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

# D4.3

## Potential integration of energy use along the food supply chain

PROJECT NO: 101036588

TYPE OF ACTION: IA (INNOVATION ACTION)

CALL: H2020-LC-GD-2020-4

# DOCUMENT INFORMATION

| | |
|---|---|
| DELIVERABLE NO. | 4.3 |
| DISSEMINATION LEVEL | Public |
| WORK PACKAGE | WP4 |
| TASK | T4.3 |
| LEAD BENEFICIARY | INRAE |
| CONTRIBUTING BENEFICIARY(IES) | LSBU, VMU, CNR |
| DUE DATE OF DELIVERABLE | 30/03/2025 |
| ACTUAL SUBMISSION DATE | 04/09/2025 |

# DOCUMENT HISTORY

| Version | DATE | CHANGE HISTORY | AUTHOR | BENEFICIARY |
|---|---|---|---|---|
| 1.0 | 30/05/20245 | First draft | Denis Leducq, Graciela Alvarez,<br>Kęstutis Venslauskas, Kęstutis Navickas<br>Silvia Minetto | INRAE<br>VMU<br>CNR |
| | | | | |
| | | | | |

| QUALITY ASSURANCE, STATUS OF DELIVERABLE | | |
|---|---|---|
| ACTION | PERFORMED BY | DATE |
| Reviewed | Pieter Verboven<br>Antonio Rosetti | 01/08/2025 |
| Approved | Kristina N. Widell | 04/09/2025 |
| Uploaded to SyGMa | Kristina N. Widell | 04/09/2025 |

# TABLE OF CONTENTS

# LIST OF FIGURES



# LIST OF TABLES

# EXECUTIVE SUMMARY

This report presents a comprehensive investigation into the potential for energy integration and recovery along the food supply chains.

A central pillar of the methodology in this report and in the ENOUGH tool is the application of exergy analysis. This approach provides a more profound understanding of thermodynamic inefficiencies, identifying the processes where the greatest potential for improvement lies.

The analysis presented in this document reveals that the most significant and untapped opportunities across all sectors of the food supply chain is the recovery of waste heat. Vasts amounts of thermal energy are continuously generated and subsequently lost to the environment from a multitude of essential operations in food processing, retail, cold storage or transport.

Mature and innovative technologies categorized by their functions are detailed. Passive heat recovery technologies including heat exchangers, thermosiphons, heat pipes and thermal storage are presented. Active heat recovery technologies such as high temperature heat pumps, cogeneration, absorption and adsorption chillers can be used to upgrade and convert waste heat into more valuable forms.

The feasibility of some of these solutions has been validated through ENOUGH project demonstrators to prove the technical viability, but also to analyse the financial viability of these systems in real world industrial environment.

While acknowledging barriers such as initial capital costs and the complexities of retrofitting, the report emphasizes that solutions like thermal energy storage that can effectively bridge the temporal gap between waste heat availability and demand, maximizing recovery potential.

# Deliverable 4.3

# 1 INTRODUCTION

Recent assessments estimate that the entire global food system accounts for roughly 21-37% of total anthropogenic GHG emissions[1]. A detailed study by Crippa et al[2] show that, within this, energy use across the supply chain (beyond the farm gate, plus energy used for inputs like fertilizers) accounts for 29% of the food emissions. Key energy consuming activities include:

- **Food Processing:** Activities like freezing, drying, pasteurizing, etc., require significant thermal and electrical energy.
- **Transport:** Refrigerated and non-refrigerated transport via trucks, ships, rail and airfreight consumes fuel [3].
- **Retail:** Refrigeration and lighting in supermarkets and stores are major energy consumers.

Sources of energy used within food supply chains vary significantly with locations, depending on the electrical production by country. Fossil fuels remain the dominant source in most cases to power trucks for transport, maritime ships and air freight transport, it is also widely used for process heat (drying, baking, pasteurizing, sterilizing, sometimes cooking…). Electricity (grid mix) is also essential for a wide range of applications (refrigeration, processing, transport, retail, domestic use…), but its primary source varies depending on the national grid mix.

Among the possible measures to mitigate emissions from the food supply chains sectors [4], heat recovery is often cited. This can make use of the waste heat generated, for example during the production of cold, using heat pumps to increase the temperature level of this waste heat. Increasing energy efficiency by implementation of low emissions practices, achieving the same outputs while also consuming less energy is also a key measure to reduce energy consumption and GHG emissions to achieve European targets in the food sector.

The primary objective of this report is to provide first a comprehensive overview of both the opportunities for integrating energy use across the food supply chain, with a sector by sector analysis of the potential for energy recovery, and secondly to present the technologies available for energy recovery, from passive systems like heat exchangers or thermal storage to active systems like high temperature heat pumps or cogeneration.

An introduction to the principles of exergy analysis, establishing the framework used to evaluate the efficiency of energy conversion processes in the ENOUGH tool is also presented.

# 2 EXERGY ANALYSIS

## 2.1 Introduction

Exergy analysis is a powerful tool that can be used to identify and help reduce energy inefficiencies along the food supply chain and also to evaluate the benefits of implementing measures such as heat recovery.

Traditional energy analysis, based on the First Law of Thermodynamics, focuses on conserving the quantity of energy. 1 kWh of electricity and 1 kWh of low-temperature heat are treated equally, even though electricity has much higher potential to be used as work than heat (using a system to convert heat into mechanical energy). Exergy analysis, based on the Second Law of Thermodynamics, focuses on the quality of energy and the useful work potential of energy relative to a reference environment (typically ambient conditions such as temperature, pressure or chemical potentials). Exergy is consumed or destroyed in any real process due to irreversibility (like friction, heat transfer across a finite temperature difference, mixing, chemical reactions). The primary benefit of exergy analysis is that it highlights where and how much useful work potential is being lost (exergy destruction or irreversibility). Processes with high exergy destruction are thermodynamically inefficient, even if they do not consume the largest absolute amount of energy. These should be the first targets for improvement.

This kind of analysis can be applied for food supply chains, and especially in activities like food processing[5–8], refrigeration and freezing, drying processes[9], waste heat recovery. It can be used also to benchmark thermodynamic performance of different technologies and even entire supply chain configurations. This analysis, implemented in the ENOUGH tool, is a little more challenging than an energy balance analysis.

Exergy analysis has shown that it offers a more profound understanding of energy use than conventional energy analysis alone. By focusing on the destruction of energy quality, it precisely identifies the processes and components within the food supply chain with the greatest potential for thermodynamic improvement. Implementation of this analysis in the ENOUGH tool will allow engineers and designers to target interventions more effectively, leading to potentially significant reductions in primary energy consumption, lower operating costs, and reduced GHG emissions associated with energy use. It is a valuable tool for moving towards more sustainable and resource-efficient food systems.

One result of the ENOUGH tool is a chart showing the use of exergy by the different processes constituting the food supply chain. An example is given below:

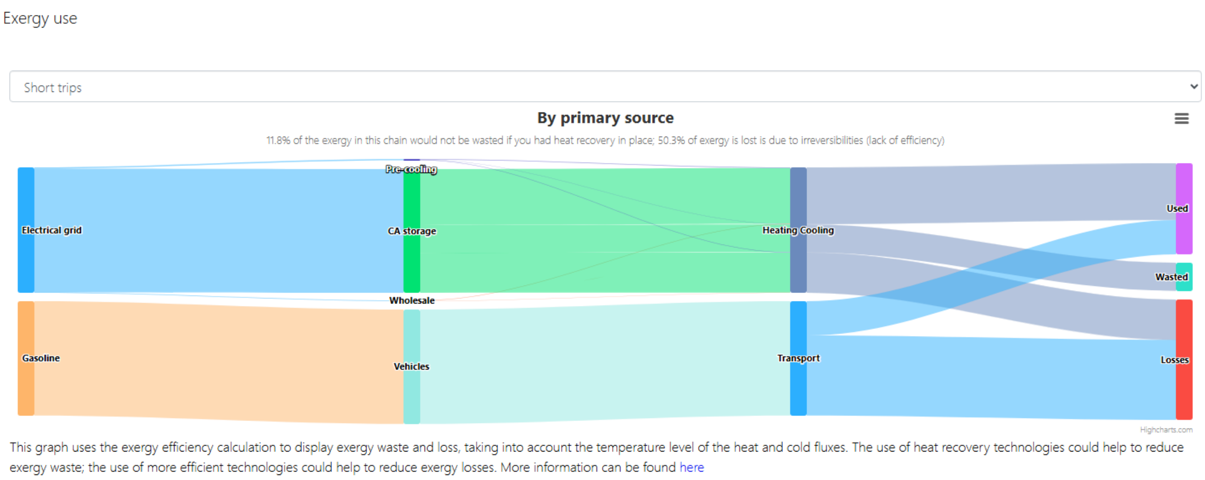


*Figure 1: Exergy use chart (ENOUGH tool).*

This chart shows how the primary sources of energy (first column) are used and especially how much is wasted or lost (last column). The food supply chain involves processes using energy listed in the second column of the chart. These processes can be grouped by category as shown in the third column.

Losses presented here are not energy losses, but exergy losses. The First Law states energy cannot be created or destroyed, only converted from one form to another form. The Second Law introduces the concept of energy quality and irreversibility and states that processes always generate entropy, meaning the quality or usefulness of energy degrades. This degradation can be seen as a loss, and can be calculated as exergy losses. The ratio of exergy used per exergy provided is used for the proportion of losses in the last column.

Waste presented in the chart is the flux of exergy that could be used, but is not because the process does not implement it. A good example is the loss of heat at the condenser of a refrigerating system.

In the example of Figure 1, thermodynamically ideal processes and implementation of heat recovery would use **only 49.7% of the exergy currently used**.

The details of the calculation to build that chart are presented in this document.

## 2.2 Exergy analysis procedure

### 2.2.1 Exergy of energy sources

Exergy quantifies the maximum useful work that can be obtained from an energy source or system as it comes into equilibrium with a reference environment (the "dead state", typically defined by ambient temperature $T_0$ and pressure $P_0$).

**Electricity from grid** is an essentially pure work or energy readily and fully convertible into work with theoretical 100% efficiency. Therefore, the exergy of electricity delivered to the user is considered equal to the electrical energy itself.

**Fuels** energy is stored in the chemical bonds (chemical energy). During the fuel combustion, they release heat. The exergy of a fuel is the maximum theoretical work obtainable when the fuel reacts and this will depend on the heat release and the level of temperature, but also the work potential associated with the change in chemical composition and concentration gradients relative to the environment.

Here are the chemical exergy values relative to $T_0$ = 298.15K and $P_0$ = 1atm used in the ENOUGH tool:

*Table 1: Exergy of primary energy sources.*

| Fuel type | Specific chemical exergy (MJ/kg) |
|---|---|
| Natural gas | 50.5 |
| Gasoline | 47.3 |
| Diesel | 46.0 |
| Diesel, 5% bio-diesel blend | 45.8 |
| Gasoline, 5% bio-diesel blend | 46.3 |
| Heavy fuel-oil | 43.3 |
| Marine gas-oil | 43.5 |
| Kerosene | 46 |
| Biomethane | 50.5 |

### 2.2.2 Exergy analysis of a vapor compression refrigeration cycle

The goal is to quantify the total exergy destruction (loss of useful work potential) in each component of the cycle and to evaluate the exergy efficiency of the refrigeration system.

The total exergy destruction is the sum of the exergy losses of every component:

$$Ex_{total}^{d} = Ex_{comp}^{d} + Ex_{cond}^{d} + Ex_{valve}^{d} + Ex_{evap}^{d}$$

To perform the exergy balance for each component, the general steady-state balance for a component is:

$$\sum \dot{m}_{in} ex_{in} - \sum \dot{m}_{out} ex_{out} + \sum Q\left(1 - \frac{T_0}{T_b}\right) - \sum W = Ex_{component}^{d}$$

where the specific flow exergy at any state *i* relative the dead state 0 is calculated by $ex = (h_i - h_0) - T_0(s_i - s_0)$ , $h_i$ being the specific enthalpy and $s_i$ the specific entropy, $h_0$ and $s_0$ the specific enthalpy and entropy at the reference state $T_0$ and $P_0$. Q is heat transfer into the component and *W* is the work done by the component. $T_b$ is the temperature at the boundary when the transfer occurs.

The exergy efficiency is the ratio of the useful exergy output (energy removed from the cold space if there is not heat recovery) to the exergy input (work):

*Equation 1*

$$\eta_{ex} = \frac{Exergy\,recovered}{Exergy\,expended} = \frac{\sum Q_{evap}(1 - \frac{T_0}{T_{be}})}{\sum W_{input}}$$

The exergy input $W_{input}$ must provide for useful and destroyed exergy. Alternatively, the exergy efficiency can be calculated by:

$$\eta_{ex} = 1 - \left(\frac{Ex_{total}^{d}}{\sum W_{input}}\right)$$

Typical values found in literature and practice for vapor compression refrigeration cycles often fall within the range of 20% to 50%. This highlights that even systems considered "energy efficient" based on COP still operate far from thermodynamic ideality. Exergy analysis is crucial because it precisely identifies why this gap exists by quantifying the losses in each component, guiding efforts towards meaningful improvements in energy efficiency along the food supply chain's cold chain.

If the heat rejected from the condenser is captured at a useful temperature (which is > $T_0$) and used for a purpose (like process heating, space heating, pre-heating water), the exergy efficiency must take into account all useful outputs and is then calculated by:

*Equation 2*

$$\eta_{ex} = \frac{\sum Q_{evap}\left(1 - \frac{T_0}{T_{be}}\right) + \sum Q_{cond}^{recovered}\left(1 - \frac{T_0}{T_{bc}}\right)}{\sum W_{input}}$$

The subscripts *c* and *e* in this equation stand for evaporator and condenser. The difference between the efficiency of Equation 1 and Equation 2 can be seen in the wasted part of the ENOUGH Tool chart (Figure 1).

### 2.2.3 Exergy of heating processes

#### Heating by electrical resistance

When heat is generated by an electrical resistance, the exergy input is electrical energy. As discussed before, electricity is high-quality energy, essentially pure work potential.

$$Exergy\,expended = Energy_{elec}$$

The useful exergy output is heat delivered to the process at a characteristic temperature $T_{process}$:

$$Exergy\,recovered = Q_{useful} \cdot \left(1 - \frac{T_0}{T_{process}}\right)$$

The exergy efficiency is then defined as:

$$\eta_{ex} = \frac{Exergy\,recovered}{Exergy\,expended} = \frac{Q_{useful} \cdot \left(1 - \frac{T_0}{T_{process}}\right)}{Energy_{elec}}$$

Using the first law applied to the conversion of electrical energy to heat, and using a heat loss ratio factor, we can assume that:

*Equation 3*

$$\eta_{ex} = \frac{Energy_{elec}(1 - loss_{ratio}).\left(1 - \frac{T_0}{T_{process}}\right)}{Energy_{elec}} = (1 - loss_{ratio}).\left(1 - \frac{T_0}{T_{process}}\right)$$

The exergy efficiency of electrical resistance heating is usually low for low-temperature applications like water heating (typically less than 15%). It only becomes reasonably efficient when very high temperatures are required. Using the highest quality energy form (electricity) to produce a low-quality energy form (low-temperature heat) represents a massive degradation of thermodynamic potential (large exergy destruction).

### Heating by combustion

When heat is generated **by combustion** and only used for a purposeful heating application (like generating steam, heating process fluids, drying, cooking...) there is no power generated simultaneously. The exergy input is the chemical exergy of the fuel consumed which represents the maximum theoretical work that could be generated from the combustion:

$$Exergy\ expended = m_{fuel}.Exergy_{fuel}$$

The useful exergy output is the energy associated with the heat that is successfully transferred to the process $Q_{useful}$ at its characteristic temperature $T_{process}$:

$$Exergy\ recovered = Q_{useful}.\left(1 - \frac{T_0}{T_{process}}\right)$$

Heat losses to surroundings, calculated using the loss ratio in the ENOUGH tool, represents an exergy loss since it reduces $Q_{useful}$.

$$Q_{useful} = Q_{fuel} * (1 - loss\ ratio)$$

The exergy efficiency is defined as:

*Equation 4*

$$\eta_{ex} = \frac{Exergy\ recovered}{Exergy\ expended} = \frac{Q_{useful}.\left(1 - \frac{T_0}{T_{process}}\right)}{m_{fuel}.Exergy_{fuel}}$$

The process temperature is crucial in this efficiency: it must be noted that if the heat is used at a low temperature (for example to generate 100°C hot water), the exergy of a combustion process can be very low.

### Heating by heat pump

Heat pumps use the high-quality electricity $W$ to move existing low-quality heat at a temperature $T_f$ to the desired temperature $T_{process}$.

The exergy efficiency is the ratio of the useful exergy output to the required exergy input:

$$\eta_{ex} = \frac{Exergy\ recovered}{Exergy\ expended} = \frac{Q_{useful}.\left(1 - \frac{T_0}{T_{process}}\right)}{W}$$

where $Q_{useful}$ is the heat delivered to the process. Typical values of the efficiency of heat pumps for heating water at 50-60°C for example is between 30 to 50%.

# 3 POTENTIAL OF ENERGY RECOVERY IN FOOD SUPPLY CHAINS

The ENOUGH tool shows in the graph displayed in Figure 1 the ratio of wasted exergy and the ratio of exergy lost. Exergy lost can be reduced by implementing more efficient technologies that are suggested by the tool. Wasted exergy can be reduced by implementing energy recovery technologies. This part of the document lists **the available technologies by** sector to recover this energy waste.

Many steps of the food supply chains such as food processes, retail, storage or transport are very energy intensive, using significant amounts of energy. Food processing and manufacturing typically require vast amounts of thermal energy for heating (cooking, pasteurising, sterilising, drying, baking, frying, evaporation) and cooling (refrigeration, freezing for preservation, chilling intermediate products and maintaining cold environments). Much of this energy is lost to the environment as **waste heat**. Energy recovery can capture and reuse this waste energy, directly reducing the need to generate new energy, which is the primary source of emissions.

Many food processes require the combustion of **fossil fuels** (such as natural gas) for heat (e.g. in boilers for steam, ovens, dryers). Energy recovery systems can capture waste heat from exhaust streams (boiler/oven flue gases, hot water discharge, hot air from dryers) and use it to preheat incoming air, water or process fluids. Preheating means that less fuel is needed to reach the target temperature. Burning less fossil fuel directly reduces the plant's emissions of greenhouse gases such as carbon dioxide ($CO_2$), nitrogen oxides ($NO_x$) and sulphur oxides ($SO_x$).

In the food process industry and more generally in the food supply chains, **refrigeration** and cooling systems are major consumers of electricity. These systems work by removing heat from a space and rejecting it (usually to the outside air via condensers). This **heat is usually wasted**. Energy recovery can capture this waste heat. Heat recovery can also reduce the need for electrical heating elements. Use of hot refrigerant gas from condensers to pre-heat water can reduce the need for separate gas boilers or electric water heaters.

The food industry also produces a significant amount of organic waste (peels, leftovers…). Anaerobic digestion can break down this waste in the absence of oxygen, producing **biogas** rich in methane ($CH_4$). Capturing methane, which is a potent greenhouse gas, prevents its release into the atmosphere and converts it into less harmful $CO_2$ while displacing fossil fuels use.

By reducing the amount of fossil fuel burned, lowering electricity demand and utilizing methane from organic waste, energy recovery is a crucial strategy to reduce emissions in the food industry.

According to [10] , 8.6% of waste heat potential in EU comes from the food and tobacco industry. The main processes identified with heat recovery potential were seed oil extraction process, solubilisation and alkalizing process, utility processes, frying and heat recovery from cooling systems. All these processes run with a temperature range from low to medium, which lead to a 1.89% Carnot's potential (potential to perform mechanical work). Thus, waste heat in food industry seems to have more potential to be used as **heat** for heat transfer.

## 3.1 Dairy processing

The European dairy sector is highly energy-intensive, as pointed out in the roadmap of WP2 on dairy process. The deliverable D2.7[11] shows the figures for dairy manufacturers in Europe. A significant amount of energy is consumed primarily for heating and cooling processes, including pasteurization, sterilization, drying and refrigeration. As a result of increasing food demand and stringent environmental regulations, such the EU Green Deal's targets for $CO_2$ reduction, reducing GHG emissions for the food industry has become a global priority and it is a main goal of the project ENOUGH.

**Opportunities of dairy industry for energy recovery**

Dairy plants operate 24/7, requiring substantial energy for continuous processing of raw milk. **Significant amounts of waste heat** are generated by processes such as pasteurization, evaporation, drying, and refrigeration systems. For instance, large and energy-intensive Italian dairy companies have a technical waste heat potential estimated at roughly 75.6 GWh/t/year, similar figures can be reported for other European countries.

Soufiyan et al. (2017)[6] presented a paper that offered a comprehensive exergy analysis of an industrial-scale yogurt drink production plant using actual operational data to quantify thermodynamic inefficiencies and identify opportunities for energy savings. The study emphasizes four main subsystems: steam generation, above-zero refrigeration, milk reception, pasteurization and standardization, and the yogurt drink production lines.

The highest exergy destruction rate (12,200 kW) occurred in the boiler and air compressor combination of the steam generator, accounting for 89.4% of the steam generation system's total exergy destruction. This is primarily attributed to high heat transfer rates with large temperature differences, intense combustion, fast water evaporation, and intensive mixing processes. Other significant exergy destruction rates were found in the pressure reducer (5.3%), heat exchanger (2.7%), and condensate tank (1.0%) within the steam generation system. This research highlighted the effectiveness of exergy analysis in pinpointing irreversibilities and losses in dairy processing plants.

Several technologies are crucial for effective energy recovery in dairy processing, focusing on maximizing heat reuse and minimizing waste. Industrial heat pumps can utilize and upgrade heat from lower-temperature sources (e.g., wastewater, cooling systems, exhaust air) to higher temperatures suitable for processes like hot water supply for pasteurization, and cleaning-in-place (CIP) systems.

Various technologies of **heat exchangers** can be used to recover heat: plate, shell and tube, air-to-water… Plate heat exchangers can be used for pre-cooling milk with well water, recovering heat from pasteurizers, and for CIP systems. Shell and tube heat exchangers are often used for larger capacities. Air to water heat recovery systems (economizers) can capture thermal energy from hot air or gas streams and transfer it to water, generating hot water for various uses.

There is a growing push to electrify heat supply, primarily when electricity is derived from renewable sources, to reduce carbon footprints. Industrial **heat pumps** are gaining significant attention. They are significantly more energy-efficient than traditional heating systems, capable of recovering waste heat from sources such as wastewater, cooling loads, and exhaust air and upgrading it to higher temperatures for reuse. Nearly all European countries offer financial subsidies or support (grants, loans, tax rebates) for companies investing in industrial-sized heat pumps, incentivizing adoption. The transition to heat pump solutions needs careful planning to integrate into ongoing operations without significant factory downtime. Addressing higher temperature levels (above 100°C) efficiently and cost-effectively remains a challenge, though progress is expected. Vapor-compression cycle heat pumps with piston or screw compression are commonly used, providing both heating and cooling up to 95°C. Efforts are ongoing to reach higher temperatures (e.g., 100°C+). They can replace traditional boilers and chillers, providing simultaneous heating and cooling, leading to significant energy savings.

Heat recovery units can capture waste **from refrigeration condensers** to preheat water, recovering 20-60% of the energy used for milk cooling.

**Condensate recovery** systems can be used to recover and reuse high-quality hot water (condensate) generated from steam systems, reducing the need for fresh water and preheating costs, saving energy, water and chemical treatment costs.

The European dairy sector is at a crossroads, facing evolving market dynamics, environmental pressures, and technological advancements. Energy recovery will be encouraged by regulation and Green Deal actions will play an even more critical role in the future. Heat pump technology is expected to become the standard for decarbonization in the dairy sector within the next decade. Future developments will focus on optimization and more integrated solutions beyond just hardware. Research and development will continue to push the boundaries of heat pump technology, enabling efficient recovery and utilization of heat at higher temperatures (beyond 100°C), thereby opening up more applications for energy recovery.

**Future energy recovery systems** are expected to be more integrated, combining heat pumps with energy storage systems and advanced energy control and management strategies for comprehensive efficiency. The increasing reliance on renewable energy sources (biofuel, geothermal, wind, hydro, hydrogen, ammonia, and solar) will be combined with energy recovery to achieve net-zero emission targets. Solar thermal technology, in particular, provides high efficiency (up to 76%) for direct hot water supply (>80°C) in dairy plants. Future trends will focus on optimizing production control, properly maintaining existing equipment, and redesigning processing lines for inherent energy efficiency rather than simply adding recovery systems (e.g., omitting pasteurization steps in UHT processes can significantly cut electricity, steam, and water usage). The future will prioritize circular economy principles, where waste heat is not only recovered but also integrated into other processes, thereby minimizing overall resource consumption. The adoption of IoT collars and AI milk analyzers for efficiency gains, primarily at the farm level, signifies a broader trend of leveraging technology for optimized resource use, which will also extend to processing plants, affecting energy management.

**Demonstrator 2 – Energy smart dairy**

The objective of the demonstrator 2 of the ENOUGH project is to conduct a meticulous analysis of a dairy existing energy flows in Norway, to identify its thermal demands, operational requirements and opportunities for optimization. Based on these findings, the project refines the existing energy system and proposes process integration strategies.

Rørosmeieriet AS (RM), Norway's leading organic dairy established in 2001, operates an integrated thermal energy system centered around a five-unit parallel $CO_2$ refrigeration plant. This system provides essential cooling for process water, cold storage, and air conditioning via a glycol loop, while simultaneously recovering heat to produce hot water for process applications, Cleaning-In-Place (CIP), and domestic needs, with surplus managed by a hot water storage system.

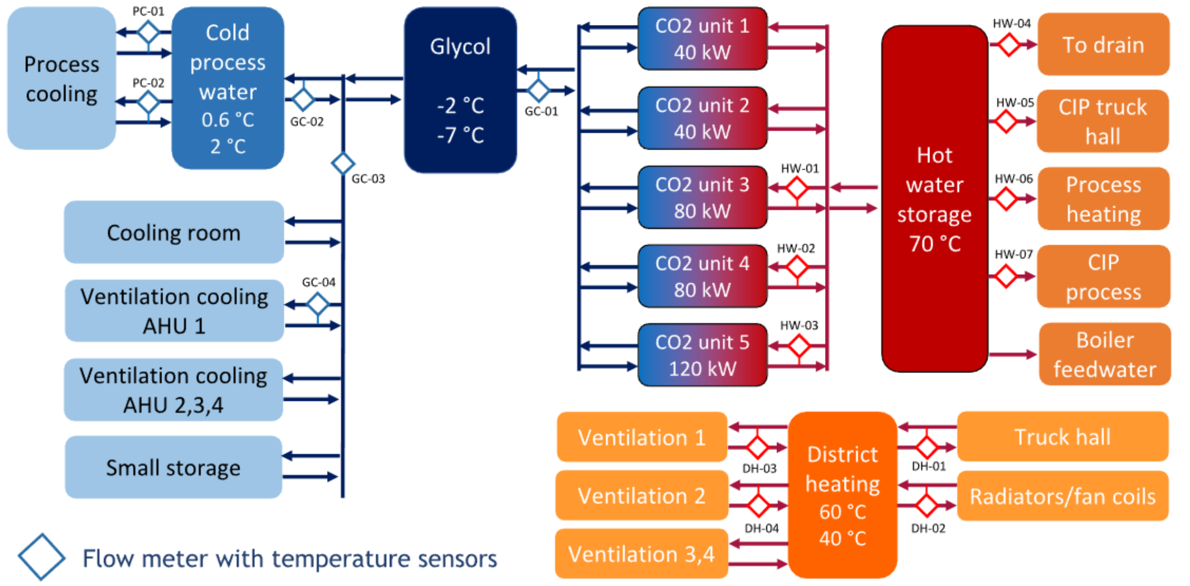


*Figure 2: Simplified overview of the thermal energy systems and the installed sensors.*

This demonstrator initiative undertakes a thorough analysis of RM's existing energy flows to precisely define thermal demands and identify areas for improvement. Subsequently, the project optimizes the energy system and proposes process integration measures aimed at substantially enhancing energy efficiency and reducing greenhouse gas emissions.

Key performance include an approximate 36% reduction in specific energy consumption to 0.09 kWh per litre of milk, coupled with water conservation. The project also evaluates the implementation of a cold thermal energy storage system to improve the refrigeration system's operational flexibility and resilience.

## 3.2 Meat and poultry processing

The meat processing industry is marked by high energy consumption across different stages, including slaughtering, refrigeration, various processing steps, and final packaging[12]. Thermal energy, mainly in the form of steam, is the main heat source in these facilities. Processes like rendering and blood processing are especially heat-intensive, collectively making up about 88% of the total process heat demand in a typical meat plant[13]. Medium-pressure steam, maintained at temperatures around 180-185°C, is directly used in these operations.

While thermal processes are important, chilling systems are the largest consumers of electricity in the meat industry, often accounting for 50-93% of the total electrical energy used in a typical slaughterhouse. Besides high-temperature steam applications, there is a steady and substantial demand for hot water (about 82°C) and warm water (around 43°C) for essential hygiene-related tasks. These include sterilization of equipment, general slaughter procedures, evisceration, and extensive cleaning and sanitization procedures. Notably, waste heat from the exhausted steam in rendering processes can significantly contribute, providing an estimated 60-70% of these hot and warm water needs.

**Opportunities of meat and poultry processing for energy recovery**

Similarly to other food processing sectors, **condensers of large refrigeration systems** (ammonia or HFC/HFO based) used for blast freezing, chillers, cold storage, and processing room cooling in the meat processing reject vast amounts of heat. This heat can be used for pre-heating or fully heating hot water for cleaning and sanitation, rendering pre-heating, domestic hot water, space heating and underfloor heating (to prevent condensation).

**Hot exhaust gases from steam boilers** used for scalding, cooking, rendering or sterilization are also a source for heat recovery. This heat can be used for pre-heating boiler feedwater, combustion air or low temperature water heating.

**Hot/warm water** from cleaning, scalding, cooking and washing operations can be used for pre-heating incoming fresh water for cleaning and sanitation, boiler or scalding makeup water.

**Hot vapors and exhaust gases** from cookers and dryers are often at high temperatures and contain significant latent heat. This heat can be used for generating low pressure steam or hot water, or pre-heating combustion air.

Meat and poultry processing plants use **compressed air** for pneumatic control, pneumatic tools, product handling, cleaning and sanitation. Compressed air systems generate significant heat, with up to 80-90% of the electrical energy input converted to heat. This heat can be recovered from the compressor's oil cooler or aftercooler to produce hot water or warm air.

Finally, **hot exhaust air** from cooking and smoking ovens can be recovered from ovens, smokehouses or cookers to pre-heat incoming air to the ovens or generating hot water.

A key challenge is the high fouling potential of fluids in meat processing. Materials such as meat slurry, mechanically deboned meat (MDM), minced meat, viscera, and blanching tank water (which may contain bristles and nails) tend to cause severe fouling. Addressing this involves using specialized heat exchangers, like scraped surface or robust welded plate types, designed to handle fluids with suspended particles and high viscosity.

Another challenge is the diverse temperature ranges in meat processing. Waste heat streams cover a wide temperature spectrum, each offering different recovery opportunities and challenges. These include high-temperature exhausts from rendering processes, which can exceed 400°C. Medium-temperature sources, like boiler flue gases, are usually between 177-400°C. There are also low-temperature sources, such as heat from refrigeration condensers, hot water used for cleaning (43°C to 82°C), and wastewater streams, typically below 100°C. While high-temperature sources are generally easier to recover and utilize, low-temperature waste heat holds the greatest untapped potential for future growth within the overall waste heat recovery market. The significant and continuous demand for hot water at moderate temperatures (43-82°C) for cleaning and sterilization across meat processing operations creates an ideal thermal sink for upgrading these low-grade heat sources.

There is a wide variety of heat recovery technologies available, each with specific design features and recommended uses (e.g., scraped surface heat exchangers for viscous fluids, welded plate heat exchangers for suspended particles, heat pumps for upgrading low-temperature sources, and ORC for electricity generation from particular temperature ranges). The best technology choice depends heavily on the characteristics of the waste heat stream itself. These include the "quality" (temperature), the "nature" (e.g., fouling potential and viscosity), and the "temporal availability" of the waste heat. The specific needs of the target for the recovered energy, whether hot water, steam, or electricity, are equally important. A detailed energy audit and process integration analysis are essential first steps for successful and cost-effective waste heat recovery implementation in the meat processing industry. This analysis must precisely identify waste heat sources and match them with suitable heat demands, guiding the choice of the most appropriate technology. The chaotic nature of industrial waste streams and the complex fluids used in meat processing make this tailored approach critical to achieving optimal performance and avoiding costly operational failures.

Factors such as national policies, existing industrial infrastructure, and distinct regional energy landscapes impact the economic feasibility of investing in heat recovery. Reported payback times range from 1 to 10 years.

In conclusion, the meat processing sector has a clear pathway to significant energy efficiency improvements and decarbonization through strategic heat recovery. Ongoing innovation in heat recovery technologies, combined with supportive policies and a comprehensive approach to energy and water management, positions the industry to attain both economic competitiveness and environmental responsibility. Future efforts should focus on further integrating these technologies, using digital monitoring for optimization, and continuing to develop solutions for challenging low-temperature and high-fouling waste streams.

## 3.3 Fish production

The fish and fish products processing industry, a cornerstone of global food security, is inherently energy-intensive. Operations such as chilling, freezing, cooking (e.g., canning, steaming, frying, smoking), drying, and sterilization necessitate significant thermal energy inputs, leading to substantial operational costs and environmental burdens from waste heat rejection.

The global demand for fish and seafood continues to rise, driving increased processing activities, in WP2 the roadmap for processing provides an overview complete of the sector. Fish sector faces mounting pressure to enhance sustainability, reduce its carbon footprint, and improve economic competitiveness. Energy consumption constitutes a major operational cost in seafood processing, with heat-intensive unit operations generating considerable amounts of waste heat[14]. The waste thermal energy represents a significant lost resource, contributing to inefficiency and environmental discharge. Heat recovery, the process of capturing and re-utilizing this waste energy, offers a robust solution to these challenges, aligning with principles of industrial ecology and circular economy models.

Waste heat in fish processing can originate from various sources, exhibiting a wide range of temperatures and thermodynamic qualities. The primary objective of heat recovery is to transfer this thermal energy from a high-temperature, low-utility stream to a lower-temperature stream that requires heating. This is achieved through various heat transfer mechanisms, predominantly convection and conduction, facilitated by specialized equipment. The thermodynamic efficiency of heat recovery is fundamentally governed by the Second Law of Thermodynamics, dictating that heat transfer occurs from higher to lower temperatures, and the maximum possible recovery is limited by the exergy content of the waste stream[15].

**Opportunities of fish plants for energy recovery**

*Refrigeration Systems:* Large-scale **chilling and freezing** operations (e.g., blast freezers, cold stores) employ vapor compression refrigeration cycles. The condensers of these systems reject significant amounts of heat, typically at temperatures ranging from 30°C to 60°C, often dissipated to ambient air or cooling water[16].

*Cooking and Sterilization Processes:* Combustion of fuels in boilers is used to generate steam for cooking, canning, and sterilization processes produce hot exhaust gases (often >150°C) with substantial sensible heat which can be recovered. Steam systems used for cooking (e.g., steaming fish fillets, crab legs) often release hot condensate or flash steam, particularly from traps and vents, carrying both sensible and latent heat. Water or brines used for blanching, boiling, or retorting operations are discharged at elevated temperatures (60-95°C). Air dryers for fishmeal, dried fish products, or fish snacks exhaust hot, humid air (50-120°C) containing both sensible and latent heat. Hot water used for sanitation of equipment and processing areas is often discharged at high temperatures (40-80°C).

Numerous studies affirm the significant energy savings and economic returns on investment for heat recovery systems in the seafood sector. Analysis by the International Finance Corporation[17] and others highlight that energy efficiency measures, including heat recovery, are crucial for reducing operational costs in fish processing. The specific energy consumption (SEC) is a key metric, with successful heat recovery implementations demonstrating substantial reductions [14].

This table consolidates information on common waste heat sources in fish processing, the technologies employed for their recovery, the typical energy savings achieved, and estimated payback periods. The data is synthesized from various scientific studies, industry reports, and case studies, reflecting a range of scenarios.

*Table 2: Waste heat sources in fish processing and technologies for recovery.*



| Fish Process Generating Waste Heat | Type of Waste Heat Stream | Temperature Range (°C) | Recovery Technology | Application of Recovered Heat | Estimated Energy Recovery / Savings | Typical Payback Period | Key References |
|---|---|---|---|---|---|---|---|
| Refrigeration & Freezing | Condenser heat from chillers/freezers (e.g., ammonia, $CO_2$ systems) | 30 - 60 | Plate Heat Exchanger, Desuperheater, Heat Pump | Domestic Hot Water (DHW), Space Heating, Defrosting, Preheating boiler feed water | Up to 600 kW recovered from large $CO_2$ systems; Significant reduction in electricity | 1.1 - 2.8 years | [18] [16] |
| | Defrosting water | 10 - 25 | Plate Heat Exchanger | Preheating incoming water for thawing or cleaning. | Moderate (recovers sensible heat) | 2 - 5 years (for general wastewater heat recovery) | |
| Fishmeal Production | Boiler Flue Gases (steam generation) | 150 - 250 | Economizer, Air-to-Air Heat Exchanger (Recuperator) | Preheating boiler feed water, Preheating combustion air. | 55.5% decrease in Specific Energy Consumption (SEC); Up to 33% fuel savings. | < 2 years | [14] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Dryer Exhaust Air (from fishmeal dryers) | 80 - 120 | Air-to-Air Heat Exchanger, Heat Pump | Preheating incoming drying air, Preheating process water. | 50-70% energy savings with HPD. | 1.5 - 3 years | [19] |
| Cooking & Sterilization | Hot Effluent (blanching water, retort cooling water, boiling brines) | 60 - 95 | Plate Heat Exchanger, Shell-and-Tube Heat Exchanger | Preheating incoming process water, Preheating boiler make-up water, CIP water preheating. | 30-60% energy recovery; Significant reduction in steam demand. | 1-3 years (highly dependent on volume & temperature) | [17] |
| | Condensate/Flash Steam from Steam Traps | 90 - 100 | Flash Steam Recovery System, Condensate Return System | Boiler feed water preheating, Low-pressure steam generation for other processes. | High (recovers both sensible and latent heat) | < 1 year | Standard industrial practice for steam systems. |
| Washing & Cleaning (CIP) | Hot Wastewater (from washing fish, equipment CIP) | 40 - 80 | Plate Heat Exchanger, Tube-in-Tube Heat Exchanger | Preheating fresh cleaning water, Preheating water for general utility. | 45.7% to 60.8% reduction in energy for DHW; 34% to 60% of energy deposited in wastewater recovered. | 2 - 5 years | [18] |
| Specific Product Drying | Exhaust Air (from dried fish, fish snacks) | 50 - 100 | Air-to-Air Heat Exchanger, Heat Pump Dryer | Preheating fresh drying air, Reduced electricity | Up to 70% energy savings for drying | 2 - 4 years (HPD systems may have longer payback due to higher CAPEX) | [19] [20] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | consumption for dehumidification. | | | |

Heat recovery from fish and fish products processing is an economically advantageous strategy for enhancing energy efficiency and environmental performance. This industry generates substantial waste heat, particularly from refrigeration, cooking, drying, and wastewater streams, offering considerable potential for energy recapture. Demonstrated case studies and extensive scientific literature underscore significant energy cost reductions, decreased GHG emissions, and improved overall sustainability.

## 3.4 Brewery

Beer is one of the oldest alcoholic beverages in the world. The brewing process is based on a recipe that dates back centuries. Beer manufacturing is a fascinating blend of art and science, heavily reliant on precise control of temperature, energy inputs, and the transformation of raw materials. Essentially, it is a biological process that converts starches into fermentable sugars, which yeast then converts into alcohol and $CO_2$.

Malt is the main source of fermentable sugars and greatly contributes to the beer's flavor, color, and body. Barley grains undergo a malting process through controlled germination (steeping, germination, kilning) that activates enzymes vital for converting starches. Other malted grains, such as wheat, rye, or oats, can also be used for certain beer styles.

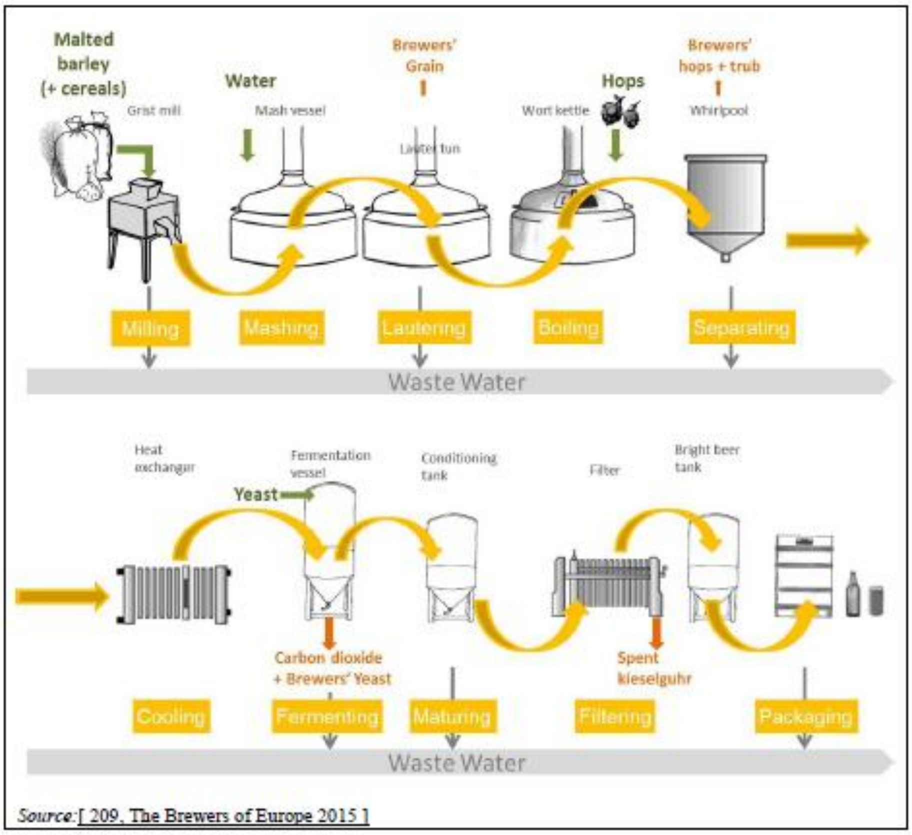


*Figure 3: Breer production process. Source Giner 2019.*

A general overview of the beer production process is presented in Figure 3 for processing malted barley.

The **milling** process consists of crushing malted grains to break open the husks and expose the starchy endosperm. The goal is to create a grist that allows for efficient extraction of starches and sugars while leaving the husks relatively intact to aid in filtration. The energy use during this process is relatively low, primarily mechanical energy.

The milled grist is mixed with hot water in a vessel called the mash turn. This process is called the **mashing**. Temperature control is important for this process, since specific temperature rests activate different enzymes. The mash typically starts around 45-55°C and is gradually raised, often through multiple steps, to 75-78°C for mash-out. The energy use of this process is significant to heat the water and maintaining mash temperatures. This typically comes from steam generated by boilers.

The "mash" (liquid wort and spent grains) is transferred to the **lauter tun** (see Figure 3), a large vessel used in brewery to separate the liquid (wort) from the solid spent grains. First, the wort is recirculated until it runs clear. Then, hot water (sparge water, typically 75-80°C) is sprayed over the grain bed to rinse out remaining sugars. This part of the process uses thermal energy for heating sparge water and pumping energy for transferring liquids.

The collected wort is transferred to the brew kettle (or copper) and brought to a vigorous boil, usually for 60-90 minutes. **Boiling** is the most energy-intensive operation, requiring significant thermal energy. This is typically supplied by direct-fired burners or, more commonly in larger breweries, steam jackets/calandria around the kettle. Energy recovery systems (e.g., wort vapor condensers) are crucial for recovering heat from the steam and preheating the incoming water or wort.

After the boil, the hot wort is rapidly circulated in the kettle or a **separate** whirlpool vessel to create a vortex. This causes insoluble solids (trub – hop residue and coagulated proteins) to collect in a cone at the center of the vessel, facilitating their removal. Pumping energy is the only energy use for this part of the process.

The hot wort (~95-100°C) must be rapidly **cooled** to fermentation temperature (typically 18-22°C for ales, 8-14°C for lagers) before yeast is pitched. This is done using a plate heat exchanger, where the hot wort flows on one side and a cooling medium (cold water, glycol) flows on the other. Rapid cooling minimizes the risk of infection and DMS (dimethyl sulfide) formation. Cold water/glycol generation (refrigeration) is energy-intensive.

The cooled wort is transferred to a **fermentation** vessel (fermenter), and yeast is added ("pitched"). Yeast consumes the fermentable sugars, producing ethanol, $CO_2$, and various flavor compounds. Temperature Control is critical in this step because yeast activity is highly temperature-dependent. Fermenters are typically jacketed and use glycol cooling to maintain precise temperatures. Cooling energy (refrigeration for glycol) is used here to manage the exothermic fermentation process and maintain the desired temperatures.

After primary fermentation, the "green beer" may be transferred to a bright tank or remain in the fermenter for a period of conditioning. For lagers, this involves extended cold storage (0-4°C) to allow flavors to mellow, undesirable compounds to settle out, and carbonation to be absorbed. Continuous cooling energy (refrigeration) is required to maintain cold temperatures. Some beers are **filtered** to remove yeast and other particles, resulting in a clearer product. This process uses continuous cooling energy (refrigeration) to maintain cold temperatures and pumping energy for transfers and filtration.

**Opportunities for breweries for heat recovery:**

Capturing waste heat from boiling, wort cooling, and refrigeration systems to pre-heat water for mashing or cleaning is often the largest opportunity for energy savings.

During wort boiling, a large amount of hot vapor is produced. This vapor carries significant thermal energy. Heat exchangers, often connected to a kettle steam condenser, can capture this heat by condensing the vapor. The recovered heat can be used to preheat fresh water for the next batch (known as hot liquor), supply hot water for the mashing process, or generate hot water for cleaning and sanitization (CIP systems). Boiling is one of the most impactful areas for heat recovery, with potential savings of 10-20% of boiling energy and significant reductions in fuel consumption and $CO_2$ emissions.

Fermentation tanks are typically jacketed and cooled to maintain optimal yeast activity. The cooling systems remove heat generated by the yeast. This waste heat can also be captured using heat exchangers and repurposed, for instance, to preheat water for various brewery processes or even for space heating in the facility.

Refrigeration units, essential for cooling wort, controlling fermentation temperatures, and chilling finished beer, produce considerable waste heat as a byproduct of their operation. This waste heat can be recovered and utilized for preheating water, especially for cleaning purposes, or for general space heating.

Many breweries rely on steam for heating processes. As steam transfers its heat, it condenses back into hot water (condensate). Instead of draining this hot condensate, it can be collected and returned to the boiler, significantly reducing the energy required to bring fresh feedwater up to temperature.

Boilers and other heating systems in a brewery produce hot flue gases that are typically vented. Heat exchangers can extract residual heat from these flue gases to preheat combustion air, boiler feedwater, or other process water. This can be particularly beneficial for breweries using biomass or biogas, although attention must be paid to potential corrosion issues from sulfur components in the flue gas.

Heat recovery directly reduces reliance on external energy sources (natural gas, electricity), leading to substantial cuts in fuel and utility bills. Savings of 5-20% on total energy costs are commonly reported, with specific measures like wort boiling heat recovery achieving up to 60% energy recovery for that process. Many heat recovery systems offer attractive payback periods, often ranging from less than one year to five years, making them a sound financial investment.

In conclusion, by strategically capturing and reusing thermal energy from various stages of the beer production process, breweries can achieve significant reductions in energy consumption, operating costs, and environmental impact. The integration of well-designed heat recovery systems, from plate heat exchangers to comprehensive energy storage solutions, represents a smart investment that benefits both the brewery's bottom line and its commitment to a greener future.

### 3.4.1 Fruit and vegetable processing

The fruit and vegetable processing industry, a vital sector in the global food supply chain, is characterized by its significant energy consumption. Operations such as washing, blanching, pasteurization, sterilization, drying, and freezing require substantial heat input, leading to considerable energy costs and environmental impact through the discharge of waste heat. Heat recovery, with the capture and reuse of this otherwise wasted thermal energy, presents a compelling opportunity to enhance the sustainability, economic viability, and energy efficiency of fruit and vegetable processing.

**Opportunities of fruit and vegetable processing for energy recovery**

*Blanching Water Heat Recovery* (e.g., frozen vegetables): In a typical frozen pea or potato processing plant, continuous blanchers consume large volumes of hot water. The spent blanching water, often discharged at temperatures ranging from 60-90°C, represents a significant source of waste heat. Installing a plate heat exchanger can recover heat from this effluent to preheat fresh cold water entering the blancher or to preheat boiler feed water. This can lead to substantial reductions in steam consumption.

*Drying Exhaust Air Heat Recovery* (e.g., fruit leathers, vegetable flakes): Drying processes, such as those for producing fruit leathers, dried herbs, or vegetable flakes, are highly energy-intensive. The exhaust air, laden with moisture and heat, is often vented directly to the atmosphere and wasted. Air to air heat exchangers can be installed to transfer sensible heat from the hot exhaust air to preheat the incoming fresh air for the dryer. This reduces the energy required by the main heating coil.

*Heat Pump Drying (HPD):* For heat-sensitive fruits and vegetables (e.g., berries, mushrooms), HPD systems are increasingly utilized. These systems recover latent heat by dehumidifying the drying air and then use a heat pump to elevate the temperature of the recovered heat, which is then recycled back into the drying chamber. This not only significantly reduces energy consumption (often by 50-70% compared to conventional dryers) but also allows for lower drying temperatures, preserving product quality (color, aroma, nutrients).

*Pasteurization and Sterilization Regenerative Heating* (e.g., fruit juices, canned vegetables): In processes involving thermal treatment of liquids like fruit juices or vegetable purées, regenerative heating is a standard and highly effective heat recovery method. After pasteurization or sterilization, the hot product is used to preheat the incoming cold product through a plate or tubular heat exchanger. This can achieve heat recovery efficiencies of 80-95%, drastically reducing the energy needed for both heating and subsequent cooling.

*Refrigeration System Condenser Heat* (e.g., fresh produce cold storage): Large cold storage facilities for fruits and vegetables use powerful refrigeration systems that reject significant amounts of heat at their condensers. This heat, typically at 30-50°C, can be captured using desuperheaters or dedicated heat exchangers to produce hot water for cleaning, showers, or even space heating in adjacent packing areas or offices.

*Hot Water Effluent from Cleaning-in-Place (CIP) Systems*: CIP systems in fruit and vegetable processing generate hot water and chemical solutions for sanitation. The hot rinse water, discharged at high temperatures, can be routed through a heat exchanger to preheat fresh water for the next CIP cycle or for general utility purposes.

In conclusion, heat recovery is an indispensable strategy for enhancing the sustainability and operational efficiency of the fruit and vegetable processing industry. The extensive body of literature and numerous practical examples demonstrate its proven benefits in reducing energy consumption, lowering operating costs, and mitigating environmental impact. Continued research and development in advanced heat recovery technologies, coupled with systematic design approaches, will further unlock the full potential of waste heat utilization in this vital sector.

## 3.5 Bakery processing

The core process of baking involves adding a massive amount of heat to a product, heat that is then wasted to the atmosphere. The primary opportunities for bakery processes are to capture this waste heat and using it to offset other energy demands within the facility.

**Opportunities of bakery processing for energy recovery**

Oven heat recovery: The exhaust from large tunnels or rack ovens is the largest source of high-quality waste heat in bakery processing. This exhaust contains sensible heat from the hot products of combustion and the hot air itself, and latent heat from the significant amount of water evaporated during baking. This heat can be used for heating water for sanitation or domestic hot water, steam generation, space heating or pre-heating of combustion air.

Product cooling heat recovery: Products exiting the oven (bread, buns, pastries…) are extremely hot and must be cooled before packaging. This cooling process releases a large amount of low to medium grade heat. This recovered heat can be used for space heating, pre-heating makeup air or proofing, for example.

Refrigeration system heat recovery: Bakery processing involves many refrigeration systems, for dough chilling, ingredient storage and freezers. Heat can be recovered from the condensers of these refrigeration systems and be used for pre-heating water, underfloor heating or preventing frost under freezer floors.

Air compressor heat recovery: Heat generated by air compressors used for packaging machines, pneumatic controls and cleaning nozzles can be recovered for hot water generation or space heating.

Hot wastewater heat recovery: Hot drain water from pan washers and sanitation cycles can be used for pre-heating the incoming cold water. This creates a simple effective loop that reduces the primary energy needed for water heating.

The most advanced systems in bakery processing integrate these opportunities, for example, using refrigeration heat to pre-heat water to 30°C, which is then further heated to 65°C by the oven exhaust heat recovery system, maximizing efficiency at each stage.

## 3.6 Transport

Food transportation plays a critical role in the supply chain, ensuring that perishable goods reach consumers in a safe and timely manner. However, this process often involves significant energy consumption, particularly for refrigerated transport. Heat recovery systems in food transportation present an opportunity to improve energy efficiency, reduce operational costs, and minimize environmental impact.

Energy integration in transport units can be envisaged as thermal energy and mechanical energy recovery from the traction or braking power system.

As for thermal energy recovery from the Internal Combustion Engine (ICE), Vapour Absorption Refrigeration System (VARS) have been proposed, trying with the aim of recovering the exhaust heat of the thermal traction engine to cool the insulated box of trailers and trucks (Maiorino et al, 2021[21]). It is however worth reminding that the trend towards more efficient ICE decreases the amount and temperature level of exhaust heat; additionally transition to electrical/hybrid traction will reduce opportunities for such systems. At the same time, the combination with fuel cell might open new scenarios for the future, as illustrated in Venkataraman et al. 2020[22]. After reviewing the literature, the authors however conclude that the integration of fuel cells with VARS would need an exceptional research and development effort for both heat recovery, integration and compact and light system design, but it would finally drive towards vehicle efficiency, emission and noise reduction, including of course the use of natural working fluids (NWF).

The adoption on large scale of hydrogen internal combustion engines for vehicle traction is another possibility that can take advantage of thermal energy recovery and VARS. For example, Li and Hou, 2025[23], analysed the possibility of recovering heat from a Bus Hydrogen Internal Combustion Engine to provide air conditioning through a double-effect lithium bromide absorption cooling system, showing the possibility of satisfying the cooling demand up to 34°C ambient at the selected conditions (water in/out 7/12°C). They also focused on space constraints. Such technology could be also explored for temperature levels suitable for fresh food transport.

Yao et al.[24] presented a dynamic simulation study of a heavy-duty refrigerated truck equipped with a novel waste heat recovery system. The goal was to analyse its real-world performance, energy savings, and operational challenges under various driving and loading conditions. The paper proposes integrating a Combined Cooling and Power Waste Heat Recovery (CCP-WHR) system into the truck. This CCP-WHR system uses the engine's waste heat to simultaneously generate electricity (power) and provide refrigeration (cooling), replacing the conventional refrigeration unit and improving the truck's overall efficiency. The CCP-WHR system has been shown to be highly adaptable and to perform best under highway conditions and with a full payload, where waste heat is abundant and stable. Under these optimal conditions, the modified truck achieved 2.8 L/100 km of fuel saving (a 6.4% reduction), an additional 9.1 kW of net power generation (a 5.5% increase) and an emission reduction of 73.9 g/km of carbon emissions.

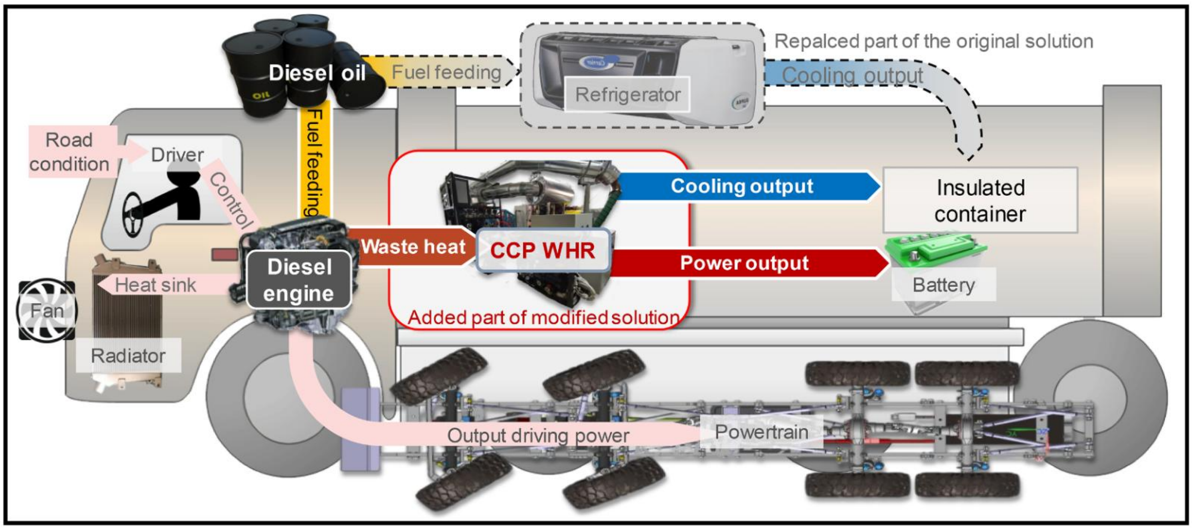


*Figure 4: Refrigerated truck equipped with CCP WHR system to recover heat from the diesel engine (Source Yao et al. [24])*

In the case of semitrailers, the implementation of e-axles enables the recovery of braking energy, which is then stored in high-capacity battery packs. These batteries support, when needed, the road-tractor's powertrain by supplying power to the e-axle defining a mild-hybrid powertrain distributed between the tractor and the semitrailers. When refrigerated semitrailers are taken into account, the energy recovered by the e-axles can be profitably used to sustain the refrigeration unit. Furthermore, as both the e-axles and electrified transport refrigeration units need batteries to store energy, the battery size, costs and the energy fluxes can be optimized to serve both the system in a centralized way.

Energy recovery in food transportation offers significant potential to enhance energy efficiency and sustainability. While challenges exist, advancements in technology and growing environmental concerns are driving adoption. Stakeholders in the food transport sector should consider energy recovery solutions as part of their energy management strategies to reduce costs and environmental impact.

### 3.6.1 Cold storage warehouses

The potential of heat reclaim/recovery for cold stores has been presented in the deliverable 2.4[25] of the Enough project through a comprehensive literature review. Refrigeration systems used in cold storage has been identified as offering substantial heat recovery potential, though the heat is typically high in quantity but low in "quality" or temperature. The use of the heat recovered is often for domestic hot water. Other cases studies use recovered heat for replacing electric defrosting, underfloor heating, space heating and reheat for humidity control. The most challenging use are wash water or boiled feed water which require temperatures over 50°C.

Overall, such heat recovery with compressor heat recovery for underfloor heating, boiler make-up feedwater pre-heating, and hot water for cleaning, can lead to up to 4% annual system energy savings. This is relatively low since the potential use of recovered heat is limited for a facility only used for cold storage. For more demanding applications, heat pumps can boost recovered heat to higher temperatures, further reducing emissions.

### 3.6.2 Retail

Supermarkets can significantly reduce their energy consumption by implementing heat recovery systems from their ventilation and refrigeration systems, either directly or indirectly via heat pumps. Heat recovery from these systems is an essential aspect of reducing the primary energy consumption of supermarkets.

The deliverable D2.2[26] of the Enough project presents high-efficiency heating technologies and heat recovery systems to reduce primary energy consumption in supermarkets, in accordance with the European Union Directive 2012/27/EU. It highlights that refrigeration is the main energy consumer, followed by heating and lighting. The document explores methods of direct heat recovery from refrigeration and ventilation systems, including the use of heat exchangers and desuperheaters to increase the temperature of the recovered heat, and methods for indirect heat recover via heat pumps, highlighting their ability to raise the temperature of waste heat and improve overall efficiency, particularly in well-insulated retail buildings.

The MultiPACK project, officially titled "Demonstration of the next generation standardised integrated cooling and heating packages for commercial and public buildings based on environment-friendly carbon dioxide vapour compression cycles," was an EU H2020 project funded under the Horizon 2020 research and innovation programme (grant agreement No 723137). In this project, there was a focus on heat recovery and expansion work recovery within its integrated $CO_2$ refrigeration, heating and cooling systems for supermarkets[27]. A primary mechanism for achieving to satisfy all the thermal needs of food retail stores was heat recovery from the refrigeration system. During winter, heat recovery is activated by discharging heat to the indoor environment. The gas cooler can be partially or totally bypassed to promote heat recovery and save fan energy[28]. If the recovered heat isn’t sufficient, a heat pump is activated utilizing an outdoor evaporator as a heat source.

The Multipack units also incorporated the recovery of expansion work via two-phase ejectors. Ejectors can be crucial for enhancing energy efficiency, particularly in warm climates like those found in South Europe[29]. They enable the shifting of refrigerant from the medium temperature compressor suction to the intermediate pressure receiver, which leads to a reduction in the total compression work required.

The savings demonstrated in the Multipack project (-28% of specific energy consumption compared to average values) were directly linked to the successful implementation and optimization of energy recovery techniques within the integrated $CO_2$ systems.

**Opportunities of energy recovery for Retail**

**Ventilation** is often the main source of heat loss in new and old retail buildings, accounting for more than 50% of the building total heat loss. To mitigate this loss, heat recovery systems are generally implemented and often integrated into air handling units. These units may include primary and secondary heat exchangers. Fresh air can be preheated or pre-cooled in the primary heat exchanger, reducing the load on the subsequent heating or cooling coils. A secondary heat exchanger can be used to increase the temperature of the supply air, particularly for dehumidification, thereby reducing the load on the heating coil. Energy wheels are a common type of exhaust air heat recovery system, capable of transferring both heat and moisture.

Heat recovery efficiency can reach 80-90% for the best systems, although overall efficiency (taking into account losses through exfiltration and infiltration) is around 60-70%. A heat pump can be integrated to increase heat recovery from the exhaust air. While rotary heat exchangers alone can achieve an overall recovery rate around 60-70%, adding a heat pump can significantly increase this rate. For example[30], a heat pump with a seasonal coefficient of performance of 3 enabled 97% of the heat demand of the air handling unit to be covered.

Normally, **residual heat from refrigeration systems** is discharged via air condensers or cooling towers. Heat recovery is typically achieved by raising the condensation pressure to a level where the heat transfer fluid at the condenser outlet has a temperature that can be used for heating. A direct heat recovery solution can be integrated via an intermediate circuit with floating condensation pressure. If heat is required, the condensation pressure is increased to provide the appropriate temperature level. Modern chillers using natural refrigerants such as ammonia or carbon dioxide offer significant potential for recovering waste heat at useful temperature levels, sometimes above 50°C. The recovered heat can be used for space heating or domestic hot water.

For higher temperatures and low heating demand, heat recovery via a desuperheater can be implemented. This method is viable for systems operating with refrigerants that have a relatively high discharge temperature, such as $CO_2$ or $NH_3$.

Direct heat recovery at floating condensing pressure is thermodynamically promising in summer, when the system is already operating at a higher condensing pressure. A cascade heat recovery system with a heat pump allows a great recovery with a good performance. In this solution, the heat pump extracts heat from an intermediate circuit that is used to cool the condenser. The use of heat rejected by the refrigeration system by the heat pump allows the refrigerating system to operate at a relatively low condensation temperature, which increases its efficiency. The integration of a heat pump after the condenser can also allow for additional subcooling of the refrigerant, improving the efficiency of the refrigeration system. During colder periods (autumn/spring and winter), indirect heat recovery via a cascade heat pump system has shown better thermodynamic performance.

**Demonstrator 16: RESHARE (Refrigerated Store Heat Advance Recovery)**

The primary aim of the demonstrator 16 of the ENOUGH project is to show the technical, carbon reduction and financial feasibility of reclaiming heat from regional distribution cold store refrigeration systems and using it on site to meet the heat demands currently supplied by natural gas and other resources.

This demonstration evaluates and identifies the most viable heat reclaim technologies for the cold storage industry, focusing on two key applications: retrofitting existing facilities and integration into new constructions. Given that the average cold store operates for 30 years, retrofitting presents the most significant opportunity for widespread energy and carbon reduction. The project's financial analysis extends beyond simple payback periods, which are the main driver for end-users. It incorporates a forward-looking assessment of energy savings, accounting for future changes to grid tariffs that are expected to become more dynamic with the integration of renewable energy.

Two cold storage sites that have been selected are at Avonmouth and Falkirk in the UK. These sites represent the two main types of refrigeration systems used in distribution centres, namely centralised ammonia 2-stage systems and ammonia/carbon dioxide cascade systems.

The main results showed that heat recovery should be considered in the design of new RDCs (Refrigeration Distribution Centers). This includes specifying water-cooled condensers with separate cooling towers for future heat utilization, or, as a low-cost measure, incorporating valved connections for heat recovery heat exchangers within standard refrigeration systems to allow for later integration.

### 3.7 Food service (restaurants, catering)

Food service should be treated as complete energy systems to emphasize the potential for thermal integration, sharing heat and coolth. This is currently not common, with kitchens that generate substantial waste that is removed by the HVAC systems but could be reclaimed for hot water or heating customer areas. A comprehensive review for heat reclaim in food service is presented in the deliverable 2.3 [31] of the ENOUGH project. While some sectors, like supermarkets, reclaim heat (often from $CO_2$ refrigeration systems), food service outlets face challenges due to their widespread use of refrigeration systems which make difficult the integration.

### 3.8 Conclusion

There are numerous and diverse sources of waste energy throughout the food supply chain and a significant potential for energy recovery. The food supply chains involve heating, cooling, drying, transportation, and generate organic waste. Food processing and manufacturing is probably the highest potential sector, but packaging, distribution, logistics and retail are also waste energy sources.

Key barriers are the initial investment for recovery systems, the lack of knowledge, sometimes space constraints for retrofitting existing facilities, and an often difficult matching between heat sources and demands. This last barrier can be often addressed by solutions like thermal storage.

Despite these barriers, the driving forces of cost savings, sustainability goals, and regulatory pressures should push the food supply chains towards greater adoption of energy recovery practices. The impact of using energy recovery in terms of emissions should be overwhelmingly positive, leading to significant reductions in greenhouse gas (GHG) emissions and often other air pollutants since many food industry processes rely on burning fossil fuels (natural gas, fuel, coal...) in boilers, ovens, dryers, etc., to produce heat. The potential is massive and largely underutilized.

## 4 ENERGY RECOVERY TECHNOLOGIES

As it can be seen in the previous parts, the majority of the energy recovery opportunities in food supply are waste heat opportunities. One of the reasons is stated in the second law of thermodynamics, which states that no energy conversion or transfer is 100% efficient, and that some energy is inevitably “lost” as low-grade, disordered energy, so as heat. Inefficiency is a fundamental property of every single energy process, and waste heat is the most abundant and available form of waste energy. The potential for recovery is far greater than for other forms of energy. Recovering heat is also often straightforward and economically attractive, relying on simple and well understood technology such as heat exchangers.

Available technologies to recover waste heat can be categorized as passive technologies, whether the heat is being used directly at the same or at lower temperature level, or as active technologies, whether it is transformed to another form of energy or to a higher temperature level (Figure 5).

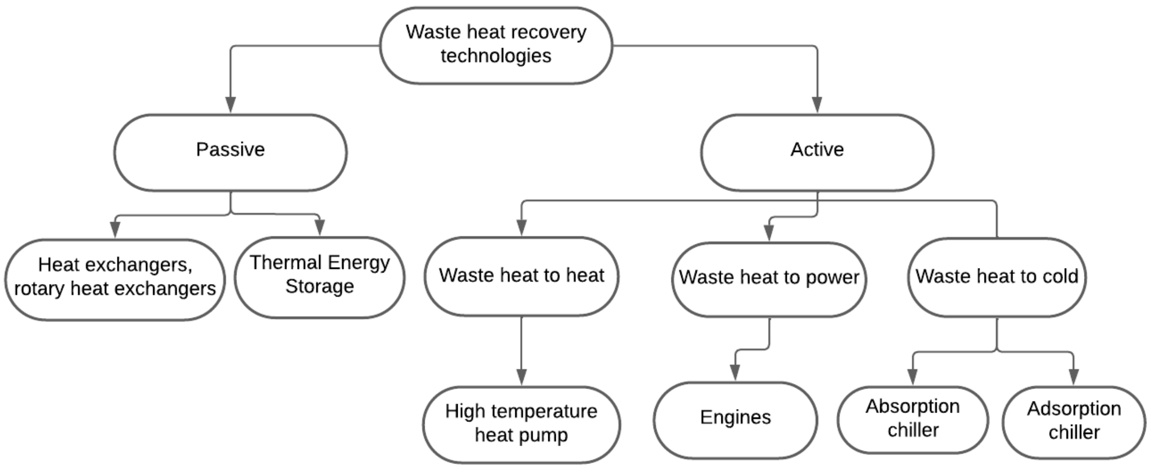


*Figure 5: Categorization of heat recovery technologies*

Other energy recovery technologies can involve mechanical or kinetic energy such as regenerative braking, but their application is limited to systems that start and stop frequently. Pressure recovery is also a possibility, but a highly specialized application.

Chemical energy recovery such as incineration or biogas production are more of waste management strategy than simple "recovery". Biogas is a good example of chemical energy recovery, taking organic waste, where energy is stored in the chemical bonds of complex molecules (carbohydrates, proteins, fats) and converts it into a different, more useful chemical form (biogas). The food and beverage industry is one of the most ideal sectors for biogas implementation. This industry generates a consistent, predictable stream of organic waste including fruit and vegetable peels, cores and pulp, meat and fish trimmings, spent grains from breweries, rejected or spoiled food products, wastewater with high organic loads, dairy byproducts, etc... Those waste streams are rich in energy and are often costly to dispose of through traditional means.

Heat recovery technologies and biogas production as chemical energy recovery will be presented in detail in the following parts.

## 4.1 Heat exchangers

Heat exchangers are the core components that make heat recovery possible, whatever the energy conversion process that follows. Their fundamental function is to transfer thermal energy (heat) from one fluid (liquid or gas) to another, without the two fluids coming into direct contact or mixing.

Cases of applications for heat recovery include desuperheaters installed on the compressor discharge line of refrigeration systems, full condensing heat recovery units placed in a refrigeration cycle, heat recovery ventilator to recover heat and moisture from exhaust air, recuperators for air and economizers for water in industrial processes to recover heat from exhaust flue gases, steam condensers to recover exhaust steam by condensing it, feedwater heaters to recover heat from steam to pre-heat boiler feedwater.

In all these examples, the heat exchanger is the critical device that enables the practical and efficient transfer of waste heat to a useful medium, leading to energy savings, cost reductions and lower environmental impact.

The proportion of waste heat that can be recovered using heat exchangers varies dramatically depending on multiple factors, and can range from 10% to 90%. The main factors influencing the proportion of recoverable heat is the temperature difference between the hot and cold streams, the smaller difference allowing higher recovery and the heat exchanger design and type, including the surface area, the material used and the flow rates of the fluids. While technically possible to recover a high percentage, the cost of increasing larger and more complex heat exchangers requires to be economically justifiable. There’s usually a trade-off between the recovery rate and the capital cost.

Heat exchanger effectiveness is a ratio that compares the actual heat transfer to the maximum possible heat transfer. It's a "performance score" on a scale of 0 to 1 (or 0% to 100%) that indicates how well a heat exchanger is operating compared to a perfect, theoretical ideal. The choice of a heat exchanger can be done partially on the basis of its effectiveness. The effectiveness correlations for different types of heat exchangers are summarized inTable 3.

*Table 3: Effectiveness for heat exchangers (source Teke et al [32]).*

| Type | $\varepsilon$ |
|---|---|
| Parallel flow | $\varepsilon = \frac{1-\exp[-NTU(1+Cr)]}{1+Cr}$ |
| Counter flow | $\varepsilon = \frac{1-\exp[-NTU(1-Cr)]}{1+Cr\exp[-NTU(1-Cr)]}$, $Cr < 1$<br>$\varepsilon = \frac{NTU}{1+NTU}$, $Cr = 1$ |
| Cross flow<br>Both fluid unmixed | $\varepsilon = 1 - \exp\left[(1/Cr)NTU^{0.22}\left\{\exp\left[-Cr(NTU)^{0.78}\right] - 1\right\}\right]$ |
| Cross flow<br>$C_{min}$(unmixed), $C_{max}$(mixed) | $\varepsilon = \frac{1-\exp\{-Cr[1-\exp(-NTU)]\}}{Cr}$ |
| Cross flow<br>$C_{max}$(unmixed), $C_{min}$(mixed) | $\varepsilon = 1 - \exp\{-(1/C)[1 - \exp(-NTU \cdot Cr)]\}$ |
| Shell and tube<br>One shell pass (2, 4, ..., tube passes) | $\varepsilon_1 = 2\left\{1 + Cr + (1 + Cr^2)^{1/2} \frac{1+\exp\left[-NTU(1+Cr^2)^{1/2}\right]}{1-\exp\left[-NTU(1+Cr^2)^{1/2}\right]}\right\}^{-1}$ |
| $n$ Shell passes ($2n$, $4n$, ..., tube passes) | $\varepsilon_n = \left[\left(\frac{1-\varepsilon_1 Cr}{1-\varepsilon_1}\right)^n - 1\right]\left[\left(\frac{1-\varepsilon_1 Cr}{1-\varepsilon_1}\right)^n - Cr\right]^{-1}$ |

## 4.2 Rotary heat exchangers

Rotary heat exchangers are primarily used for air-to-air heat recovery. An example of use for heat recovery in an industrial process is to recover heat from the hot, moist exhaust air from dryers to pre-heat the incoming fresh air used for drying.

A rotary heat exchanger, also known as a heat wheel, thermal wheel, or enthalpy wheel (if it transfers moisture too), is a type of regenerative heat exchanger. It consists of a circular, rotating matrix or "wheel" made of a heat-absorbent material, housed within a casing that is divided into two (or sometimes more) parallel air streams.

Advantages of rotary heat exchangers compared to other types of heat exchangers are their high sensible heat effectiveness, their latent heat (moisture) transfer capability, their relative compactness and their suitability for large-scale air handling units.

The core of the device is a cylindrical wheel filled with a porous material that has a high thermal mass and large surface area. This material can be aluminium, synthetic polymers, or treated paper/fibers (especially for enthalpy wheels). The wheel rotates slowly, typically between 3 to 20 revolutions per minute (RPM). If the wheel matrix is coated with or made of a hygroscopic (moisture-absorbing) material (e.g., a desiccant like silica gel or lithium chloride, or specially treated polymers/paper), it can also transfer moisture in addition to sensible heat.

The casing around the wheel is partitioned so that two separate air streams pass through different sections of the wheel simultaneously: the hot air stream, typically the exhaust air from a building or process, and the cold air stream, typically the fresh, incoming supply air. As a section of the rotating wheel passes through the hot air stream, the material of the wheel absorbs heat from this air, causing the air to cool down before it is exhausted. The wheel material itself heats up. As the now-heated section of the wheel passes through the cold air stream, it releases the stored heat to this incoming air, pre-heating it. The wheel material cools down in this process.

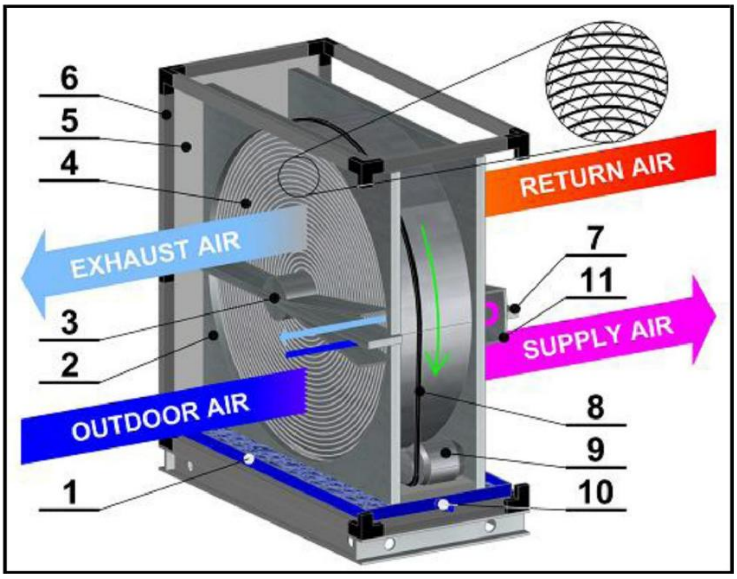


*Figure 6: Rotary wheel heat exchanger (Source Jedlikowsky et al.[33])*

Rotary heat exchangers can achieve high sensible heat recovery effectiveness (typically 70-90%) and can handle large volumes of air in a relatively compact unit. A disadvantage is the presence of a moving part that requires a motor to rotate the wheel, which consumes a small amount of energy and introduces a component that needs maintenance (motor, belt, bearings, seals).

The range of temperatures for heat that can be recovered by a rotary wheel heat exchanger is very large, but depends significantly on the materials used in its construction (especially the wheel matrix and seals) and the specific application. It ranges between 60 to 250°C for food industrial processes such as exhaust from dryers or ovens.

Akbari et al.[34] presented the use of a rotary heat exchanger to recover heat from the exhaust gases (or smoke) of an impact air jet dryer used for drying food. More specifically, the hot air leaving the dryer was directed to a rotary regenerative heat exchanger to transfer its thermal energy to the cold air entering the dryer The hot air at the dryer inlet, before being discharged, generally has a temperature ranging between 70 and 140 °C. For the experiments, the hot air inlet temperatures in the regenerator were set at three levels: 70 °C, 105 °C and 140 °C. The cold air entering from the atmosphere had a temperature between 30 and 40 °C. Efficiency of the heat recovery in this study could reach 42.2 %.

In summary, rotary heat exchangers are highly effective devices for recovering sensible and latent heat from air streams, already widely used in HVAC for energy-efficient ventilation and increasingly in industrial applications for process heat recovery.

*Table 4: Datasheet rotary heat exchangers*

| | |
|---|---|
| **Temperature of waste heat** | 60 to 250°C |
| **COP average** | Not relevant - 40-90% of the heat recovered |
| **Overall system energy balance** | Heat recovered from hot air – Losses = Heat transfered to cold air |
| **Payback time if used with waste heat** | 2 to 7 years |

## 4.3 Thermosiphons, heat pipes

Thermosiphons and heat pipes are used in a variety of applications due to their ability to transfer heat with very high efficiency, higher than that of a copper tube[35,36]. They can operate without any moving parts, making them highly reliable and low maintenance[37–41]. This contrasts with traditional cooling systems that rely on pumps or compressors, which can break down and require regular maintenance, but also require electric power supply to operate. The absence of moving parts in thermosiphons also ensures quiet operation, making them suitable for applications where noise is a concern. Generally inexpensive to manufacture and maintain, thermosiphons can use environmentally friendly working fluids, such as carbon dioxide[42,43].

Thermosiphons can be used for energy recovery and particularly heat recovery. Their efficiency, passive nature (no pump required) and ability to transfer large amounts of heat with small temperature differences make them an attractive solution. They do not require external power, cooling water or lubrication systems to operate, which reduces maintenance and increases reliability.

Thermosiphons and heat pipes are both passive heat transfer devices that use the phase change of a fluid to transfer heat from a hot source to a cold heat sink. Heat pipes use capillarity as driving force when thermosiphons use gravity. Usually made of a porous material that creates a capillary force drawing the liquid towards the evaporator [44,45], heat pipes can operate in any condition, even against gravity, whereas thermosiphon needs a vertical orientation. Generally more efficient at low thermal output, thermosiphons can outperform heat pipes at higher thermal outputs where the driving force of gravity becomes more important. Both are used in a wide range of applications.

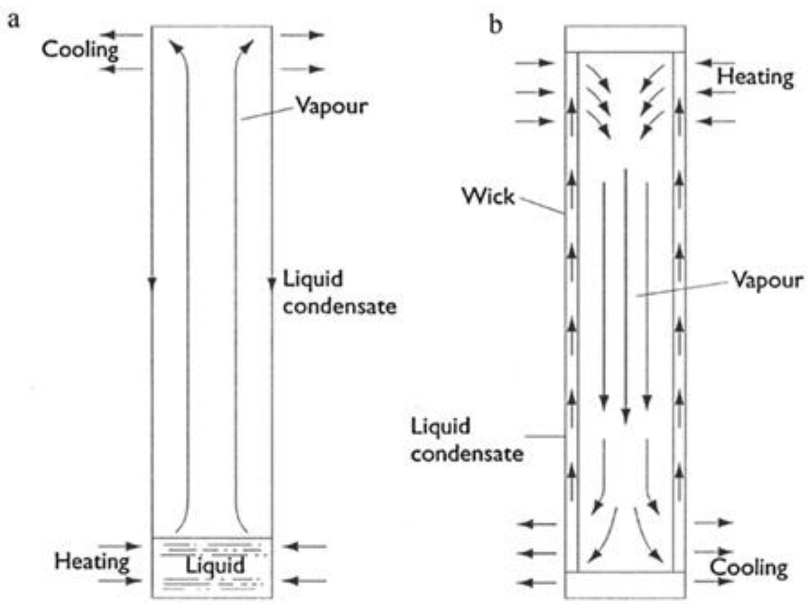


*Figure 1: Conventional heat pipe (CHP) and two-phase thermosiphon loop (TPTL). Source Srimuang et al. [46]*

Thermosiphons are mostly used in two-phase which use the latent heat of vaporization of a fluid to transfer heat, but thermosiphons can be also used in single phase. A single-phase thermosiphon uses buoyancy force to drive the heat transfer fluid. The fluid remains in the same phase throughout the heat transfer process. This configuration can be more appropriate in situations where heat flows are low and a simple design is preferred. Two-phase thermosiphon loops use the phase change of a fluid to transfer heat. The fluid absorbs heat at an evaporator, causing the liquid to begin to evaporate. The vapour flows upward in a pipe to the condenser, releases heat condensing back to liquid and flows back in a pipe by gravity to the evaporator. This natural circulation process allows TPTL to transfer heat with high efficiency, even higher than most conductive materials would do. The liquid line is commonly referred as the down-comer and the vapour line as the riser.

Heat pipes and thermosiphons are particularly well suited to heat recovery due to their advantages already cited. Examples of heat recovery applications include hospital operating rooms, air conditioning systems, bakeries, humidity control in air conditioning systems, air preheating for drying. An example of the use of thermosiphon heat recovery for air conditioners is given by Abu-Mulahwe et al.[37]. A thermosiphon heat recovery system has been designed to recover heat rejected by a window air conditioner to heat water for residential and commercial use. This system eliminated the need for a circulation pump, thereby reducing potential mechanical problems and noise. In general, a water heater can be designed using thermosiphons to recover some of the heat rejected by an air conditioner.

Hybrid systems, combining a thermosiphon and a mechanical refrigeration system[47], allow year round-operation, switching between thermosiphon, refrigeration or combined modes depending on the outside temperature.

A new defrosting system[48] using thermosiphon principles (flash defrosting) has been used to recover heat from the liquid line after the condenser and store it for use during defrosting, reducing refrigeration energy consumption and eliminating electric heaters. The thermosiphon is used here in combination with phase change materials (PCMs) to store heat rejected by the refrigerant during cooling operation.

In summary, thermosiphon's ability to transfer large amounts of heat with small temperature differences, without requiring a pump or compressor, makes it particularly suitable and effective for energy recovery in a wide range of industrial and domestic contexts.

*Table 5: Datasheet thermosiphon heat recovery*

| | |
|---|---|
| **Temperature of waste heat** | -50°C to 300°C |
| **COP average** | Not relevant |
| **Overall system energy balance** | Qc – Qlosses = Qf |
| **Payback time if used with waste heat** | Depends entirely on the specific application, from 1 year to 5-10+ years |

## 4.4 Refrigeration heat recovery units

The use of waste heat in refrigeration cycles is an effective way of utilising low-grade industrial waste heat. Refrigeration systems are essentially heat pumps that move heat from a cold source to a hot source. The rejected heat from the condenser is often just wasted, but can be seen as a free source of thermal energy with a significant potential for recovery and use.

Widely adopted in supermarkets where refrigeration is the dominant energy user and where there is constant hot water demand, awareness and adoption of heat recovery from refrigeration systems are growing across the broader food supply chain driven by energy costs and sustainability initiatives.

The total heat rejected at the condenser for a vapour compression system is typically 1.2 to 1.5 times (or more) the actual cooling load. In the food industry, with large cold stores, blast freezers and process chillers, this represents a significant amount of thermal energy.

The main use of heat recovered from refrigeration systems in the food industry are:

- **Sanitary hot water production** for cleaning and hygiene, but also for general washdown and domestic hot water. Usually the higher grade heat from desuperheaters, and lower grade heat from condensers can be used to pre-heat the water
- Process **water pre-heating** for boilers and any process that requires heated water. Sending warmer water significantly reduces the energy required by a conventional boiler
- Space heating such as offices and amenities, administrative areas, labs, locker rooms
- Ground warehouse heating to provide frost protection
- Defrosting: using heat recovery can be used as an alternative method for evaporator coil defrosting [49]
- Pre-heating air for drying applications
- Cold source for **high temperature heat pumps** (demo 3 and 4 ENOUGH)

Heat recovery technologies for refrigeration systems can differ with the temperature level and the source of the heat that is recovered.

**Desuperheaters** are relatively simple heat exchangers installed on the compressor discharge line before the main condenser. The refrigerant gas temperature leaving the compressor can range from 70°C to over 120°C depending on the refrigerant (e.g., $CO_2$ systems run hotter), compressor type, and operating conditions. Capturing heat here (desuperheating) can provide heat suitable for producing hot water (60-80°C). However, it typically only recovers 10-25% of the total rejected heat.

**Full condensing** heat recovery uses large heat exchangers that can capture a much larger portion of the wasted heat. The majority of the heat is rejected during the phase change from gas to liquid in the condenser. This heat is available at the condensing temperature, typically 30°C to 55°C. While lower grade, the quantity is much larger. In food industry, this heat can be used typically to preheat water, but also for space heating such as offices[37], underfloor heating to prevent frost.

*Table 6: Datasheet refrigeration heat recovery*

| | |
|---|---|
| **Temperature of waste heat** | 30 to 120°C |
| **COP average** | From 6 to 10 with full heat recovery |
| **Overall system energy balance** | W + Qf = Qc |
| **Payback time if used with waste heat** | 1 to 5 years |

## 4.5 High Temperature Heat Pumps

High-Temperature Heat Pumps (HTHPs) are a specialized type of heat pump designed to deliver heat at significantly higher temperatures than conventional heat pumps (which are typically used for space heating or domestic hot water up to around 55-65°C). HTHPs aim to supply heat at temperatures suitable for industrial processes. They are ideal to upgrade industrial waste heat to produce hot water or steam, or for drying processes.

They are a key technology for industrial decarbonization because they can upgrade low-grade waste heat (which is abundant but often unusable directly) to high-grade[19], useful process heat, thereby reducing reliance on fossil fuel-fired boilers, often in the range of 80°C to 160°C, and sometimes even higher.

Refrigerants used in HTHP must be able to operate efficiently at high condensing temperatures and pressure. Common choices include hydrocarbons, ammonia and $CO_2$. Compressors must be designed for high discharge temperatures and pressures. Materials and components must withstand as well high operating temperatures and pressures.

The typical payback time for a high temperature heat pump can vary significantly, generally ranging from 2 to 10 years. The key factors are the capital cost, the operating hours, the availability of the "free" heat source and the coefficient of performance of the system.

*Table 7: Datasheet high temperature heat pumps*

| | |
|---|---|
| **Temperature of waste heat** | 30 to 50°C |
| **COP average** | Qc / W, 2.5 to 5 at 80-90°C, 1.5 to 3 at 120-150°C |
| **Overall system energy balance** | Qc = Qf + W |
| **Payback time if used with waste heat** | 2 to 10 years |

**Demonstrator 3: High Temperature Heat Pump for a Dairy**

The demonstrator 3 of the ENOUGH project is located at Ennstal Milch KG, Stainach, Austria, and focuses on the dairy industry. A high temperature heat pump (HTHP) with a heating capacity of 500 kW is directly integrated into an existing ammonia chiller (refrigeration capacity ~900 kW). This allows the recovery of waste heat from the chiller, which was previously dissipated unused to the environment. The recovered heat is upgraded to about 90°C and used to supply process heat, notably for the cleaning-in-place (CIP) system, reducing the demand for steam traditionally generated by natural gas.

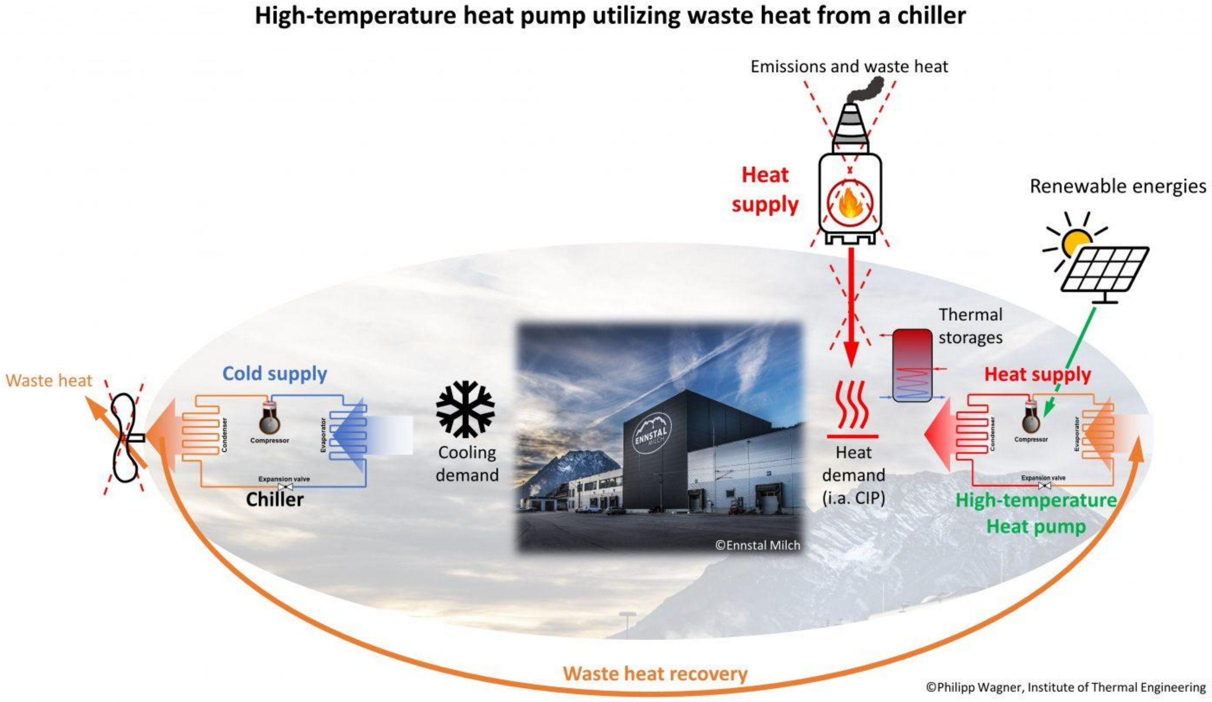


*Figure 7: Schematic integration of the high temperature heat pump – Demonstrator ENOUGH project*

The system achieves a greenhouse gas emission reduction of approximately 200 tonnes of $CO_2$ per year compared to natural gas-based steam supply. Further potential exists if additional hot-water consumers are integrated. The HTHP is already in operation and is being monitored. Simulation models are being developed to optimize operation and evaluate the integration of more heat consumers to maximize the system's potential.

This demonstrator showcases how waste heat recovery and high temperature heat pumps can significantly reduce energy demand and greenhouse gas emissions in dairy processing.

## 4.6 Anaerobic digestion systems

Anaerobic digestion (AD) systems utilize a consortium of microorganisms to decompose organic matter in the absence of oxygen, producing biogas—a renewable energy source primarily composed of methane ($CH_4$) and carbon dioxide ($CO_2$). These systems can vary in scale from small on-farm digesters to large industrial and municipal facilities, reflecting their versatility across sectors.

The produced biogas can be directly combusted to generate heat or used in cogeneration units (combined heat and power, CHP) to simultaneously produce electricity and heat. In addition, upgraded biogas (removing $CO_2$ and impurities) yields biomethane, which can be injected into natural gas grids or used as a vehicle fuel, thus substituting fossil-derived methane and reducing carbon footprints.

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. Poorly managed food waste poses health risks by promoting pathogen proliferation, contributes to greenhouse gas emissions, and contaminates water bodies through mineral and leachate runoff, creating vectors for diseases. Moreover, the disposal of food waste in landfills generates methane underscoring the urgency for better waste management practices. Beyond environmental damage, food waste exacerbates nutritional, social, and economic challenges by squandering edible resources and burdening collection and treatment infrastructures. Food waste primarily consists of lipids, cellulose, hemicellulose, starch, lignin, and protein, collectively making up 82%–96% of its volatile solids fraction. This high biodegradability makes food waste an excellent substrate for AD compared to lignocellulosic feedstocks. Co-digestion with agricultural residues (e.g., manure) can balance carbon-to-nitrogen (C/N) ratios, optimize biogas yield, and improve process stability. It shares similarities with other organic or carbonaceous solid waste used in bioenergy applications, such as woody biomass, agricultural waste, and municipal waste.

Food waste can be managed in a number of ways, but anaerobic processing is one of the best alternatives to food waste management in terms of greenhouse gas emissions. One reason for this is that food waste is rich in readily available nutrients for methane-producing anaerobic bacteria. Another reason is that the main product, methane, can replace fossil fuels and the waste produced during the biogas production process (digestate) can be used as a substitute for mineral fertilizers returning nutrients to agricultural soil and closing nutrient cycle. As a renewable biofuel, biogas can play a very important role in alleviating concerns related to the rapidly increasing energy demand and the instability of the energy resource market. Biogas can be used in various ways: for the production of electricity and heat by combustion biogas in cogeneration plants, supplied to natural gas networks or used as fuel in transport vehicles. Based on LCA studies, it has been shown that biogas can have positive environmental impacts, including volatile GHG emissions, eutrophication, acidification, and the generation of photochemical oxidants.

Anaerobic microbial conversion of organic matter into biogas as a regenerative energy source is a well-known, technically mature and modern process. Any organic matter, whether solid, pasty or liquid, can be converted into biogas by microbial digestion under anaerobic conditions. The main objective of anaerobic digestion in industry is the treatment of residues in order to reduce the biological activity of the material, obtain an energy carrier and consequently reduce the costs of further treatment or disposal. The process design must take into account factors such as hydraulic retention time (HRT), organic loading rate (OLR), temperature (mesophilic or thermophilic), pH control and mixing regimes in order to maintain microbial health and maximize yield.

The digestion of solid or pasty by-products from the food and beverage industry takes place on-site or in external co-digestion facilities not directly located on-site. By-products with a high total solids content (e.g. cellulose, spent grains) have a smaller volume and usually a higher biogas potential, making their transportation to another location relatively economically justified.

Anaerobic digestion of solid or pasty by-products is aimed at meeting waste management legal restrictions, e.g. due to the biological stabilization of organic waste or the generation of a nearly inert waste fraction for further use or disposal[50]. If necessary, the anaerobic digestion process can also include a material sanitation process.

Anaerobic fermentation plant technologies and techniques are state-of-the-art and proven worldwide. Local laws and site specifics shape the individual structure of an anaerobic fermentation plant connected to a food processing plant. Technically and economically sound anaerobic fermentation plants require a consistent action plan, a holistic approach and focused project management.

Solid and pasty waste from the food and beverage industry is often collected and co-digested in centralized anaerobic digestion plants together with other industrial or agricultural raw materials and wastes, such as kitchen waste, organic fractions of municipal waste or manure. Co-digestion is usually carried out in a biogas production system similar to agricultural biogas plants, in a continuous stirred tank reactor (CSTR). The effluent, or rather the remaining fraction of the raw material, can be used as fertilizer. It can be used on agricultural land after aerobic post-treatment by composting or even directly without post-treatment.

The physical properties of the raw material determine the handling of the material and, consequently, the type of anaerobic digestion system and subsequently the type of post-treatment or digestate treatment. Physical properties include water content, particle size, content of impurities and inert materials, resistance to mechanical particle size reduction, viscosity. Physical properties have a significant impact on pumping, mixing, grinding, screening, grinding, separation technologies. Before the process begins, unpacking and separation may be important. During subsequent processing, the properties of the digestate affect the choice of technology when agriculture, separation, if applicable, composting, drying, pelleting will be used [50].

The pay back depends on solution (origin and quality of raw material, plant size, cost of waste transportation, chosen technology, cogenerator type etc.). E.g., 1 MW plant power payback time is 3.2–4.8 years [D2.2].

An example of such technology is shown on Figure 8.Fish co-stream and liquid effluent are considered here as residue and are used for biogas and fertiliser production[51].

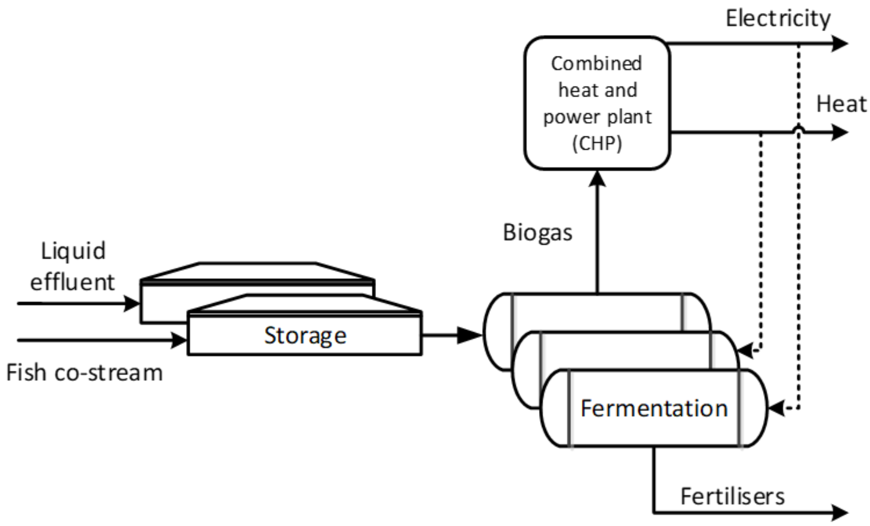


*Figure 8: Processing fish co-stream to biogas and fertilisers*

The chemical properties determine the quantity and quality of the biogas produced, as well as the process design with regard to retention time and additional nutrient requirements, the handling of inhibitory substances or the tendency to foam.

Microbial properties are closely related to the physical and chemical aspects of microbial degradation: inhibitory compounds (disinfectants, cleaning agents, heavy metals, ammonia), the degradation rate of the feedstock in general and, if applicable, fractions with different rates, the need to supplement it with trace elements or enzymes. Another aspect is the possible presence or formation of pathogens in the substrate.

The biogas production potential from a feedstock or its mixture $B_m$ ($m^3/t$) can be expressed by the equation:

$$B_m = \sum (M_i . B_i) / \sum M_i$$

where: $M_i$ – quantity of raw material type (t);

$B_i$ – specific biogas yield from raw material ($m^3/t$).

Specific biogas yield might be found from statistical data or determined experimentally. The specific biogas yield is an important parameter for calculations of the efficiency of biogas plant production.

Biogas energy potential of food waste biomass $E_B$ (kWh/t):

$$E_B = B_m \cdot e_B$$

where: $e_B$ - energy value of biogas, kWh/$m^3$.

Energy value of biogas:

$$ee_B = \frac{e_M}{100} C_M$$

where: $C_M$ – methane concentration in biogas, %;

$e_M$ - energy value of methane (around 9,8 kWh/$m^3$).

The energy balance of the energy system with implementation of anaerobic biogas production from food wastes can be expressed as the difference between input and output and can be defined by the equation:

$$E_{final} = E_B - E_{input}$$

where: $E_{final}$ – final useful energy (kWh/t);

$E_B$ – energy potential of biomass (kWh/t);

$E_{input}$ – energy input of the system (kWh/t).

Energy input $E_{input}$ might be expressed as energy used for different technological processes for biogas production (mainly electricity) and thermal energy:

$$E_{input} = E_{EM} + E_{th},$$

where: $E_{EM}$ – energy used for technological processes (kWh/t);

$E_{th}$ – thermal energy demand (kWh/t).

Various equipment and machinery are used for technological operations and processes; therefore the total energy input can be expressed by the equation:

$$E_{EM} = \sum_1^i E_{TEi},$$

where: $E_{TEi}$ – energy inputs of single equipment or machinery (kWh/t);

*i* – number of technological operation or processes.

Thermal energy is used for warming up the substrate and to compensate the heat losses to the surrounding environment through the walls of the digester. Thermal energy input for heating can be calculated by the following equation:

$$E_{th} = E_{thl} + E_{thb},$$

where: $E_{thl}$ – energy loss (kWh/t);

$E_{thb}$ – energy input to warm raw biomass (kWh/t).

*Table 8: Datasheet anaerobic digestion systems*

| | |
|---|---|
| **Temperature of waste heat** | - |
| **COP average** | - |
| **Overall system energy balance** | $E_B = B_m \cdot e_B$ where: feedstock or its mixture $B_m$ ($m^3$/t), $e_B$ - energy value of biogas (kWh/$m^3$). |
| **Payback time if used with waste heat** | 3 to 5 years |

## 4.7 Cogeneration

Cogeneration, also known as combined heat and power (CHP) systems produce both electricity and useful thermal energy from a single energy source. This source can be natural gas, biogas or waste heat. This combined production is generally more efficient than generating heat and electricity separately. A trigeneration system is and extension of cogeneration which uses the waste heat from the combined heat and power system to generate chilled water for cooling via an absorption or adsorption chiller.

Opportunities for cogeneration using recovered heat are in the sectors of the food supply chain that have a simultaneous and continuous demand for electricity, heating or/and cooling. Most of food processing and manufacturing plants have a large, stable and simultaneous demand for those energy forms. For food industries with a main cooling demand, the integration of absorption refrigeration plants with cogeneration units (trigeneration) allows for the complete utilization of the generated heat for cooling production[52]. This is especially beneficial where refrigeration demand is constant, particularly at low temperatures (e.g., between -15 and -55 °C). Typical examples are dairies, breweries, meat and poultry processing plants, ready-meal factories and frozen food producers. Supermarkets also have a suitable energy profile for smaller scale systems.

Those systems use an engine or a gas turbine to generate electricity, and a heat distribution system to recover waste heat from the very hot engine's exhaust gases through a exhaust gas heat exchanger (Figure 6). They can recover heat also from cooling systems to produce hot water or steam and can use any excess heat to feed an absorption chiller to produce chilled water, which supplements or replaces traditional electric-powered chillers. Usually a sophisticated Programmable Logic Controller (PLC) is used to monitor the plant real time demand for electricity, heating and cooling and to modulate the engine and direct the flow of thermal energy to where it's needed.

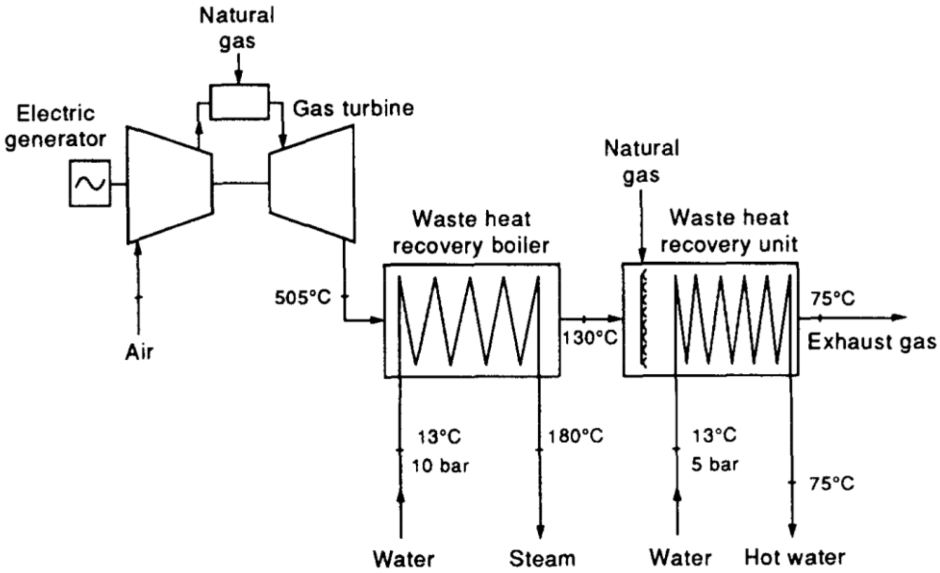


*Figure 9: Schematic view of a cogeneration plant (source Calderan et al.[53])*

Self-cogeneration can lead to relevant energy savings[53]. In one food industry case, the system reduced annual electrical energy demand from 9.7 GWh to 4.3 GWh[53]. An existing ICE-based cogeneration unit in a confectionery facility demonstrated calculated primary energy savings of 15.60%[54]. In a general way, electrical efficiency from an engine or turbine is 35 to 45%, 40% to 50% of waste heat can be captured and used, which leads to an 80 to 90% total system efficiency.

Even if cogeneration is based on combustion engines, typically natural gas, it can also be a way to save $CO_2$ emissions due to its higher efficiency compared to the separate generation of heat and electricity[54].

Cogeneration plants are generally considered economically rewarding, especially when there is low availability or high costs of electrical energy. Payback periods typically range from very short (around 1 year) to several years, depending on the specific technology, plant design, and operational context.

*Table 9: Datasheet cogeneration*

| | |
|---|---|
| **Temperature of waste heat** | Exhaust gases 450-500°C |
| **COP average** | 80 to 90% (sum of the electrical and thermal efficiencies) |
| **Overall system energy balance** | Energy from Fuel = Net Electrical Output + Useful Thermal Output + Exhaust Gas Losses + Other Heat Losses |
| **Payback time if used with waste heat** | 1 to 5 years |

## 4.8 Absorption or adsorption systems driven by waste heat recovery

### 4.8.1 Absorption systems

Absorption refrigeration systems have significant potential for heat recovery, especially in industries like food processing. If waste heat cannot be used as a “free” heat source for other processes, an alternative can be to use waste heat to power the generator of an absorption chiller and transform this “free” thermal energy to refrigeration capacity. This displaces the need for electrically-driven chillers leading a reduced electricity consumption. Suitable waste heat sources in the food industry can be gases exhaust from boilers, oven, dryers... An absorption chiller can be driven by heat sources with temperature range from 70°C to 120°C. The COP is typically around 0.6 to 0.8. This a relatively low COP compared to vapor compression systems, but this is acceptable if the heat powering the system is “free” waste heat.

The potential depends on the cooling demand, and especially if there is a need for a chiller when the waste heat is available. The payback period depends on the electricity prices and if the waste heat is consistent, abundant, easily accessible and align well with the cooling load, but can be estimated between 3 to 10 years.

The core principle of an absorption system is similar to a conventional vapor-compression refrigeration system using evaporation of a refrigerant to absorb heat. However, instead of a mechanical compressor to raise the refrigerant's pressure, an absorption system uses a thermo-chemical "compressor" driven by heat (Figure 10). These systems typically use two fluids:

- a refrigerant: the fluid that evaporates to produce cooling
- an absorbent: a liquid that has a strong affinity for the refrigerant vapor (example water for ammonia refrigerant)

Waste heat (such as hot water from a process, steam, hot gases…) is supplied to the generator to boil and have the refrigerant out of the dilute solution. This waste heat is a “free” primary energy input. The electricity consumption for such a system is the electricity for the solution pump and the fans or pumps for the evaporator and condenser, which is much less than the electricity needed for a vapour compression system.

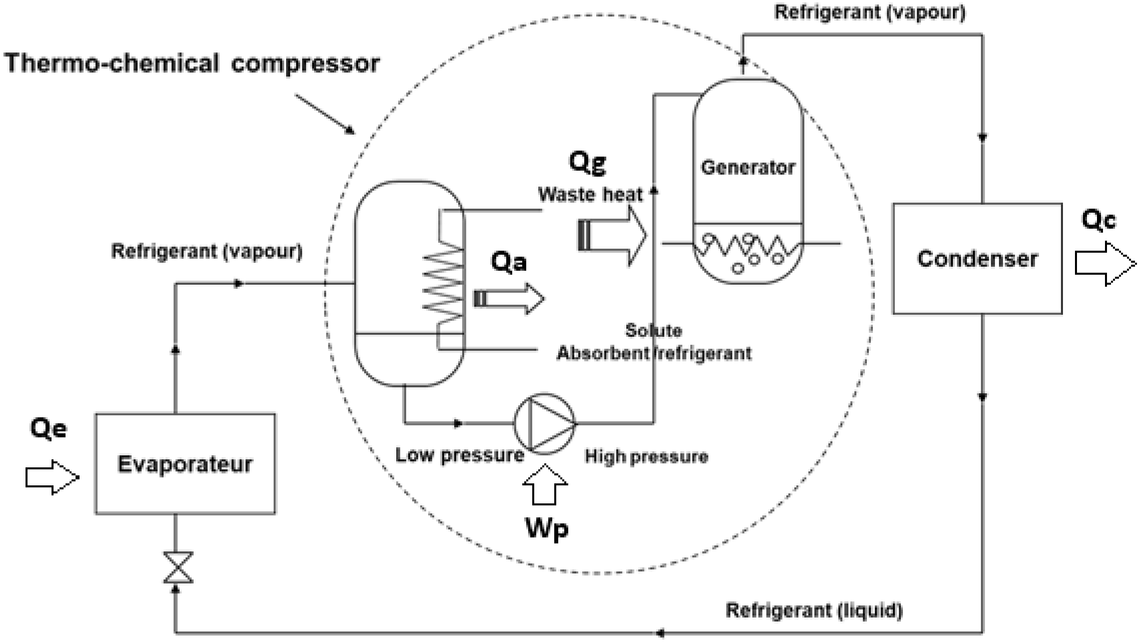


*Figure 10: Absorption system driven by waste heat*

*Table 10: Datasheet absorption*

| | |
|---|---|
| **Temperature of waste heat** | 70 to 120°C |
| **COP average** | 0.6 to 0.8 ( = Qe / (Qg + Wp ) ) |
| **Overall system energy balance** | Qg + Qe + Wp = Qc + Qa |
| **Payback time if used with waste heat** | 3 to 10 years |

**Demonstrator 14 ENOUGH: an ammonia-water Absorption-Compression heat pump**

The technology demonstrated in the ENOUGH project is an ammonia water absorption compression heat pump (AHCP) [55] used to recover low temperature waste heat and to produce 150°C steam. The key components include an oil-free twin-screw compressor with liquid injection for lubrication, cooling and sealing, and allowing high temperatures without oil degradation, an absorber, a desorber, an internal heat exchanger (IHX) to recover heat between the rich and lean solutions, an expansion valve, a solution pump and a liquid vapour separator (Figure 11).

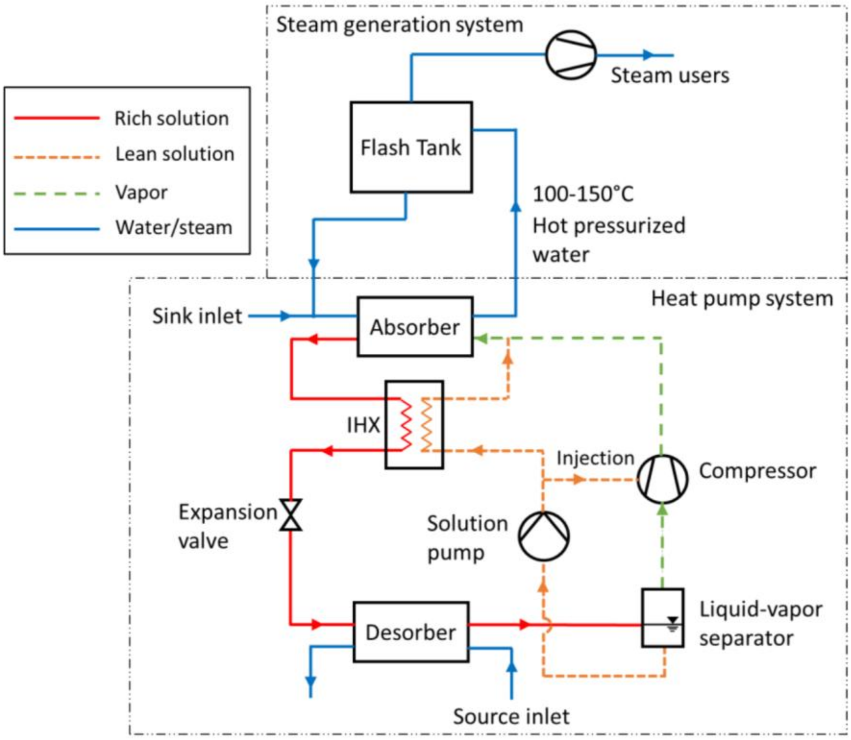


*Figure 11: Principle of the ACHP steam generation system [55]*

This AHCP produces high temperature pressurized hot water from 100°C to 150°C used for steam generation in food processing. The COPs achieved are between 1.8 to produce heat at 120°C and 2.85 at 105°C.

This technology provides a low emission alternative to fossil fuel-fired steam boiler.

### 4.8.2 Adsorption systems

Adsorption chillers, like absorption systems, use thermal energy as their primary input to produce cooling. This makes them excellent candidates for waste heat recovery, especially for low quality heat.

Adsorption chillers can be driven by even lower temperature heat sources than single-effect absorption chillers. They can often effectively utilize heat in the range of 50°C to 90°C. Similar to absorption systems, adsorption systems reduce electricity consumption for cooling systems and improve the general site energy efficiency by valorising waste heat. The heat rejected by conventional vapour compression systems can also be a source for adsorption chillers. This can create a cascading effect where heat from a cooling system drives another refrigeration system.

Fewer moving parts compared to absorption systems can be seen as an advantage. A challenge is that their cyclic operation (adsorption / desorption phases) often requires multiple systems to provide a continuous cooling.

Adsorption principle is similar in some way to absorption principle since it produces cooling from heat, but is also different since it uses a solid adsorbent material instead of a liquid absorbent material. For continuous cooling systems, use of at least two adsorbent beds that operate in alternating phases (Figure 12) is necessary. The fluid and material used for an adsorption chiller are:

- The adsorbent material: a solid material (silica gel, zeolites…) with a porous structure and a strong affinity for adsorbing the refrigerant vapour
- The refrigerant: a fluid that can be easily adsorbed by the chosen adsorbent

Liquid refrigerant evaporates at a low temperature in the evaporator. The refrigerant vapor is adsorbed into the adsorbent material. This process is exothermic and the heat must be rejected. During the desorption phase, the waste heat is supplied to the bed, causing the adsorbed refrigerant to desorb. The waste heat is circulated through the adsorbent that is in desorption / regeneration phase, the heat providing the energy to break the bonds between the adsorbent material and the refrigerant, releasing it as vapor. The refrigerant vapor then flows through the condenser at high pressure and is cooled down, causing it to condense into liquid.

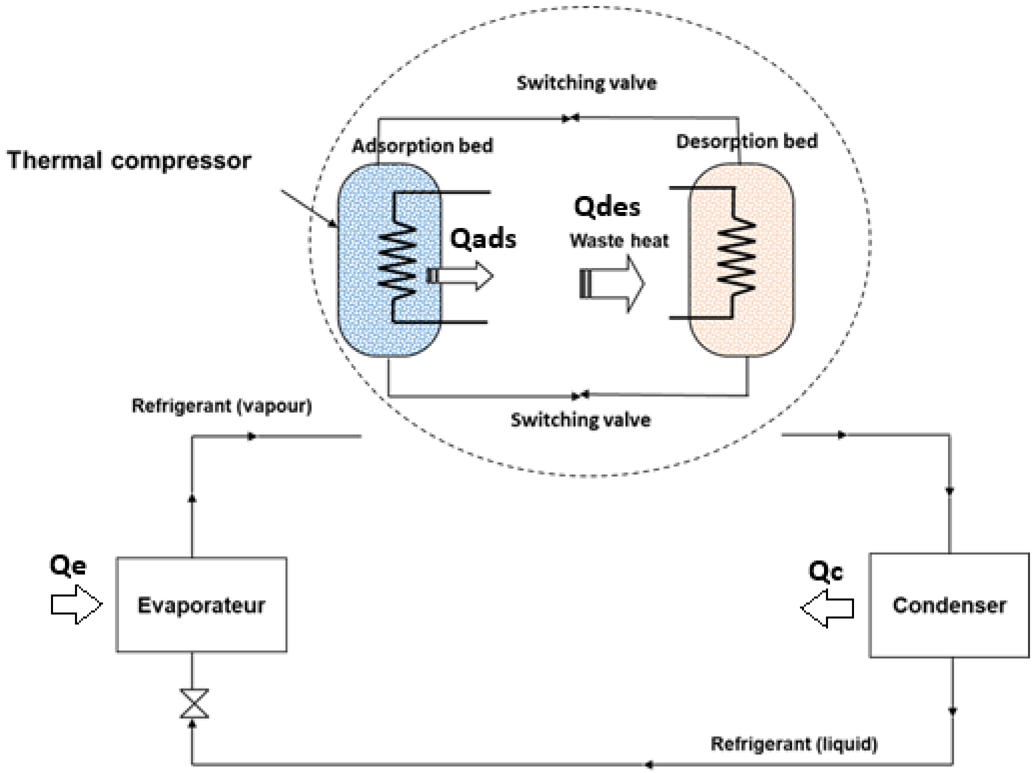


*Figure 12: Adsorption refrigeration system*

Adsorption chillers offer significant potential for heat recovery in the food industry, particularly when utilising low-grade waste heat (50-90°C) which would otherwise be wasted. The main obstacles to developing this technology are probably the large size of the chillers and the relatively high investment cost[14]. Although their coefficient of performance (COP) is low (between 0.4 and 0.7) and they can be bulky, their ability to run on 'free' heat makes them an attractive option for reducing electricity consumption for cooling purposes and improving overall energy efficiency. The economic viability depends on similar factors to those of absorption systems: the cost of electricity, the availability of waste heat, the cooling demand and the capital cost.

Examples of heat recovery using adsorption are given by Choudhury et al. [56]. A zeolite-water adsorption refrigeration system has been developed to produce chilled water using the exhaust gases from a fishing boat’s diesel engine (available temperatures from 200 to 300°C). Another example is a zeolite-water adsorption air conditioning system drive by automobile exhaust gases (approximately

400-600°C). The authors mention specific advantages of adsorption systems such as a low sensitivity to temperature fluctuations, no crystallisation or corrosion problems that can occur in absorption systems, a good reliability mostly due to the absence of moving or rotating parts, the simplicity of the components and a low sensitivity to shocks and movements that make them suitable for mobile applications.

*Table 11: Datasheet adsorption*

| | |
|---|---|
| **Temperature of waste heat** | 50 to 300°C |
| **COP average** | 0.4 to 0.7 ( = Qe / Qdes ) |
| **Overall system energy balance** | Qdes + Qe = Qc + Qads |
| **Payback time if used with waste heat** | 3 to 10 years |

## 4.9 Thermal energy storage

The amount of recoverable waste heat also depends on the timing between heat production and heat consumption. Waste heat is often generated during specific production windows (when ovens are on, during batch cooking or when refrigeration systems are at peak load ….). The demand for this heat (for example for cleaning, preheating the next batch, space heating) might occur at different times.

Thermal Energy Storage (TES) can help to maximize the efficiency of heat recovery by addressing the mismatch between when waste heat is available and when it is needed. The rate of waste heat generation can also vary, and so can the demand for heating. Thermal energy storage can also help to manage those fluctuating heat loads and supply and to improve performance of the heat recovery systems that usually operate more efficiently with consistent flow and temperature.

Heating systems like boilers can be sized more appropriately for average loads rather than for peak loads if TES is available to handle the peaks. TES can then lead to more efficient operation of the primary equipment and potentially lower capital costs.

Practical examples of thermal storage in food industry heat recovery are refrigeration heat recovery for hot water used for cleaning in place, wort cooling heat recovery for brews used for the mashing stage of the next brew, refrigeration condenser heat of meat processing plant used for extensive plant washdown and equipment sanitation (usually at the end of the production day), heat recovered from flue gases in baker used for hot water for ingredient mixing or cleaning, heat from hot water used for blanchers in fruit or vegetable processing used to make-up water for the blancher or general cleaning. In all these examples, the thermal storage system acts as an “energy bank”, allowing the facility to deposit recovered waste heat and withdraw it when there is a demand.

The most common form of thermal energy storage is **sensible heat storage** using hot water tanks. **Latent heat storage** such as PCMs are less common.

**Sensible heat storage** is the simplest and most widely used method of thermal energy storage. It works by storing thermal energy by changing the temperature of a storage medium (solid or liquid) without changing the phase of the medium (e.g. water remains liquid, rock remains solid)[57]. A hot fluid (hot water, hot air....) passes through a storage medium that absorbs heat, increasing its temperature. The heated medium is usually insulated to minimize heat loss over time. When heat is needed, a cooler fluid passes through the heated storage medium which releases its stored heat, decreasing its temperature.

The amount of sensible heat (*Q*) stored is given by:

$$Q = mC_p\Delta T$$

where *m* is the mass of the storage medium, $C_p$ the specific heat capacity and $\Delta T$ the temperature change.

The most common sensible heat storage media is water with a relatively high specific heat capacity, a low cost, easy to pump and handle. A disadvantage is the limit of 100°C at atmospheric pressure, though this limit can be higher if pressurized. Another disadvantage is its potential for corrosion. Expansion when freezing is also a difficulty. Hot water is typically stored in insulated tanks. These tanks can be mixed to minimize the temperature heterogeneity, but are also often used as stratified. In food industry, stratified hot water tanks are often preferred, allowing to get hotter water to be drawn from the top for high temperature needs.

Applications of sensible heat storage can be to recover heat from refrigeration condensers using hot water for preheating cleaning, domestic or boiler water, heating spaces, storing heat from boiler condensate return, accumulating heat from flue gases recovery systems or storing heat from batch processes that releases intermittent heat. All these applications help with the gap between availability and demand, thereby saving energy.

Advantages of sensible heat storage are the simplicity, the low cost and its reliability since they are relatively simple systems with few moving parts. Main disadvantages are the lower energy density compared to latent heat storage, requiring large volumes to store energy, and the temperature glide during discharge which might be not ideal for some applications.

**Latent heat storage** utilises the heat absorbed or released when a material undergoes a phase change. The most common phase changes are from solid to liquid (melting) and from liquid to solid (freezing). The material used is called a phase change material (PCM).

When storing heat in a liquid to solid phase change material, the PCM is initially in solid state and heat is supplied to it. The PCM temperature rises until it reaches the melting point. The PCM then starts to melt, absorbing a significant amount of heat (the latent heat of fusion) at a nearly constant temperature (depending if the material is pure or composite). Once fully melted, the temperature of the material can rise further, heat being added as sensible heat. When releasing heat, heat is extracted from the liquid PCM. The temperature drops until it reaches its freezing point. PCM begins to solidify, releasing the latent heat at a nearly constant temperature. Once fully solidified, its temperature can drop further if more heat is still extracted.

The amount of latent heat stored is given by:

$$Q = mL$$

where *m* is the mass of the storage medium and *L* the specific latent heat of fusion.

Types of phase change material are organic PCMs, the most common being the paraffins, and inorganic PCMs, typically salt hydrates. PCMs can be a mixture of two or more substances. Some mixtures are eutectic, melting and freezing congruently at a specific temperature.

Main advantages of latent heat storage compared to sensible heat storage is the high energy storage density (PCMs can typically store 5 to 14 times more heat per unit of volume) and the nearly constant temperature during discharging, which can be very beneficial for some applications. PCMs are available commercially with a wide range of phase change temperatures, allowing a selection based on the specific applications needs. Main disadvantages are the often low thermal conductivity which can be mitigated by using enhanced heat transfer (fins, encapsulation...). The cost of PCMs can be another disadvantage since they are often more expensive than sensible heat medium.

Retrofitting existing systems can be complex and costly and payback periods depends heavily on utilization rates. The economic feasibility also depends highly on the distance between the heat demand and the refrigeration plant room, and it is usually higher if the heat source is relatively close to the heat consumption to minimize piping costs and heat losses.

# 5 CONCLUSION

This report provides a comprehensive analysis of the significant potential for energy integration and recovery across the European food supply chain. Through the application of exergy analysis and its implementation in the ENOUGH tool, the analysis has moved beyond simple energy accounting to identify the true thermodynamic inefficiencies in various processes, pinpointing where the greatest opportunities for improvement lie in food supply chains.

A detailed sector-by-sector review – from dairy, meat, fish processing to bakeries, transport and retail reveals a wealth of underutilized energy streams. The analysis highlights that waste heat, generated from essential processes such as refrigeration, cooking, pasteurization and drying, is the most abundant and accessible form of energy for recovery.

A board array of technologies capable of harnessing this potential has been detailed. These solutions range from passive technologies like heat exchangers and thermosiphons to active systems such as high temperature heat pumps, cogeneration and thermally driven absorption and adsorption chillers. The potential for chemical energy recovery through the anaerobic digestion of organic waste has also been identified as a crucial strategy for food industry.

Despite the clear opportunities, the report acknowledges the barriers to widespread adoption, including initial capital investment, the technical complexity of retrofitting existing facilities and the challenge of matching heat availability with demand, a problem that can be addressed by thermal energy storage.

The benefits of implementation of those technologies can be evaluated through the simulation using the ENOUGH tool, where most of these technologies can be selected to evaluate the impact on energy efficiency and GHG emissions.

The potential for energy integration in the food supply chain is currently largely untapped opportunity. The technologies exist, the economic and environmental drivers are strengthening and the pathway to a more energy-efficient, low carbon food system is clear. By implementing recovery and integration strategies such as detailed in the report, stakeholders can achieve multiple benefits such as reduced operational costs, enhance sustainability and a substantial contribution to meeting climate targets.

# 6 REFERENCE


1. Intergovernmental Panel On Climate Change. (2022). *Climate Change and Land : IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* (1re éd.). Cambridge University Press. https://doi.org/10.1017/9781009157988

2. Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, *2*(3), Article 3. https://doi.org/10.1038/s43016-021-00225-9

3. Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, *360*(6392), 987-992. https://doi.org/10.1126/science.aaq0216

4. *ENOUGH D1.2—A report on energy and emissions for 1990 and 2019*. (s. d.).

5. Husnain, S. N., Amjad, W., Munir, A., & Hensel, O. (2022). Energy and Exergy Based Thermal Analysis of a Solar Assisted Yogurt Processing Unit. *Frontiers in Energy Research*, *10*. https://doi.org/10.3389/fenrg.2022.887639

6. Mojarab Soufiyan, M., Aghbashlo, M., & Mobli, H. (2017). Exergetic performance assessment of a long-life milk processing plant : A comprehensive survey. *Journal of Cleaner Production*, *140*, 590-607. https://doi.org/10.1016/j.jclepro.2015.11.066

7. Sorgüven, E., & Özilgen, M. (2012). Energy utilization, carbon dioxide emission, and exergy loss in flavored yogurt production process. *Energy*, *40*(1), 214-225. https://doi.org/10.1016/j.energy.2012.02.003

8. Zisopoulos, F. K., Rossier-Miranda, F. J., van der Goot, A. J., & Boom, R. M. (2017). The use of exergetic indicators in the food industry – A review. *Critical Reviews in Food Science and Nutrition*, *57*(1), 197-211. https://doi.org/10.1080/10408398.2014.975335

9. Icier, F., Colak, N., Erbay, Z., Kuzgunkaya, E. H., & Hepbasli, A. (2010). A Comparative Study on Exergetic Performance Assessment for Drying of Broccoli Florets in Three Different Drying Systems. *Drying Technology*, *28*(2), 193-204. https://doi.org/10.1080/07373930903524017

10. Agathokleous, R., Bianchi, G., Panayiotou, G., Aresti, L., Argyrou, M. C., Georgiou, G. S., Tassou, S. A., Jouhara, H., Kalogirou, S. A., Florides, G. A., & Christodoulides, P. (2019). Waste Heat Recovery in the EU industry and proposed new technologies. *Energy Procedia*, *161*, 489-496. https://doi.org/10.1016/j.egypro.2019.02.064

11. *ENOUGH 2.7*. (s. d.).

12. Selvaraj, R. C. A., Elumalai, C., Sekar, D. A., Kavin, S., & Angamuthu, M. (2025). Energy Efficiency in the Meat and Meat Processing Sector : Introduction to Energy Efficiency in the Meat Industry. In A. A. Hamad, P. Singh, D. Saxena, & A. K. Haghi (Éds.), *Advances in Environmental Engineering and Green Technologies* (p. 99-126). IGI Global. https://doi.org/10.4018/979-8-3693-8342-1.ch007

13. *4.4.2 Meat Processing*. (s. d.). Issuu. Consulté 26 juin 2025, à l'adresse https://issuu.com/racefor2030/docs/b3_oa_project_final_report_july_2021_-_20210721a/s/14901980

14. Tung, T. V., Nga, N. T. T., Van, H. T., Vu, T. H., Kuligowski, K., Cenian, A., Tuan, N. Q., Le, P.-C., & Tran, Q. B. (2023). Energy Efficiency and Environmental Benefits of Waste Heat Recovery Technologies in Fishmeal Production Plants : A Case Study in Vietnam. *Sustainability*, *15*(17), Article 17. https://doi.org/10.3390/su151712712

15. Kemp, I. C. (2011). *Pinch Analysis and Process Integration : A User Guide on Process Integration for the Efficient Use of Energy*. Elsevier.

16. ARUN B. S, KUMAR S, NINAN G, SAMUEL M, WIDELL K. N, SINGH S, ELAGRA H, & HAFNER A. (s. d.). *Study on retaining natural refrigerant in seafood processing industries in India.* [Jeu de données]. International Institute of Refrigeration (IIR). https://doi.org/10.18462/IIR.ICR.2023.0091

17. *Environmental, Health, and Safety Guidelines for Fish Processing*. (2007). International Finance Corporation (IFC). https://www.ifc.org/content/dam/ifc/doc/2000/2007-fish-processing-ehs-guidelines-en.pdf

18. Laoghaire, D. (s. d.). *A Study of the Viability of Heat Recovery in the Irish Seafood Processing Industry*.

19. Goh, L. J., Othman, M. Y., Mat, S., Ruslan, H., & Sopian, K. (2011). Review of heat pump systems for drying application. *Renewable and Sustainable Energy Reviews*, *15*(9), 4788-4796. https://doi.org/10.1016/j.rser.2011.07.072

20. *Energy-efficient climate control for the fish processing industry*. (2024, décembre 1). Dantherm Group. https://www.danthermgroup.com/uk/insights/energy-efficient-climate-control-for-the-fish-processing-industry

21. Maiorino, A., Petruzziello, F., & Aprea, C. (2021). Refrigerated Transport : State of the Art, Technical Issues, Innovations and Challenges for Sustainability. *Energies*, *14*(21), 7237. https://doi.org/10.3390/en14217237

22. Venkataraman, V., El-Kharouf, A., Pandya, B., Amakiri, E., & Steinberger-Wilckens, R. (2020). Coupling of engine exhaust and fuel cell exhaust with vapour absorption refrigeration/air conditioning systems for transport applications : A review. *Thermal Science and Engineering Progress*, *18*, 100550. https://doi.org/10.1016/j.tsep.2020.100550

23. Li, Z., & Hou, J. (2025). Exploring waste heat recovery in hydrogen internal combustion engine buses for absorption air conditioning. *Journal of Physics: Conference Series*, *2968*(1), 012007. https://doi.org/10.1088/1742-6596/2968/1/012007

24. Yao, Y., Shi, L., He, J., Tian, H., Wang, X., Zhang, X., Sun, X., Lu, B., & Shu, G. (2023). Dynamic analysis of refrigerated truck integrated with combined cooling and power cycle under various driving conditions. *Energy Conversion and Management*, *278*, 116716. https://doi.org/10.1016/j.enconman.2023.116716

25. Evans, J., Foster, A., Eid, E., & Verboven, P. (2020). *ENOUGH D2.4 Technological road maps for food cold storage* (p. 126).

26. Evans, J., Foster, A., Eid, E., & Lsbu, P. V. (2023). *ENOUGH D2.2 : Technology road maps and models for food retail*. 295.

27. ROSSETTI A, FABRIS F, MARINETTI S, & MINETTO S. (s. d.). *Field-data based model for integrated supermarkets system seasonal performance evaluation.* [Jeu de données]. International Institute of Refrigeration (IIR). https://doi.org/10.18462/IIR.ICCC2022.1156

28. Tosato, G., Minetto, S., Hafner, A., Rossetti, A., & Girotto, S. (s. d.). *Field assessment of the performance of a state- of-the-art CO2 integrated system for supermarket with distributed HVAC terminals in the shopping area*.

29. Minetto, S., & Schlemminger, C. (2021). *MultiPack D4.7 Technical report on verified supermarket packs* (p. 36).

30. Wallin, J., & Claesson, J. (2014). Improving heat recovery using retrofitted heat pump in air handling unit with energy wheel. *Applied Thermal Engineering*, *62*(2), 823-829. https://doi.org/10.1016/j.applthermaleng.2013.09.059

31. Evans, J., Foster, A., & Eid, E. (s. d.). *ENOUGH D2.3 Catering roadmap*.

32. Teke, İ., Ağra, Ö., Atayılmaz, Ş. Ö., & Demir, H. (2010). Determining the best type of heat exchangers for heat recovery. *Applied Thermal Engineering*, *30*(6), 577-583. https://doi.org/10.1016/j.applthermaleng.2009.10.021

33. Jedlikowski, A., Kanaś, P., & Anisimov, S. (2020). Heat and mass transfer inside the rotary heat exchanger operating under high speed rotor conditions. *International Journal of Heat and Mass Transfer*, *152*, 119558. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119558

34. Akbari, A., Kouravand, S., & Chegini, G. (2018). Experimental analysis of a rotary heat exchanger for waste heat recovery from the exhaust gas of dryer. *Applied Thermal Engineering*, *138*, 668-674. https://doi.org/10.1016/j.applthermaleng.2018.04.103

35. Ding, T., Chen, X., Cao, H., He, Z., Wang, J., & Li, Z. (2021). Principles of loop thermosyphon and its application in data center cooling systems : A review. *Renewable and Sustainable Energy Reviews*, *150*, 111389. https://doi.org/10.1016/j.rser.2021.111389

36. Li, F., Gao, J., Shi, X., Liang, F., Zhu, K., & Li, Y. (2018). Experimental investigation of an R600a two-phase loop thermosiphon to cool a motorized spindle shaft. *International Communications in Heat and Mass Transfer*, *97*, 9-16. https://doi.org/10.1016/j.icheatmasstransfer.2018.06.005

37. Abu-Mulaweh, H. I. (2006). Design and performance of a thermosiphon heat recovery system. *Applied Thermal Engineering*, *26*(5), 471-477. https://doi.org/10.1016/j.applthermaleng.2005.08.003

38. Chauhan, A., & Kandlikar, S. G. (2019). Characterization of a dual taper thermosiphon loop for CPU cooling in data centers. *Applied Thermal Engineering*, *146*, 450-458. https://doi.org/10.1016/j.applthermaleng.2018.10.010

39. Sutanto, B., Indartono, Y. S., Wijayanta, A. T., & Iacovides, H. (2022). Enhancing the performance of floating photovoltaic system by using thermosiphon cooling method : Numerical and

experimental analyses. *International Journal of Thermal Sciences*, *180*, 107727. https://doi.org/10.1016/j.ijthermalsci.2022.107727

40. Meng, F., Zhang, Q., Lin, Y., Zou, S., Fu, J., Liu, B., Wang, W., Ma, X., & Du, S. (2022). Field study on the performance of a thermosyphon and mechanical refrigeration hybrid cooling system in a 5G telecommunication base station. *Energy*, *252*, 123744. https://doi.org/10.1016/j.energy.2022.123744
41. Battistin, M., Berry, S., Bitadze, A., Bonneau, P., Botelho-Direito, J., Boyd, G., Corbaz, F., Crespo-Lopez, O., Riva, E. D., Degeorge, C., Deterre, C., DiGirolamo, B., Doubek, M., Favre, G., Godlewski, J., Hallewell, G., Katunin, S., Lefils, D., Lombard, D., … Zwalinski, L. (2015). The Thermosiphon Cooling System of the ATLAS Experiment at the CERN Large Hadron Collider. *International Journal of Chemical Reactor Engineering*, *13*(4), 511-521. https://doi.org/10.1515/ijcre-2015-0022
42. Ye, C., Zheng, M. G., Wang, M. L., Zhang, R. H., & Xiong, Z. Q. (2013). The design and simulation of a new spent fuel pool passive cooling system. *Annals of Nuclear Energy*, *58*, 124-131. https://doi.org/10.1016/j.anucene.2013.03.007
43. Bieliński, H., & Mikielewicz, J. (2016). Application of a two-phase thermosyphon loop with minichannels and a minipump in computer cooling. *Archives of thermodynamics*, *37*(1), 3-16. https://doi.org/10.1515/aoter-2016-0001
44. Fu, W., Li, X., Wu, X., & Zhang, Z. (2015). Investigation of a long term passive cooling system using two-phase thermosyphon loops for the nuclear reactor spent fuel pool. *Annals of Nuclear Energy*, *85*, 346-356. https://doi.org/10.1016/j.anucene.2015.05.026

45. Dhumane, R., Ling, J., Aute, V., & Radermacher, R. (2017). *Modeling of a Thermosiphon to Recharge Phase Change Material Based Thermal Battery for a Portable Air Conditioning Device*. https://ep.liu.se/en/conference-article.aspx?series=ecp&issue=132&Article_No=52

46. Srimuang, W., & Amatachaya, P. (2012). A review of the applications of heat pipe heat exchangers for heat recovery. *Renewable and Sustainable Energy Reviews*, *16*(6), 4303-4315. https://doi.org/10.1016/j.rser.2012.03.030

47. Daraghmeh, H. M., Sulaiman, M. W., Yang, K.-S., & Wang, C.-C. (2018). Investigation of Separated Two-Phase Thermosiphon Loop for Relieving the Air-Conditioning Loading in Datacenter. *Energies*. https://doi.org/10.3390/EN12010105

48. Foster, A., Campbell, R., Davies, T., & Evans, J. (2015). *A novel passive defrost system for a frozen retail display cabinet with a low evaporator*.

49. Foster, A., Campbell, R., Davies, T., & Evans, J. (2013). *A novel PCM thermosiphon defrost system for a frozen retail display cabinet*.

50. Pesta, G., Hansemann, E., Bochmann, G., Drosg, B., Gabauer, W., & Liebetrau, J. (2025). *Implementation of anaerobic digestion facilities in the food and beverage industry*.

51. Venslauskas, K., Navickas, K., Nappa, M., Kangas, P., Mozūraitytė, R., Šližytė, R., & Župerka, V. (2021). Energetic and Economic Evaluation of Zero-Waste Fish Co-Stream Processing. *International Journal of Environmental Research and Public Health*, *18*(5), Article 5. https://doi.org/10.3390/ijerph18052358

52. Bassols, J., Kuckelkorn, B., Langreck, J., Schneider, R., & Veelken, H. (2002). Trigeneration in the food industry. *Applied Thermal Engineering*, *22*(6), 595-602. https://doi.org/10.1016/S1359-4311(01)00111-9

53. Calderan, R., Spiga, M., & Vestrucci, P. (1992). Energy modelling of a cogeneration system for a food industry. *Energy*, *17*(6), 609-616. https://doi.org/10.1016/0360-5442(92)90096-I

54. Vellini, M., Gambini, M., & Stilo, T. (2020). High-efficiency cogeneration systems for the food industry. *Journal of Cleaner Production*, *260*, 121133. https://doi.org/10.1016/j.jclepro.2020.121133

55. REN S, AHRENS M. U, HAMID K, TOLSTOREBROV I, HAFNER A, EIKEVIK T, & WIDELL K. N. (s. d.). *Performance modelling of an ammonia-water absorption-compression heat pump for steam generation in food processing.* https://doi.org/10.18462/iir.nh3-co2.2023.0022

56. Choudhury, B., Saha, B. B., Chatterjee, P. K., & Sarkar, J. P. (2013). An overview of developments in adsorption refrigeration systems towards a sustainable way of cooling. *Applied Energy*, *104*, 554-567. https://doi.org/10.1016/j.apenergy.2012.11.042

57. Li, G. (2016). Sensible heat thermal storage energy and exergy performance evaluations. *Renewable and Sustainable Energy Reviews*, *53*, 897-923. https://doi.org/10.1016/j.rser.2015.09.006

enough-emissions.eu

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