Renewable and Sustainable Energy Reviews*, 39, pp. 262–269. doi:10.1016/j.rser.2014.07.061.

consistent results, and reduced processing times, Ohmic heating remains to be adopted on a commercial production scale (Varghese et al., 2014)[322].

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.[323] [324] [325] [326] [327] [328]

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[329] as well as the environmental and energy impact of the application of Ohmic

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[322] Varghese, K.S., Pandey, M.C., Radhakrishna, K. and Bawa, A.S. (2014) 'Technology, applications and modelling of ohmic heating: A review', *Journal of Food Science and Technology*, 51(10), pp. 2304–2317. doi:10.1007/s13197-012-0710-3.

[323] 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

[324] 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

[325] Aurina, K., and Sari, A., 2022. 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

[326] 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.

[327] 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.

[328] 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

[329] Abea, A., Gou, P., Guàrdia, M.D., Picouet, P., Kravets, M., Bañón, S. and Muñoz, I., 2022, *Dielectric heating: a review of liquid foods processing applications*, Food Reviews International, 39(8), pp. 5684–5702. https://doi.org/10.1080/87559129.2022.2092746.

heating[324] refer to energy savings up to 65% in pasteurisation treatments.[330] 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 CO_2 emissions was determined. Similarly, 73% energy savings was reported[331] 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.[332] [333]

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

330 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

331 Balthazar, C.F., Cabral, L., Guimarães, J.T., et al., 2022, *Conventional and ohmic heating pasteurization of fresh and thawed sheep milk: energy consumption and assessment of bacterial microbiota during refrigerated storage*, Innovative Food Science and Emerging Technologies, 76, 102947. https://doi.org/10.1016/j.ifset.2022.102947

332 Majid, I., Khan, S., Aladel, A., Dar, A. H., Adnan, M., Khan, M. I. and Ashraf, S. A., 2023. Recent insights into green extraction techniques as efficient methods for the extraction of bioactive components and essential oils from foods. CyTA-Journal of Food, 21(1), 101-114. tandfonline.com

333 Chinnamayan, S., Anvarsha, N. and Palanichamy, K., 2024. Carbon-Based Nanocomposites: A Comprehensive Review of Their Multifunctional Applications. In: Nanocomposites - Properties, Preparations and Applications. IntechOpen. https://doi.org/10.5772/intechopen.114402

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	TRL 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)	

10.2.15 Recovery of exhaust heat

Exhaust heat from cooking/baking operations has been reported an important energy loss of food processing operations.[334] 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.[335] These authors propose waste heat recovery as a very effective technique to offset these losses. In their review, Mukherjee et al.[335] 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 CO_2 emissions, based on previous work by Law et al.[336] Enjay GmbH[337] 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.[338] for a pilot scale and industrial scale wafer baking oven study indicate that utilising an

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[334] 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

[335] 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

[336] 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.

[337] Enjay GmbH., 2025 https://content.enjaysystems.com/articles-english/lepido-by-enjay-a-heavy-duty-heat-exchanger

[338] 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

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 CO_2 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). CO_2 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[339] [340] [341], 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 oven. 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

[339] 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

[340] 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

[341] 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

	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.

10.2.16 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.[342], 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

342 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

1 h with a specific energy consumption of 1.5 kWh/kg[343] 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.

10.2.17 Reduce thermal mass of tins

As part of the energy efficiency analysis for the bakery sector[344], 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.

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343 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

344 Carbon Trust. (2016). Industrial Energy Efficiency Accelerator. Guide to the Industrial Bakery Sector. . https://issuu.com/mikeglanfield/docs/ctg034-bakery-industrial-energy-eff

Paton et al.[345] 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

10.2.18 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.

[345] Paton, J., Khatir, Z., Thompson, H., Kapur, N., & 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.

Foundational work by Barreiro et al.[346] and Bhowmik et al.[347] developed detailed methods for estimating the total energy consumption of the retort process. Simpson et al.[348] further advanced this by creating a procedure to quantify both total and transient energy consumption.

Simpson and Almonacid[349] 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.[350] 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.[351], Bhowmik et al.[352], and Simpson et al.[353], 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

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346 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.

347 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.

348 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.

349 Simpson, R. and Almonacid, S., 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.

350 Simpson, R., Jiménez, D., Almonacid, S., Nuñez, H., Pinto, M., Ramírez, C., Vega-Castro, O., Fuentes, L. and Angulo, A. 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, 109839. https://doi.org/10.1016/J.JFOODENG.2019.109839.

351 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.

352 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.

353 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.

create more opportunities for VRTPs. Pitarch et al.[354] 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.[355]

Scope 1/2 emissions savings (% or another quantifiable metric)	Up toto 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)

10.2.19 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

[354] 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.

[355] Kubo, M.T.K., Baicu, A., Erdogdu, F., Poças, M.F., Silva, C.L.M., Simpson, R., Vitali, A.A. and Augusto, P.E.D. 2023. Thermal processing of food: challenges, innovations and opportunities. A position paper. *Food Reviews International*, 39(6), 3344–3369. https://doi.org/10.1080/87559129.2021.2012789..

reduced total energy use by approximately 40%, 26%, and 26% for coffee, chocolate, and black malts, respectively.[356] [357]

Superheated steam roasting is a modern technique in which water is heated beyond its boiling point at a given pressure to create superheated steam.[358] [359] [360] 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.[361] 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.[362]

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[356] Gunel, Z., Torun, M. and Sahin-Nadeem, H. 2020. Effects of different roasting methods on energy consumption and quality characteristics of roasted carob powder. *Journal of Food Processing and Preservation*, 44(11).

[357] Akkarachaneeyakorn, S., Laguerre, J.C., Tattiyakul, J., Neugnot, B., Boivin, P., Morales, F.J. and Birlouez-Aragon, I., 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–E207. https://doi.org/10.1111/j.1750-3841.2010.01567.x

[358] Suleman, R., Ahmad, M., Ahmad, N., Ullah, R. and Ahmad, S. 2020. Effect of superheated steam roasting on physicochemical properties and antioxidant activity of almond kernels. *Journal of Food Processing and Preservation*, 44(5), e14417.

[359] Idrus, N.F.M., Shamsudin, R., Adzahan, N.M. and Kadir, A.A. 2017. Effects of superheated steam roasting on the quality attributes of cocoa beans. *International Food Research Journal*, 24(5), 1983–1989.

[360] Chindapan, N., Soydok, S. and Devahastin, S., 2019. ‘Roasting kinetics and chemical composition changes of Robusta coffee beans during hot air and superheated steam roasting’, *Journal of Food Science*, 84(2), pp. 292–302. doi:10.1111/1750-3841.14422.

[361] Sruthi, N.U., Premjit, Y., Pandiselvam, R., Kothakota, A. and Ramesh, S.V., 2021. An overview of conventional and emerging techniques of roasting: effect on food bioactive signatures. *Food Chemistry*, 348, p. 129088. https://doi.org/10.1016/J.FOODCHEM.2021.129088.

[362] Keppler, J., Schwarz, S., Teutsch, I., Jäger, H. and Rohm, H., 2016. ‘Vibration roasting of cocoa beans: effects on product quality and process efficiency’, *Journal of Food Engineering*, 190, pp. 44–52. *Journal of Food Engineering* Volume 190, Pages 44–52.

Far infrared (IR) radiation, with electromagnetic waves ranging from 3 to 1000 μm in wavelength, is another method used in roasting.[363] 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.[364] These time reductions align with findings by Hebber et al.[365], 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[366] and average investment cost ranges of industrial roasters.[367] (**Error! Reference source not found.**).

Table 9: 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

[363] Bagheri, H., Kashaninejad, M., Ziaiifar, A.M. and Aalami, M. 2016. Novel hybridised infrared–hot air method for roasting of peanut kernels. *Innovative Food Science and Emerging Technologies*, 37, 106–114. https://doi.org/10.1016/j.ifset.2016.08.014

[364] Yang, W., Sokhansanj, S., Tang, J. and Winter, P. 2010. Roasting of peanuts using infrared and hot air. LWT – Food Science and Technology, 43(1), 112–119.

[365] Hebbar, H.U., Vishwanathan, K.H. and Ramesh, M.N., 2004. Development of infrared-assisted hot air dryer for vegetables. Journal of Food Engineering, 65(4), 557–563.

[366] Tsai, W.-H., Lee, K.-H. & Huang, C.-C. (2025) 'Energy Efficiency and Carbon Emission Reduction in Coffee Roasting: Approach of Activity-Based Costing (ABC) Methodology', *Energies*, 18(5), article 1018. doi:10.3390/en18051018.

[367] Porter, J. 2024. Industrial coffee roaster investment costs: market overview and equipment price ranges. Industry report.

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)

10.2.20 Steaming - efficiency improvements, novel options

Karayannakidis et al.[368] 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.[369] 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

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368 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.

369 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.

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[370] 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.[370] Estimated pay back times are given in Table 10: Pay back times, depending on yearly production volumes.[371] [372] [369]

Table 10: Pay back times

Scenario	Annual through-put (tons)	Conventional energy use (kWh/ton)	Advanced energy use (kWh/ton)	Enery 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)	-

[370] Anon., 2021. How much does Steam Infusion cost? https://steaminfusion.oalgroup.com/blog/cost. Consulted on 30/4/2025.

[371] 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.

[372] 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.

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)

10.3 Other

10.3.1 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[373], heat pump technology[374], air humidification technology[375], and mechanical vapour recompression (MVR) technology.[376] 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.

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[373] 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.

[374] 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.

[375] 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.

[376] Han, D. 2015. "Study on Zero-emission Desalination System Based on Mechanical Vapor Recompression Technology." Energy Procedia 75: 1436-1444.

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.[373]

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.[377] This concentration process enhances the product's flavour and nutritional value while minimising storage and transportation costs.[378]. Moreover, it provides microbiological stability to the food product.[379] 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.[380] [381] 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.[382] 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 CO_2-equivalent, alongside energy savings of 39,943

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[377] Giner Santonja, G., Karlis, P., Raunkjær Stubdrup, K., Brinkmann, T. and Roudier, S. 2019. *Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries*. JRC Science for Policy Report, EUR 29978 EN. European Commission.

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

[379] 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.

[380] Giner Santonja, G., Karlis, P., Raunkjær Stubdrup, K., Brinkmann, T. and Roudier, S. 2019. *Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries*. JRC Science for Policy Report, EUR 29978 EN. European Commission.

[381] 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.

[382] 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.

GJ.[383] A case study of Chivas Brothers distilleries in Scotland reported an annual reduction of over 4,300 tonnes of CO_2 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.[384]

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	-

383 EECA, 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/.

384 Renewable Thermal Collaborative, 2018. Case Study: MVR Heat Pumps and Thermal Efficiency at Chivas Brothers Distillery.

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

10.3.2 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.[385] 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.[386]

The availability of biodiesel is regarded as low, however, the adaption to fishing vessels is at a rather high maturity level. Furthermore, the CO_2 emissions are reduced by about 50 % compared to diesel oil when biodiesel is utilised.[386] The study by Lin and Huang[387] 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 conclude that 20 wt% of biofuel blended with diesel has the highest cost-benefit ratio.[387]

On a long-term perspective (2030 – 2050), the use of hydrogen, batteries and methanol is foreseen to be used in ships.[385]

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

[385] 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.

[386] Gabrielii, C. H., and Jafarzadeh, S., 2020. Alternative fuels and propulsion systems for fishing vessels. Trondheim: Sintef Energy AS.

[387] 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.

hydrogen included,[386] with the possibility of being an almost carbon neutral fuel source when produced “green”.[388]

While the current status of batteries deployed in fishing vessels requires further advancements, Gabrielii and Jafarzadeh 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.[386]

Methanol as a fuel source cuts SO_x emissions, decreases particulate matter emissions and NOx emissions are dependent on the engine type. CO_2 emissions are dependent on the type of methanol production, and significant CO_2 savings are achieved when the production is based on renewable sources.[389]

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

388 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.

389 Gabrielii, C. H., and Jafarzadeh, S., 2020. Alternative fuels and propulsion systems for fishing vessels. Trondheim: Sintef Energy AS.

10.3.3 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 by Szepessy and Thorwid[390] 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™[391] 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

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[390] 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

[391] 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/

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	TRL 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

10.3.4 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[392] showed reducing pressure from

[392] 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.

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.[393]

Šešlija et al.[394] 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.[395] 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,

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[393] 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.

[394] 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.

[395] 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.

multi-stage specific power is approximately 16 to 18 kW/100 cfm, compared to 18 to 19 kW/100 cfm for single stage.[396]

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.[396]

Air compressors generate a lot of heat, according to compare,[397] 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[397] 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.

10.3.5 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,

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396 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

397 CompAir, 2025. Sustainable Heat Recovery Systems for Oil-free Compressors. https://www.compair.com/en-gb/air-treatment-and-accessories/heat-recovery-oil-free.

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 coching 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[398] conducted a modelling study on the energy required for structural modification in continuous conching systems. Medina-Torres et al.[399] 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[400] 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.[401] 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

[398] 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.

[399] 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.

[400] 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.

[401] 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.

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	TRL 6-8
Maintainability issues	Wear of high shear parts, must be accessible and adjustable.
Legislative concerns	None
Payback time (years)	Not yet available.

10.3.6 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".[402] [403]

Gontarz et al.[404] 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 can affect efficiency and effectiveness of grinding, limiting overall availability of ground food products.
TRL level	TRL 7-9
Maintainability issues	Maintenance costs represent a significant portion of total cost of ownership, about 40%.
Legislative concerns	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)	

402 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.

403 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.

404 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.

10.3.7 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.[405] 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'.[406]

little work to investigate the potential energy savings although these are claimed to be substantial (40 - to 50% claimed by Taylor[405], and repeated by Pisula and Tyburcy[407]).

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	High, 8 -9.
Maintainability issues	Nothing unusual for abattoir facilities.
Legislative concerns	None.
Payback time (years)	No information.

405 Taylor, A. A. 1985. Optimal chilling and ES parameters for hot boning. In: Romita, A., Valin, C. and Taylor, A. A. (eds) *Accelerated Processing of Meat*. EEC Report of Working Party, Rome, 29–31 October, pp. 3–19. Elsevier Applied Science Publishers Ltd.

406 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.

407 Pisula, A. and Tyburcy, A. 1996. Hot processing of meat. *Meat Science*, 43, 125–134.

10.3.8 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, we 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.[408]

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.[409] [410] [411]
- **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.[412]
- **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

[408] 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.

[409] Subash, A., Ramanathan, H. N. and Šostar, M. 2024. From catch to consumer: enhancing seafood processing management with Industry 4.0 innovations. *Discover Food*, 4(1), 43. Available at: https://link-springer-com.ezproxy.cad.univpm.it/article/10.1007/s44187-024-00115-6.

[410] Bunian, S., Al-Ebrahim, M. A. and Nour, A. A. 2024. Role and applications of artificial intelligence and machine learning in manufacturing engineering: a review. *Engineered Science*, 29, 1088. Available at: https://www.espublisher.com/journals/articledetails/1088.

[411] Biswas, P., Rashid, A., Biswas, A., Nasim, M. A. A., Gupta, K. D. and George, R. 2024. AI-driven approaches for optimizing power consumption: a comprehensive survey. *arXiv preprint*, arXiv:2406.15732. Available at: https://arxiv.org/html/2406.15732v1.

[412] Ahmadzadeh, S., Ajmal, T., Ramanathan, R. and Duan, Y. 2023. A comprehensive review on food waste reduction based on IoT and big data technologies. *Sustainability*, 15(4), 3482. Available at: https://www.mdpi.com/2071-1050/15/4/3482.

its use and minimizing reliance on grid electricity, thus significantly reducing Scope 2 emissions.[413] [414]

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:

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[413] Miller, M., Kisiel, A., Cembrowska-Lech, D., Durlik, I. and Miller, T. 2023. IoT in water quality monitoring—Are we really here? *Sensors*, 23(2), 960. Available at: https://www.mdpi.com/1424-8220/23/2/960.

[414] Cowell, N. 2024. Sustainable AI – At the core of the energy revolution. *Fujitsu Corporate Blog*, 19 December 2024. Available at: https://corporate-blog.global.fujitsu.com/fgb/2024-12-19/01/.

- **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.[415]
- **EU Cybersecurity Act/Cyber Resilience Act**: This act aims to enhance cybersecurity and cyber resilience across the EU.[416] [417]
- **EU Artificial Intelligence Act**: This act aims to ensure the safe and ethical use of AI.[418]

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,

[415] European Parliament. 2017. *EU Official Controls Regulation*. EU. Available at: https://eur-lex.europa.eu/eli/reg/2017/625/oj.

[416] European Parliament. 2019. *EU Cybersecurity Act*. EU. Available at: https://eur-lex.europa.eu/eli/reg/2019/881/oj.

[417] European Parliament. 2024a. *EU Cyber Resilience Act*. EU. Available at: https://eur-lex.europa.eu/eli/reg/2024/2847/oj.

[418] European Parliament. 2024b. *EU Artificial Intelligence Act*. EU. Available at: https://eur-lex.europa.eu/eli/reg/2024/1689/oj.

	2019; European Parliament, 2024a). EU AI Act (European Parliament, 2024b).
Payback time (years)	Not available.

10.3.9 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. Other food products include nut butter, spices and coffee and tea. There are several traditional milling methods that can be listed: stone milling, where this age-old technique involves grinding grains between two stones. While slow and labour-intensive, it produces flour with a distinct flavour and texture.[419] The other is the roller milling, which method uses a series of smooth rollers to crush and grind grain. It offers greater control over particle size and is widely used in commercial milling operations.[420] Traditional mills are not suitable for large-scale industrial production, so modern methods like hammer mills are now used. 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.[420]

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 VSDs 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.

Thermoelectric generators (TEGs)

Using TEGs to recover waste heat from milling processes and convert it into electrical energy can improve energy efficiency and reduce environmental impact.[421]

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[419] Tufts Food Lab., 2025. https://foodlab.nutrition.tufts.edu/milling-and-storage/#:~:text=Health%2Dconscious%20consumers%20associate%20%E2%80%9Cstone,is%20the%20oldest%20milling%20technology.

[420] Pingle., 2025. What Are the Different Between Hammer Mills and Roller Mills. https://www.pinglemachine.com/news/what-are-the-different-between-hammer-mills-and-roller-mills.html#:~:text=Roller%20mills%20offer%20excellent%20control,require%20precise%20particle%20size%20distribution.

[421] Abdel-Aal, E.S.M., 2024. Insights into Grain Milling and Fractionation Practices for Improved Food Sustainability with Emphasis on Wheat and Peas. Foods, 13(10), p.1532.

During milling, a significant amount of heat is generated at the cutting tool-workpiece interface. This heat is often transferred to the coolant used to maintain optimal operating temperatures. A TEG can be integrated into the coolant system to capture the heat from the coolant before it is dissipated. The TEG converts this heat into electrical energy, which can be used to power auxiliary systems or fed back into the grid. This method not only recovers waste heat but also improves the overall energy efficiency of the milling process.[422]

The direct heat recovery can also be applicable for the milling process: The surfaces of milling machines and tools can become quite hot during operation. TEGs can be attached directly to these surfaces to capture the heat. TEG modules can be mounted on the milling machine's hot surfaces, such as the spindle or cutting tool holder. These modules convert the heat into electricity, which can be used to power sensors, control systems, or other low-power devices.[423]

Advanced milling techniques

Adopting advanced milling techniques, such as cryogenic milling and microwave-assisted milling, can reduce energy consumption and improve product quality.[424]

Cryogenic milling uses liquid nitrogen to cool grains before milling. This makes the grains more brittle and easier to grind. Suitable for heat-sensitive grains and spices. Reduces heat generation, preserves nutritional quality, and improves the texture of the final product.

Microwave energy can be used to heat and soften grains before milling. This technique reduces the hardness of grains, making them easier to mill. Used for various grains and pulses. Reduces energy consumption and improves milling efficiency.

Ultrasound can be applied to create micro-cavities in grains, which helps in breaking them down more easily during milling. Used for grains and pulses. Enhances milling efficiency, reduces energy consumption, and improves the quality of the final product.

High-pressure milling involves applying high pressure to grains to break them down before milling. Suitable for tough grains and pulses. Improves milling efficiency and reduces energy consumption.[425]

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[422] Şahin, O. and Karayel, D., 2024. Development of an Original Integrated System for Heat Recovery from Coolant in the Machining Process and Investigation of Its Efficiency. Applied Sciences, 14(24), p.11499.

[423] Aridi, R., Faraj, J., Ali, S., Lemenand, T. and Khaled, M., 2021. Thermoelectric power generators: state-of-the-art, heat recovery method, and challenges. Electricity, 2(3), pp.359-386.

[424] Abdel-Aal, E.S.M., 2024. Insights into Grain Milling and Fractionation Practices for Improved Food Sustainability with Emphasis on Wheat and Peas. Foods, 13(10), p.1532.

[425] Gazda, P. and Glibowski, P., 2024. Advanced technologies in food processing—Development perspective. Applied Sciences, 14(9), p.3617.

Scope 1 emissions savings (% or another quantifiable metric)	
Quality of scope 1 emissions information	N/A
Scope 2 emissions savings (% or another quantifiable metric)	
Quality of scope 2 emissions information	High
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	Need to have environmental regulation, safety and healthy instruction, and the companies are increasingly required to report and reduce their GHG emissions by their energy consumption
Payback time (years)	No information

10.3.10 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[426] found that alternative heat exchanger networks or heat pumps generally had better energy saving potential and payback than CHP systems.

The UK Government[427] 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 mesopourous silica or alumina.[428] 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.[429]

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.[430] 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.[431]

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.

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[426] Fritzson, A. and Berntsson, T., 2005. Energy efficiency in the slaughter and meat processing industry – opportunities for improvements in future energy markets. Journal of Food Engineering 77, 792-802, 2005.

[427] UK Government. 2022. Combined heat and power. https://www.gov.uk/guidance/combined-heat-and-power.

[428] Critoph, R. E. and Zhong, Y., 2005. Review of trends in solid sorbtion refrigeration and heat pumping technology, Proc. ImechE, Vol. 219, Part E, J. Process Mechanical Engineering.

[429] Invernizzi, C. and Iora, P. 2005. Heat recovery from micro-gas turbine by vapour jet refrigeration systems. *Applied Thermal Engineering*, 25, 1233–1246.

[430] Sonar, D., Soni, S.L. and Sharma, D., 2014. Micro-trigeneration for energy sustainability: Technologies, tools and trends. Applied Thermal Engineering, 71(2), pp.790-796.

[431] Bassols J, Kuckelkorn B, Langreck J, Schneider R and Veelken H, 2002. Trigeneration in the food industry, Applied Thermal Engineering 22, 595-602.

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.

10.3.11 Refining and extraction

De Rosa et al.[432] report that producing Roundtable for Sustainable Palm Oil (RSPO) certified palm oil results in 3.41 kg CO_2-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 CO_2-equivalent/kilogram of oil) of the total CO_2 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 CO_2 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 CO_2 emissions for 60 tons/hour CPO input.[432]

The direct carbon intensity for each unit was determined by dividing its direct CO_2 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 CO_2/$, respectively. Although RBDPO has a

[432] De Rosa, M., Schmidt, J. and Pasang, H., 2022. Industry-driven mitigation measures can reduce GHG emissions of palm oil. Journal of Cleaner Production, 365, p.132565.

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 CO_2 emissions were found to be 2339.97 kg, within an average carbon intensity of 0.0432 kg CO_2/$. The target is to reach the average carbon intensity reduction of refinery by 20%, which means 0.0345 kg CO_2/$ based on the article.[433]

There are four scenarios proposed to achieve the 20% reduction in CO_2 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 CO_2 emissions while managing capital costs.

Results from the different scenarios, the first with lowering ΔT_{min} to 10°C or 15°C reduced CO_2 emissions by 25% and 13.9%, respectively, with significant cost savings. Other scenarios: heat recovery from deodorizing column vapour, reduced CO_2 emissions by 33.6% and 15% for different options (with potential cost savings) and implementing biomass boilers achieved a 24.9% reduction in CO_2 emissions (but required high capital investment). The fourth scenario reduces the CO_2 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 CO_2 emissions.[433]

Alternative refining techniques include

- **Cold pressing**: this method involves extracting oils and juices without using heat, preserving nutrients and reducing energy consumption.[434]
- **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.[435]

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[433] 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.

[434] Moore, R. 2024, Exploring Cold-Pressing: A Nutrient-Preserving Processing Method.

[435] Charcosset, C. 2021, Classical and Recent Applications of Membrane Processes in the Food Industry.

- **Supercritical CO_2 extraction**: uses supercritical CO_2as a solvent to extract essential oils and flavours, offering a cleaner alternative to traditional solvent-based methods.[436]
- **Ultrasonic processing**: employs high-frequency sound waves to enhance extraction and refining processes, improving efficiency and reducing the need for chemical additives.[437]
- **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.[438]
- **Fermentation**: leveraging natural fermentation processes to refine and enhance food products, reducing the need for synthetic additives and improving sustainability.[439]
- **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.[440]

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.[441]
- ***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.

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[436] Wang, W., Rao, L., Wu, X., Wang, Y., Zhao, L., and Liao, X. (2020). Supercritical carbon dioxide applications in food processing. Volume 13, 570-591.

[437] McHugh, T. 2016, Putting Ultrasound to Use in Food Processing.

[438] Raso, J., Heinz, V., Alvarez, I. and Toepfl, S., 2022. Pulsed electric fields technology for the food industry. Cham, Switzerland: Springer International Publishing.

[439] 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.

[440] Wang, C., Wang, Z., Wang, X., Li, N., Tao, J., Zheng, W., Yan, B., Cui, X., Cheng, Z. and Chen, G., 2022. A review on the hydrothermal treatment of food waste: processing and applications. Processes, 10(11), p.2439.

[441] Luo, Y., Jagtap, S., Trollman, H. and Garcia-Garcia, G., 2022. A framework for recovering waste heat energy from food processing effluent. Water, 15(1), p.12.

- ***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%[442]
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	TRL 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, Quality Assurance (QA) standards, environmental regulations, import-export regulations, which may also affect to the carbon footprint.
Payback time (years)	No information

[442] 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.

10.3.12 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[443] and dairy products.[444] 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.[445] [446] 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.[447] Often, RO is used only as a pretreatment for evaporative processing, therefore lowering the energy saving impact.

Chamberland et al.[444] 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.

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[443] Ma, Z., Noor, I.I., Wang, X., Ren, Y., Wang, J., Wang, Q., Gao, J., Gao, X. and Liu, H., 2024. A comprehensive review on the recent advances in membrane-based processes for fruit juice concentration. *Food and Bioproducts Processing*.

[444] Chamberland, J., Benoit, S., Doyen, A. and Pouliot, Y., 2020. Integrating reverse osmosis to reduce water and energy consumption in dairy processing: a predictive analysis for Cheddar cheese manufacturing plants. *Journal of Water Process Engineering*, *38*, p.101606.

[445] Cheryan, M., Veeranjaneyulu, B. and Schlicher, L.R., 1990. Reverse osmosis of milk with thin-film composite membranes. *Journal of membrane science*, *48*(1), pp.103-114.

[446] Rautenbach, R., and Albrecht, R. 1989. Membrane Separation Processes. John Wiley. https://www.wiley.com/en-us/Membrane+Processes-p-9780471911104.

[447] Patil, M.H., Tanguy, G., Floch-Fouéré, C.L., Jeantet, R. and Murphy, E.G., 2021. Energy usage in the manufacture of dairy powders: advances in conventional processing and disruptive technologies. *Drying Technology*, *39*(11), pp.1595-1613.

Operational costs, including production run times and cleaning requirements, must be factored in to optimise performance.[447] Depping et al.[448], building on the findings of Stefansdottir et al.[449] (018), 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.[450] 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.[451]

Payback times were analysed by Chamberland et al.[452] and Ma et al.[453] 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

[448] Depping, V., Grunow, M., van Middelaar, C. and Dumpler, J., 2017. Integrating environmental impact assessment into new product development and processing-technology selection: Milk concentrates as substitutes for milk powders. *Journal of Cleaner Production*, *149*, pp.1-10.

[449] 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.

[450] 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.

[451] Patil, M.H., Tanguy, G., Floch-Fouéré, C.L., Jeantet, R. and Murphy, E.G., 2021. Energy usage in the manufacture of dairy powders: advances in conventional processing and disruptive technologies. *Drying Technology*, *39*(11), pp.1595-1613.

[452] Chamberland, J., Benoit, S., Doyen, A. and Pouliot, Y., 2020. Integrating reverse osmosis to reduce water and energy consumption in dairy processing: a predictive analysis for Cheddar cheese manufacturing plants. *Journal of Water Process Engineering*, *38*, p.101606.

[453] Ma, Z., Noor, I.I., Wang, X., Ren, Y., Wang, J., Wang, Q., Gao, J., Gao, X. and Liu, H., 2024. A comprehensive review on the recent advances in membrane-based processes for fruit juice concentration. *Food and Bioproducts Processing*.

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

10.3.13 Smoking – efficient technologies

Recent advancements in smoking technology focus on improving efficiency, productivity, quality, precision, and sustainability.[454] Advanced smoke generators[455], 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[456] 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[456] 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

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[454] Addy, R. 2021. *Meat smoking tech from GEA offers smokehouse-style taste.*

[455] Protech Food Machinery AB, 2024. *Smoke generator for hot and cold smoking*. Available at: https://protech-ab.se/en/product-range/smoke-generator/

[456] euromeatnews.com, 2024. *Closer to the climate targets with Clean Smoke.* Published 6 January. Available at: https://www.euromeatnews.com/Article-Closer-to-the-climate-targets-with-Clean-Smoke/4397

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.[457]

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.[457]

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

[457] euromeatnews.com, 2024. *Closer to the climate targets with Clean Smoke.* Published 6 January. Available at: https://www.euromeatnews.com/Article-Closer-to-the-climate-targets-with-Clean-Smoke/4397

Legislative concerns	-
Payback time (years)	Not available

10.3.14 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[458] 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, businesses can reduce their environmental impact, lower operational costs, and contribute to a greener future. Implementation of photovoltaic (PV) technologies may be processed in order to supply electric energy. The power generation may be processed 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 [459].

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. 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.

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. Photovoltaic (PV) systems are particularly effective in the fruit and vegetable processing and canning sector, where they can simultaneously meet cooling and hot water demands, reducing

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[458] EU, 2022. 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. {SWD(2022) 148 final}. Brussels, 18.5.2022. COM(2022) 221 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN

[459] Monteiro, A.N.T.R., Santos, D.F.L., Miyazaki, M.R., de Oliveira Neto, G.C., Ometto, A.R. and Pinto, H.F. (2021) 'Framework to Assess Eco-Efficiency Improvement: Case Study of a Meat Production Industry', *Sustainability*, 13(17), 9753. https://doi.org/10.3390/su13179753

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.

Thermal processing is an important unit operation in the food industry for the production of prepackaged foods with extended shelf-life. Conventional thermal processes, such as canning, are widely employed in the food industry, but the energy efficiency of these processes is typically low. In addition, a significant amount of water is wasted during these processes. In recent years, advanced microwave-based pasteurisation and sterilisation systems have been developed for the production of extended shelf-life products at refrigeration and room temperatures, respectively. Microwave systems are relatively more water and energy efficient, can be directly powered by renewable electricity sources (e.g., solar, wind, or hydropower), and have potential to reduce greenhouse gas emissions, and thus environmentally sustainable. Industrial scale microwave-assisted pasteurisation and microwave-assisted thermal sterilisation systems are powered by microwave generators with a total electric power requirement of 40 to 150 kW. Such a level of electrical power can be easily supplied by locally generated electricity from solar, wind, and hydro energy.

Recent advancements in the integration of solar photovoltaics, battery storage, and demand response programs have made peak shaving even more attractive. Solar electric power can be used in food processing by integrating solar panels with battery storage systems, ensuring a reliable and continuous energy supply. These systems reduce electricity costs by storing excess solar energy for use during peak demand, while also enhancing power quality, improving energy resilience, and lowering the carbon footprint of food processing operations. Large-scale battery energy storage systems are often associated with other renewable energy assets, especially solar. For some businesses, though, there might be an advantage to standalone battery storage.

New types of solar power storage batteries utilise the AI installed in the battery, which ensures that unused electrical energy is stored as efficiently as possible. The AI module in battery predicts the generation of the solar plant, uses tomorrow's weather forecasts, takes electricity prices from the market exchange. Based on this, the algorithm calculates the optimal mode to minimise electricity bills, when it will be cheapest to charge or the best time to discharge [ccc]. Merei, Berger, and Sauer[460] showed that using batteries in combination with the renewable energy sources was economic and ecological.

Battery-based storage systems, particularly lithium-ion batteries, have gained significant attention due to their high energy density, efficiency, and cost effectiveness. These systems store excess solar energy in the form of chemical energy and release it as electricity when

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[460] Merei, G., Berger, C. and Sauer, D.U., 2013. *Optimization of an off-grid hybrid PV–wind–diesel system with different battery technologies using genetic algorithm.* Solar Energy, 97, pp.460–473.

needed. A study by Vieira et al.[461] evaluated the performance of a lithium-ion battery energy storage system integrated with solar PV installations. The study found that the battery system improved self-consumption of solar energy from 30% to 60% and reduced the reliance on grid electricity. Studies of PV systems coupled with battery energy storage have shown that self-consumption can increase from approximately 30–60% without storage to 70–85% with appropriately sized battery systems, substantially reducing electricity imports from the grid [462].In another study, Qusay et al.[463] evaluated the techno-economic performance of a lithium-ion battery energy storage system for solar self-consumption. The study showed that the battery system improved self-consumption rates by up to 42%, leading to substantial savings in electricity costs.

It was demonstrated a vigorous analysis of the potential annual power savings for a food manufacturer applying photovoltaic technology for harvesting solar energy into the energy supply of the factory. The system design methodology has considered the objective of reducing grid power while maintaining 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 several 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.

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.[464] 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

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[461] Vieira, F.M., Moura, P.S. and de Almeida, A.T., 2017. Energy storage system for self-consumption of photovoltaic energy in residential zero-energy buildings. *Renewable Energy*, 103, pp.308–320.

[462] Huld, T., Ruf, H. and Heilscher, G. (2015) 'Self-Consumption of Electricity by Households: Effects of PV System Size and Battery Storage', in *Proceedings of the 31st European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)*. Hamburg, Germany, pp. 1286–1290.

[463] Hassan, Q., Abbas, M.K., Sohrabi Tabar, V., Tohidi, S., Sameen, A.Z. and Salman, H.M., 2024. Techno-economic assessment of battery storage with photovoltaics for maximum self-consumption. *Energy Harvesting and Systems*, 11(1), Article 20220050. https://doi.org/10.1515/ehs-2022-0050

[464] Celić, D., Pavlović, T. and Radonjić, I., 2018. Life cycle assessment of different photovoltaic technologies in Serbia. *Energy*, 157, pp. 1208–1216. https://doi.org/10.1016/j.energy.2018.05.196

storage solutions, a study by Yudhistira et al.[465] 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. 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.

A Croatian fish-processing case study with an annual production capacity of 5,030 t found that the facility's annual electricity demand (226,458 kWh) could be met by either two 20 kW wind turbines, 3,460 photovoltaic panels (830 kWp, 5,674 m²), or a hybrid system comprising one 20 kW wind turbine and 1,702 photovoltaic panels (408 kWp) [466]. 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% [629].

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

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[465] Yudhistira, R., 2021. *Comparative life cycle assessment of different lithium-ion battery chemistries and lead-acid batteries for grid storage application.* Master's thesis, KTH Royal Institute of Technology, Stockholm. Available at: https://www.diva-portal.org/smash/get/diva2:1587593/FULLTEXT01.pdf

[466] Bujas, T., Koričan, M., Vukić, M., Soldo, V., Vladimir, N. and Fan, A. (2022) 'Review of Energy Consumption by the Fish Farming and Processing Industry in Croatia and the Potential for Zero-Emissions Aquaculture', *Energies*, 15(21), 8197.

been developed for determining the optimised operation intervals of appliances and optimal use of local renewable energy sources [467].

More than 50% of the energy consumed by a bakery is dedicated to baking. Another way is to substitute the electricity supply locally, using a stand-alone renewable energy system such as solar PV panels coupled with storage. The 52 kW containerised solution is being developed by German start-up Solarbakery[468]. 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.

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 [469].

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 [470]. 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) [622].

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

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[467] Ateyah Alzahrani, Ioan Petri and Yacine Rezgui (2020) 'Developing Smart Energy Communities around Fishery Ports: Toward Zero-Carbon Fishery Ports', Energies, 13(11), 2779.

[468] Lichner, C. (2021) 'Solar bakery as a containerized solution', *pv magazine*, 20 December. Available at: pv magazine article

[469] McMillan, C.A., King, J., Li, X., Jin, M., Miller, D.C., Cresko, J. and Gkatzikis, K. (2021) *Opportunities for Solar Industrial Process Heat in the United States*. Golden, CO: National Renewable Energy Laboratory (NREL)

[470] Akinyele, D.O. and Rayudu, R.K. (2020) 'Potential of Off-grid Solar PV/Biogas Power Generation System: Case Study of Ado Ekiti Slaughterhouse'. *IEEE PES/IAS PowerAfrica Conference*.

distribution is crucial to increase the self-sufficient energy supply. Energy storage in the production process is a method to compensate for this [471].

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	TRL 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. {SWD(2022) 148 final}. Brussels, 18.5.2022. COM(2022) 221 final.
Payback time (years)	Dependent on technological solution and processing industry – from 2 to 7 years.

10.3.15 Thermal energy systems

10.3.15.1 TES integration at processing plants; low, medium and high temperature

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°C) supports freezing and refrigeration, medium-temperature MTES (0°C-100°C) aids in cooling

[471] Höhendinger, M., Krieg, H.-J., Dietrich, R., Rauscher, S., Hartung, C., Stumpenhausen, J. and Bernhardt, H. (2023) ‘Requirements and Economic Implications of Integrating a PV-Plant-Based Energy System in the Dairy Production Process’, *AgriEngineering*, 5(4), pp. 2196–2215.

and pasteurisation, while high-temperature HTES (>100°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; Selvnes 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, sensitive 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 or in ruth accumulators. In addition, there are 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 CO2 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	TRL 9 sensible (liquid, all temperature levels) TRL 7 sensible (solid, all temperature levels) TRL 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

10.3.15.2 TES integration on fishing vessels (fish)

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. Onboard fishing vessels, require thermal energy for freezing, chilling and cooling as well as for hot water, space heating, snow melting and processing of fish RRM. While the focus is on chilling and freezing the fish as fast as possible to ensure the food quality and safety, utilizing the excess heat increases the overall efficiency of the refrigeration unit. Optimizing the thermal systems, alongside integrating thermal energy storage (TES), can significantly reduce greenhouse gas emissions from fishing vessels, as full electrification remains impractical with current battery technology and unpredictable operational demands lead to inefficient energy use., to fully optimise this, TES must be carefully designed and integrated with suitable TES materials and the right capacity[472] [473] .

For the freezing of fish on board, temperatures between -30°C and -50°C degrees are required. CO2 refrigeration systems are usually used for this purpose. Therefore Hafner et al.[474], Saeed et al.[473] and Verpe et al.[475] have looked into the possibility of using CO2 as the phase change material. According to Hafner et al.[474], this can result in electrical energy savings of up to 30% in stationary applications in freezing tunnels.

There are currently several approaches to cooling onboard. If we exclude the pure 'putting fish on ice', refrigerated seawater (RSW) and sometimes ice slurry are often used. The pure RSW

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472 Vingelsgård, E., Svendsen, E.S., Widell, K.N. and Nordtvedt, T.S., 2022. 'Evaluation of cold thermal energy storage in fishing vessels'. In: International Institute of Refrigeration (IIR). doi:10.18462/IIR.GL2022.0105.Widell, Kristina N., Eirik S. Svendsen, and Tom Ståle

473 Saeed, M.Z., Widell, K.N., Hafner, A., Nordtvedt, T.S. and Svendsen, E.S., 2020. 'Integrated thermal storage and heat recovery of the CO_2 refrigeration system for fishing vessels'. In: International Institute of Refrigeration (IIR). doi:10.18462/IIR.GL.2020.1116.

474 Hafner, A., Nordtvedt, T.S. and Rumpf, I. 2011. 'Energy saving potential in freezing applications by applying cold thermal energy storage with solid carbon dioxide'. *Procedia Food Science*, 1, pp. 448–454. doi:10.1016/j.profoo.2011.09.069.

475 Verpe, E.H., Tolstorebrov, I., Sevault, A., Hafner, A. and Ladam, Y. 2019. 'Cold thermal energy storage with low-temperature plate freezing of fish on offshore vessels'. In: International Institute of Refrigeration (IIR). doi:10.18462/IIR.ICR.2019.1168.

system is a cold-water tank filled with seawater which is cooled to 0°C to -1.9°C before fishing. It is therefore a sensible TES that buffers the initial load required to cool the fish down quickly.[472 476] Saeed et al.[476] integrated a 1 m³ thermal energy storage tank with PCM into the return line of an RSW system, achieving an average charging capacity of 31.6 kWh and discharging capacity of 30 kWh in simulations, indicating that charging was slightly faster than discharging, with a 3°C phase change material showing potential for fishing vessels.

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.[477] and Vingelsgård et al.[478] found that using a 20% ice slurry concentration 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.[479] 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, up to 30% electric energy savings (Hafner, Nordtvedt, and Rumpf 2011)
Quality of scope 1 emissions information	

476 Saeed, M.Z., Widell, K.N., Hafner, A., Svendsen, E.S. and Nordtvedt, T.S. 2021. 'Thermal energy storage with PCM for refrigerated sea water system of fishing vessels'. In: International Institute of Refrigeration (IIR). doi:10.18462/IIR.PCM.2021.1947.

477 Widell, Kristina N., Eirik S. Svendsen, and Tom Ståle Nordtvedt. 2023. 'Possibilities of Ice Slurry Systems Onboard Fishing Vessels'. In . doi:10.18462/iir.nh3-co2.2023.0017.

478 Vingelsgård, E., Svendsen, E.S., Widell, K.N. and Nordtvedt, T.S., 2022. 'Evaluation of cold thermal energy storage in fishing vessels'. In: International Institute of Refrigeration (IIR). doi:10.18462/IIR.GL2022.0105.

479 Saeed, M.Z., Widell, K.N., Hafner, A., Nordtvedt, T.S. and Svendsen, E.S., 2020. 'Integrated thermal storage and heat recovery of the CO_2 refrigeration system for fishing vessels'. In: International Institute of Refrigeration (IIR). doi:10.18462/IIR.GL.2020.1116.

Scope 2 emissions savings (% or another quantifiable metric)	Many review articles available, difficult to get concrete numbers
Quality of scope 2 emissions information	N/A, reduced freezing time has a positive effect on fish quality and thus reduces food loss and waste
Availability barriers	Many review articles available, difficult to get concrete numbers
TRL level	Sensible: L; Latent: H, M, L
Maintainability issues	
Legislative concerns	
Payback time (years)	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

10.3.16 Utilisation of processing wastes

Presently, about one third of fresh harvest is wasted among the food processing chain, hence discarded as landfill and in marine. Industrial input to shift this discarded mass to quality term is one and all significant contribution within this stream to potentially identify, recover, and hence reutilise them is the only way out. Over the next decade, worldwide food waste production is projected to rise by 33%.[480] 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.[481] 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.[482] These wastes are rich source of energy, micronutrients and dietary fibre and can be recycled into biofuel, essential oils, phenolic compounds, high-value prebiotics and carotenoids.

The slaughterhouse and poultry processing are among the fastest-growing industries, owing to rising food availability requirements, subsequently the wastes generated by poultry industries are massive, hence recovery of value-added proportion from them is appreciable

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[480] Pour, N. and Makkawi, Y. (2021) 'Food waste-to-energy conversion technologies', in *Sustainable Food Waste-to-Energy Systems*. Academic Press, pp. 23–48.

[481] Bartek, L., Strid, I., Henryson, K., Junne, S., Rasi, S., & 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

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

that somehow reduce our reliance on fossil fuels. Out of 220 million tons world meat output, about 50-54% of bovine, 52% of caprine, 60–62% of pig, and 68–72% of fowl is utilised for meat and the remaining is disposed of as waste.[483] 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.

Abattoir shops, on an average, 32.5–37.0% of poultry waste occurs in chicken processing where 57.37% is from feathers and skin; 20.35% of intestinal viscera; 14.8% of claws and beak to about <1%. In actual term, more than half of animal by-products are not meant for human consumption, while they do possess capacity to generate protein hydrolysate[484], lipids bioactive peptides [485], and other protein rich adhesives [486]. The other by-product fractions could be processed for the release of animal and pet feed, and poultry meal.

Blood is an example of a protein-rich waste product. However, the high protein content in blood makes it useful in the food industry and can potentially be used to enhance the nutritional value of foods, and act as water-binding and emulsifying agent. Skin, bones and cartilages are also rich in proteins, such as collagen.[487] Meat waste is as a good source for bioactive peptides. Bioactive peptides are short sequences of amino acids ranging from 2 to 30 amino acids (Mora et al. 2014). Some bioactive peptides can be generated with help of endogenous enzymes in post-mortem meat, and other - through microbial fermentation, chemical/enzymatic hydrolysis and with the help of proteolytic enzymes. The most common way to produce bioactive peptides is through enzymatic hydrolysis, because of low amount of used toxic compounds, high

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specificity and mild conditions.[488] Another commonly used method to obtain bioactive peptides are microbial fermentation and in vitro digestion.[489]

Today, aquaculture is the fastest growing food-producing sector, originally developed to support an increasing global population with nutritious food and essential Omega-3 fatty acids. About 75% of by-products from fish processing are either thrown or are used for feed, fertilisers or silage.[490] [491] Currently, these by-products are in practice as fish meal and fish oil production.[492] Other aquatic animals like; shellfish, seaweeds and plants, are being increasingly used for food, feed, pharmaceutical and cosmetic products, as well as to yield biofuels, fertilisers, soil improvers cum biosorbents[493] [494] [495]. Aquaculture, in nutshell wasted about 35% of total global output/annum [492], hence some wise valorisation should be adopted to get minimal discards as waste.

Dairy industry is significant figure among food that also generates high organic content laden waste to the surroundings [496]. In addition to excessive amount of milk, large volume of whey (9-10 l for 1 kg of cheese production), are also discharged throughout during cheese-making process, poses threat to environment as of high BOD (Biological Oxygen Demand) issue.[497] During the production, several dairy by-products such as skim milk, spoilt milk, spilt milk and curd chunks are also discharged.[498] These by-products are potential sources of fats, lactose and protein and thus could be better as an energy source for hunger and individuals who are

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malnourished, in addition to their use as food additive like enzymes, polymers, biofuels and solvents [499].

In the case of Denmark, milk and dairy products contribute around 71,000 tons of food waste annually [500], while in the grouping of 14 European countries around 43 to 48% of milk and dairy wastes were produced in the processing stage [501] . Methods for reducing milk wastes include capture of fat, protein, and sugars from wastewater produced during milk processing using processes such as evaporation, centrifugation, ultrafiltration, reverse osmosis, and bioconversion. These recapture processes can significantly reduce the amount of milk and dairy wastes being discharged into the environment [5].

Cereals itself is a symbol of lignocellulosic biomass, its processing resulted in 12.9% of food waste generally produced and get wasted [502]. Depending, selection of type of cereal and adopted process, stream of waste cum by-products sequentially comes as; straw and cob through cleaning time, bran while in milling hours, corn and rice oil while in processing stages.[503] These are some cited score for bioactive constituents' recovery from cereal industry waste, possess sustainable futuristic approaches to perform more novelties in food domain. There are notable losses during the storage (damage by insects and rodents), processing (lower efficiency machinery), transportation (improper handling) and other post-harvest unit operations that could be responsible for the said waste generation.[504] [505] In addition, the processing of various kinds of food grains also generates wastes (or by-products), which often do not find any suitable application and cause environmental concerns after spoilage, when stored for a long time. Sirohi et al.[506] studied the synthesis of poly-3-hydroxybutyrate (PHB)

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505 Sirohi, R., Pandey, J.P., Gaur, V.K., Gnansounou, E., Sindhu, R. and Kumar, D. (2021a) 'Food waste management: A comprehensive review of valorisation technologies', *Bioresource Technology*, 322, Article 124537.

506 Sirohi, R., Tarafdar, A., Singh, A., Kumar, V., Gnansounou, E. and Sindhu, R. (2021b) 'Green synthesis of poly(3-hydroxybutyrate) from damaged wheat grains through enzymatic hydrolysis and fermentation', *Bioresource Technology*, 344, Article 126219.

from damaged wheat grains using a green process (enzymatic hydrolysis followed by fermentation).

Each year, around 45% of total fruit and vegetable production is lost during various stages of food chain (a) from the field (infestation, post-harvest), (b) from processing (handling, distribution/retail), and (c) to consumption (consumer levels).[507]

In recent years, food and fruit industry wastes have drawn much attention on their utilisation for the production of value-added products, including PHB.[508] [509] [510] [511] Reshmy et al.[512] reported the development of an eco-friendly biodegradable plastic from jack fruit peel cellulose with different plasticisers and Boswellia serrata as filler.

The fruit and vegetable industry generates more waste compared to other food processing sectors, accounting for 25–30% of the total waste, which might be anything from peels and rinds to seeds, cores, rags, stones, pods, vines, skins, and pomaces.[513] As fruit and vegetable waste is biodegradable, it decomposes rapidly, emitting unpleasant odours. If not managed promptly, this can lead to significant environmental and health issues. Fruits and vegetable waste that is improperly disposed of can produce germs and attract disease-carrying insects, such as flies and mosquitoes. It can also contaminate the surface and groundwater, leading to phytotoxicity and significant health-related issues. Waste valorisation in a circular economy involves the production of valuable products, such as fuels, materials, and chemicals. In addition to producing value-added goods, such as organic fertilisers, animal feed, biofuels, and electricity from food waste, it contributes to economic, social, and environmental

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improvements. Over the last decade, numerous studies have focused on the transformation of value-added products from FW, including edible ingredients, functional foods, nutraceuticals, medicines, and cosmetics. However, conventional practices of food waste management may include animal feeding of surplus food materials, orthodox landfilling, composting for organic manure, and incineration as thermal treatments. The aforementioned individual techniques face challenges because of their limited efficiency, high energy consumption, high moisture content, low calorific value, variable composition, and potential contamination. These traditional methods can indirectly increase economic profits, but they may lead to the loss of valuable biomaterials extracted from food waste streams.

Vegetable waste streams are a neglected portion of the food industry worldwide. However, the vegetable waste stream has been reported as a rich source of extracted pectin. Early observations documented the potential of rejected vegetable waste streams (carrot, green bean, and leek) from the food industry to extract commercial pectin.[514]

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	n. a.
Availability barriers	L
TRL level	TRL3-9 depends on selected food waste treatment technology
Maintainability issues	n. a.
Legislative concerns	
Payback time (years)	n. a.

[514] Christiaens, S., et al. (2015) 'Isolation and characterisation of pectin from vegetable processing waste streams', *Food Chemistry*, 188, pp. 275–285.

10.4 Ancillaries

10.4.1 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.[515] 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-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/m^2K (RSI value of 3.85).

To meet the demands of nearly zero-energy and zero-emission buildings, thicker building envelopes are typically required when conventional insulation materials are used. In temperate European climates, wall U-values of approximately 0.2 $W/m^2 \cdot K$ are widely considered representative of cost-optimal, high-performance building envelopes, although the optimum varies with climate [516]. 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.[517]

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.

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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.[518] Commercially available products (Kingspan OPTIM-R) quote an aged design value thermal conductivity of 0.007 W/m·K.

According to Simões[519] to achieve a U-value (takes into account thermal bridging) of 0.24 W/m^2K would require an encapsulated VIP of thickness 40 mm and to achieve a U value of 0.12 W/m^2K 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.[520] Aerogels have a large specific surface area, a very low apparent density.[521] Thermal conductivities of the aerogel board were reported as 15-17 mW/(m·K).[518]

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. 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.[522]

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[518] Johansson, P. and Adl-Zarrabi, B., 2020. Long-Term Performance of Super-Insulating-Materials in Building Components and Systems. Energy in Buildings and Communities Programme.

[519] Simões, N., Gonçalves, M., Serra, C. and Resalati, S., 2021. Can vacuum insulation panels be cost-effective when applied in building façades? Building and Environment, 191, p.107602.

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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.[523] Cooling during peak load hours in Los Angeles could be reduced by more than 80% without a negative impact on thermal comfort conditions.

Kisilewicz [524] 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.[525] carried out numerical simulations of thermally anisotropic building envelope (TABE). These add thin conductive layers between the insulation shown in Figure 42: Thermally anisotropic building envelope.. 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.

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[523] Antretter, F., Hun, D.E., Boudreaux, P.R. and Cui, B. 2019. *Assessing the potential of active insulation systems to reduce energy consumption and enhance electrical grid services*. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, United States.

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[525] Biswas, K., Shrestha, S., Hun, D. and Atchley, J., 2019. Thermally anisotropic composites for improving the energy efficiency of building envelopes. Energies, 12(19), p.3783.

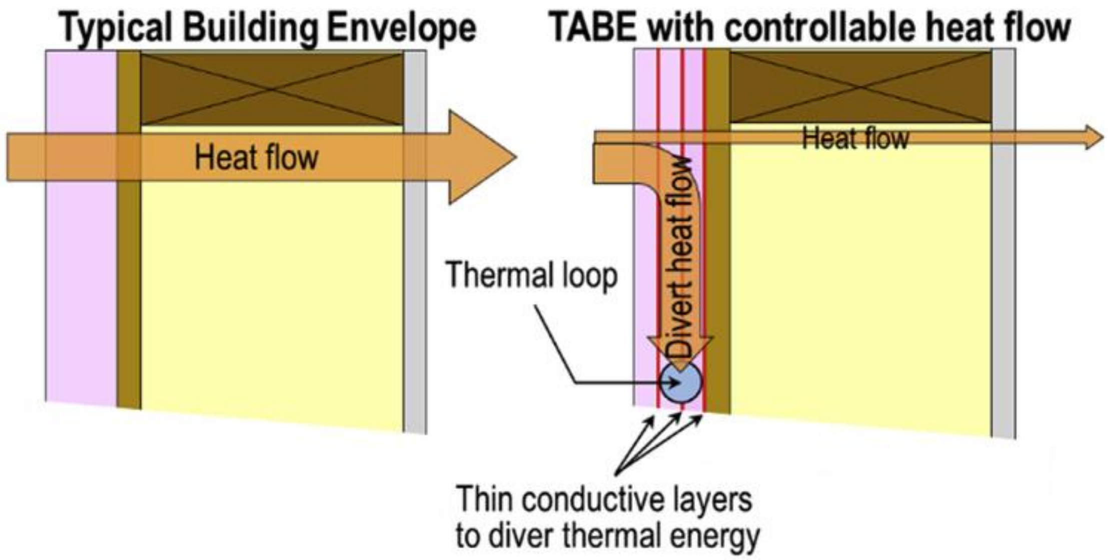

Figure 42: Thermally anisotropic building envelope.

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.[526]

Konstantinidou[527] 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.

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[526] Harris, C., 2019. *Grid-interactive efficient buildings technical report series: windows and opaque envelope* (No. DOE/GO-102019-5222). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[527] Konstantinidou, C.A., Lang, W., Papadopoulos, A.M. and Santamouris, M., 2019. Life cycle and life cycle cost implications of integrated phase change materials in office buildings. International Journal of Energy Research, 43(1), pp.150-166.

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/(m^2 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	TRL7-9 for increasing U-value by conventional means
Maintainability issues	No issue
Legislative concerns	No concern
Payback time (years)	Payback is generally negative

10.4.2 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.[528]

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

[528] European Parliament, 2010. Energy performance of buildings directive http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32010L0031.

(25.6 lm/W).[529] In the future, it may be possible to achieve system luminous efficacy in the range of 200 to 250 lm/W.[530]

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.

529 DIAL, 2025a. Efficiency of LEDs: The highest luminous efficacy of a white LED. DIAL GmbH. https://www.dial.de/en-GB/articles/efficiency-of-leds-the-highest-luminous-efficacy-of-a-white-led#:~:text=While%20energy%20conversion%20efficiency%20of,power%20is%20lost%20as%20heat.

530 DIAL, 2025b. The Truth About How Efficient a White LED Can Be. Architect Magazine, Zonda Media. https://www.architectmagazine.com/technology/products/the-truth-about-how-efficient-a-white-led-can-be#:~:text=In%20the%20future%2C%20it%20may,information%20and%20articles%20about%20DIAL

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