Technology Collaboration Programme
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Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

# Annex 58

# High-Temperature Heat Pumps

# Task 2 – Integration Concepts

## Task Report

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## Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

**The IEA**
The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

**The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)**
The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or "Annexes", in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.

The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

**Disclaimer**
The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes or TCPs. The TCPs are organised under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

**The Heat Pump Centre**
A central role within the HPT TCP is played by the Heat Pump Centre (HPC).
Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimise the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology, including researchers, engineers, manufacturers, installers, equipment users, and energy policymakers in utilities, government offices, and other organizations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
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## Operating Agent

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The Annex is being operated from 01/2020 to 12/2023. The main information can be found on the Annex 58 homepage: https://heatpumpingtechnologies.org/annex58/

## Participating countries of Annex 58

There is a high number of countries participating in Annex 58, while each country is represented by a national team consisting of several organizations. The following countries are formally participating in the Annex:

- Austria
- Belgium
- Canada
- China
- Denmark
- Finland
- France
- Germany
- Japan
- Netherlands
- Norway
- South Korea
- Switzerland
- USA

A presentation of all national teams can be found on the Annex 58 homepage.

## Authors of the report and contributors to Task 2

The report was prepared as a collaborative effort with contributions from various authors and was coordinated by the main author, Benjamin Zühlsdorf. An overview of the contributors is shown in Table 0-1.

Table 0-1: Overview of authors of the report, sorted by organization and country.

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## Foreword

This report has been compiled as part of the IEA HPT Annex 58 about High-Temperature Heat Pumps (HTHP). The Annex is structured into the following 5 tasks:

- Task 1: Technologies – State of the art and ongoing developments for systems and components
- Task 2: Integration Concepts – Development of best practice integration concepts for promising application cases
- Task 3: Applications and Transition – Strategies for the conversion to HTHP-based process heat supply
- Task 4: Definition and testing of HP specifications – Recommendations for defining and testing of specifications for high-temperature heat pumps in commercial projects
- Task 5: Dissemination

The overall objective of the Annex is to provide an overview of the technological possibilities and applications as well as to develop best practice recommendations and strategies for the transition towards heat pump-based process heat supply. The intention is to improve the understanding of the technology's potential among various stakeholders, such as manufacturers, potential end-users, consultants, energy planners, and policy makers. In addition, the Annex aims to provide supporting material to facilitate and enhance the transition to a heat pump-based process heat supply for industrial applications.

This will be achieved by the following sub-objectives:

- Provide an overview of the technology, including the most relevant systems and components that are commercially available and under development (Task 1).
- Identify technological bottlenecks and clarify the need for technical developments regarding components, working fluids, and system design (Task 1).
- Present best practice system solutions for a range of applications to underline the potential of HTHPs (Task 2).
- Develop strategies for the transition to heat-pump-based process heat supply (Task 3).
- Enhance the information basis about industrial heat pumps, potential applications, and potential contribution to the decarbonization of the industry (Task 1, 2 & 3).
- Develop guidelines for handling industrial heat pump projects with a focus on the HP specifications and the testing of these specifications (Task 4).
- Disseminate the findings to various stakeholders and add to the knowledge base for energy planners and policy makers (Task 5).

Annex 58 focuses on HTHPs, which are heat pumps that supply a relevant share of their heating capacity at temperatures above 100 °C. In this context, the focus is on developing, summarizing, and communicating information about the most relevant technologies and applications rather than covering all technologies. The relevance was mainly determined by the various participants and indirectly given by the technologies' application potential and market perspectives. Therefore, the Annex is primarily focused on applications for industrial heat supply but will not specifically be limited to these applications.

This report documents the work of Task 2 – Integration concepts. Chapter 1 describes the terminology used and the method and templates used to structure the analysis of the concepts. Chapter 2 provides an overview of the integration concepts for selected processes and systems and includes a literature review with examples. In Chapter 3, typical heat pump applications are identified and heat pump concepts for those application are described. Chapter 4 provides guidelines for the selection of integration and heat pump concepts for selected processes and application. Finally, the findings of the report are summarized and conclusions are drawn in Chapter 5.

## Executive Summary

High-temperature heat pumps are a key technology for decarbonising industrial process heating, which is often based on fossil fuels and accounts for a considerable share of the final energy consumption and greenhouse gas emissions of industries. Heat pumps are a promising alternative to the current fossil fuels-based solutions as they can provide process heating and cooling based on electricity (potentially emissions-free) at the highest efficiencies. However, due to the wide range of technological solutions available for HTHPs and the diversity of processes and their requirements, it is challenging to define generally applicable integration guidelines and concepts. Therefore, this report aims to provide an overview of the best practices for integrating HTHPs into the most promising application areas, improving understanding of the technology's potential.

The description of the concepts was structured using two templates: one for the development of integration concepts for processes or systems, and another for the development of heat pump concepts for selected heat pump applications. The use of standardized templates allowed for a structured collection and presentation of information despite the heterogeneity of the authors.

In the first part of the study, 12 industrial systems or processes with heating demands and supply temperatures above 100 °C have been selected and described based on their characteristics, such as mass flows, heating and cooling demands, temperatures, and production patterns. Based on this information, 27 integration points for HTHPs were identified. The integration concepts were defined by a system layout, including the heat transfer media, the heat exchanger network, and other devices, such as storage and heat pumps.

It was found that the best practices for system layout and conditions vary depending on the specific case, but unit operations share similar process requirements. Therefore, heat pump concepts can be standardized to meet these requirements and can be assigned to three basic heat pump applications: hot water production, steam production and applications with large temperature glides.

The second part of the study describes these typical heat pump applications. by the direct boundary conditions, such as the temperature profiles, capacities and media of source and sink. For each of these heat pump applications, various heat pump concepts can be developed. In this report, 15 heat pump concepts were defined by their main functioning principle, system layout, refrigerant, compressor types, and expected performance.

Based on these findings, recommendations were developed for the selection of sensible heat pump concepts for processes within the same unit operation. The recommendations are not intended to be comprehensive, but they aim to demonstrate the application potential of high-temperature heat pumps in a wide range of processes.

# Nomenclature

**Abbreviations**

| | |
|---|---|
| CCHP | Closed Compression Heat Pump |
| COP | Coefficient of Performance |
| GCC | Grand Composite Curve |
| HEX | Heat exchanger |
| HFO | Hydrofluorooefin |
| HTHP | High Temperature Heat Pump |
| IHX | Internal Heat Exchanger |
| MVR | Mechanical Vapor Recompression |
| RES | Renewable Energy System |
| SGHP | Steam Generating Heat Pump |
| TRL | Technology Readiness Level |

**Symbols**

| | |
|---|---|
| $\dot{H}$ | Enthalpy rate, kW |
| $h$ | Specific enthalpy, kJ/kg |
| $\dot{m}$ | mass flow, kg/s |
| $p$ | Pressure, bar |
| $RH$ | relative humidity, % |
| $s$ | Specific entropy, kJ/(kg K) |
| $T$ | Temperature, °C or K |
| $x$ | absolute humidity, g/kg |

**Subscripts and superscripts**[1]

| | |
|---|---|
| *in* | inlet |
| *out* | outlet |

[1] Self-explaining subscripts and superscripts are excluded from the nomenclature.

# Table of Content

# 1. Introduction

## 1.1. Scope

High-temperature heat pumps (HTHP) are a key technology for decarbonizing industrial heating processes and systems. However, the wide range of technological solutions for HTHPs on the one hand and the diversity of processes and their requirements on the other are challenges to define generally applicable integration guidelines and concepts. Therefore, Task 2 of the IEA HPT Annex 58 project aims to determine best practices for application areas identified as most promising for integrating HTHPs, thereby improving the understanding of the technology's application potential. The focus will be on developing integration concepts for selected processes from the unit operations drying, thermal treatment, thermal preservation as well as thermal separation (e.g. Spray dryers, sterilisation, distillation columns, etc.) and systems (such as dairies, breweries, slaughterhouses, pharmaceutical and chemical production sites ) Based on this, typical heat pump applications (steam generation, hot water production, large temperature glide) will be identified, and heat pump concepts for these applications will be developed.

Figure 1-1 provides an overview of the scope of Task 1 (Technology), Task 2 (Integration Concepts), and Task 3 (Application) in IEA HPT Annex 58, showing how Task 2 is connected to the other tasks: Each heat pump application can be realised by several heat pump concepts. Heat pump concept contains information about suitable heat pump technologies which are based on the collection of Task 1. The integration concepts from Task 2 can be used as building block for specific measures as part of the concept solution developed, as suggested in Task 3.

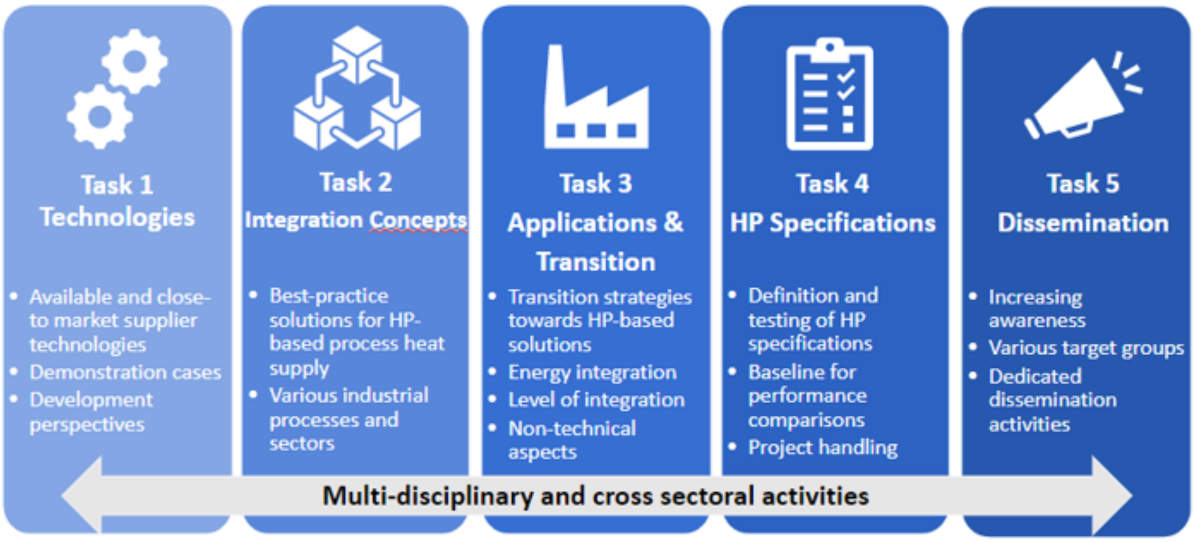



*Figure 1-1: Overview of the scope of the tasks in IEA HPT Annex 58*

## 1.2. Terms and definitions

The key terms used in Task 2 are process, system, integration concept, heat pump application and heat pump concept. Figure 1-2 provides an overview of the terminology and the definitions.

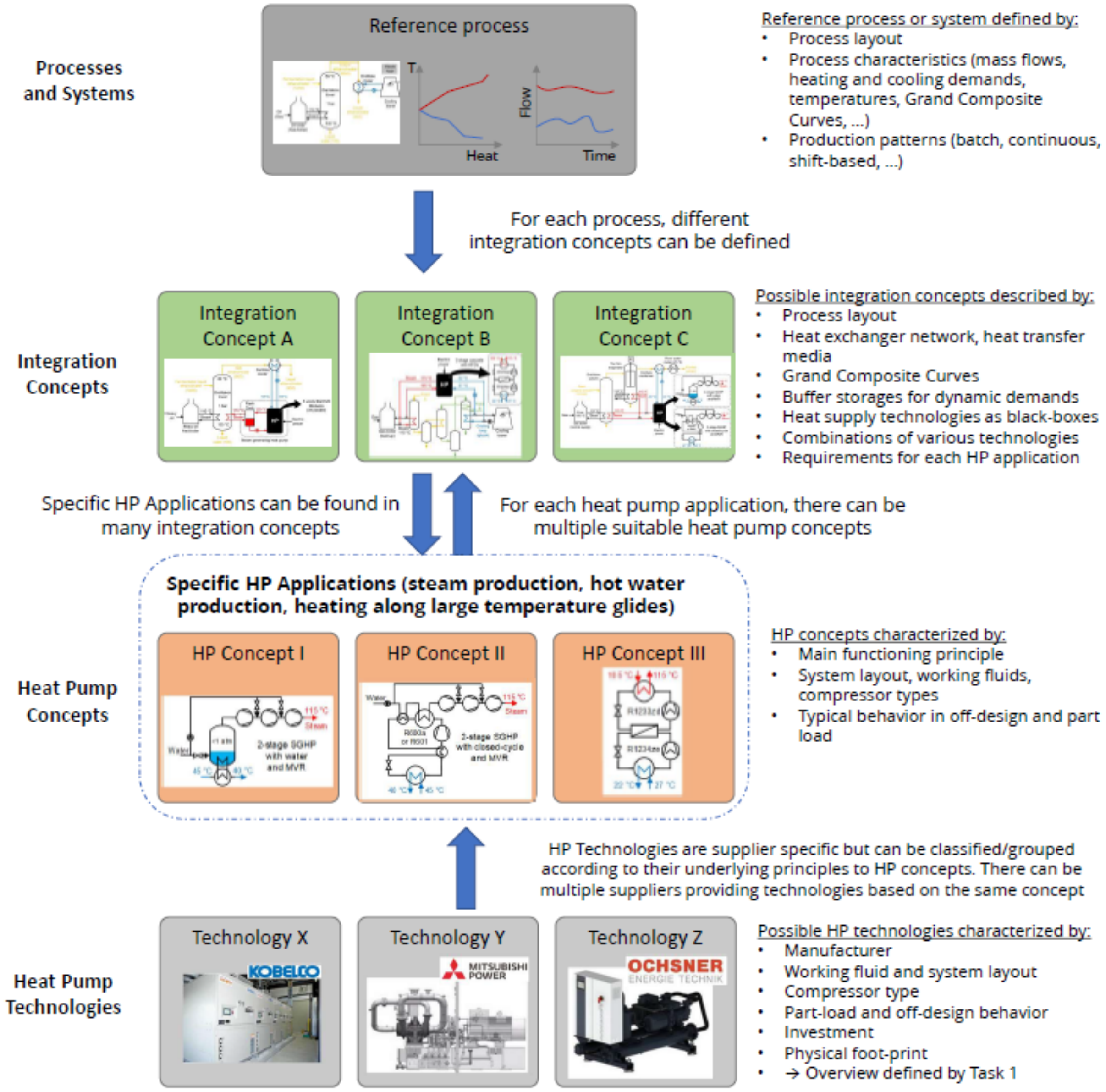



*Figure 1-2: Overview of terminology related to Task 2 of Annex 58*

### Process

Task 2 defines a process as an industrial production process to produce one or more products. Primarily, processes with heating demands and supply temperatures above 100 °C are relevant for Annex 58. Some relevant processes include drying processes, autoclaves, baking ovens, and distillation columns.

### System

A system is defined as a combination of various processes, typically on the level of an entire production process. Examples of relevant systems include different kinds of dairies, slaughterhouses, breweries, pharmaceutical and chemical production sites, industry symbioses, hospitals, and others.

Processes and systems are described by their process layout, including the main process parameters, such as mass flows, heating and cooling capacities, temperatures, pressures, and production patterns.

### Integration concept

An integration concept describes solutions for process integration, including the supply, conversion, distribution, storage and recovery of heating and cooling. They are defined by a system layout, including the heat transfer media, the heat exchanger network, and other devices, such as storage and heat pumps. The heat pump systems are considered black box units, while the boundary conditions (temperatures and capacities) define the specifications for each heat pump application.

**Heat pump application**

A heat pump application describes the direct boundary conditions for the heat pump, such as the temperature profiles, capacities, and media of the source and sink. Examples of heat pump applications include steam production, hot water production, and heating with large temperature glides. A heat pump application can occur in various processes and systems depending on the integration concept.

**Heat pump concept**

Various heat pump concepts can be developed for each of these heat pump applications. For example, for steam generation, there are various heat pump concepts to produce steam, such as open cycles, closed cycles, cascade systems, steam compression, and more. A heat pump concept consists of one or more heat pump cycles, is defined by a system layout, and typically uses components and working fluids (i.e., refrigerants).

## 1.3. Templates

This report collects various integration concepts and heat pump concepts, and their description was structured following two templates:

- **Template for the development of integration concepts for processes or systems.** The template consists of two parts:
  - Description of the reference process or system, including capacities, product, stream utilities, heat sources, temperatures, operating schedule, operating parameters, Grand Composite Curve (GCC), if available
  - Detailed description of the integration concepts, including capacities, media, temperatures, time patterns, potential and challenges, as well as potential integration points
- **Template for the development of heat pump concepts for selected heat pump applications.** The template is also split into two parts:
  - Description of the heat pump application, including main products, streams, utilities, temperatures, and capacity range
  - Description of the heat pump concepts, including the compressor, heat exchanger, storage technology, expected performance, technology maturity, advantages, and challenges.

# 2. Integration concepts

## 2.1. Overview of developed integration concepts

This chapter provides an overview of the integration of high-temperature heat pumps in different processes and systems. The processes and systems covered in this report are:

- baking ovens (Section 2.1.1),
- distillation (Section 2.1.2),
- spray drying (Section 2.1.3),
- batch sterilization (Section 2.1.4),
- anodizing processes (Section **Fel! Hittar inte referenskälla.**),
- automotive painting and drying (Section 2.1.6),
- brick drying (Section 2.1.7),
- oil and gas processing (Section 2.1.8),
- molded fiber dryers (Section **Fel! Hittar inte referenskälla.**),
- extrusion cooking (Section 2.1.10),
- plastic granules drying (Section 2.1.11) and
- biosludge drying (Section 2.1.12).

According to the template described in Section 1.3**Fel! Hittar inte referenskälla.**, every section includes a brief description of the process followed by a detailed description of the integration concepts.

### 2.1.1. Baking ovens

#### Process description

Globally, baking is one of the most widespread ways of preparing food and has a long history. Flatbread goes back more than ten thousand years, while the use of leavening agent and closed ovens originates from Egypt, about 4500 years ago. The ingredients are very few and simple, water, flour, salt and raising agent as a base and in modern times oil/butter/margarine, sugar and eggs and flavorings are added depending on the products. Various breads, cookies, biscuits, pre-prepared meals, and pastries/pies are baked at a baking temperature typically in the range of 180 to 220 °C.

Despite the few ingredients in the base recipe, the baking process is rather complex as the baking temperature causes physical transitions and chemical reactions to take place in the dough [1],[2],[3].

- The dough gradually increases in volume as encapsuled air and released $CO_2$ heats up. At 50 – 60 °C the yeast cells are killed, the enzyme-driven conversion of starch to sugar and the break of proteins to amino acids has a maximum of 60 °C. At 50 – 80 °C starch gelatinization, gluten denaturation, and later coagulation take place as well as inactivation of enzymes – the dough crumb formation starts at 85 °C.
- The dough water content is typically 15 - 30 % at the start, and the drying to 5 – 15 % water content takes place during the baking process as a front of evaporation starting at the surface and working its way into the product. The final moisture content is dependent on a number of factors including oven temperature and humidity.
- The colour formation starts at 105 °C by the Maillard reaction between amino acid and sugar, while it requires 160 – 180°C to start the caramelization of sugar.

The point is that the product quality is paramount, and that proper control of the process conditions – air flow, temperature level and humidity - is essential for the baking of the wide variety of products.

The baking process has been mathematical modelled with reasonable results, for example [4],[5],[6], in particular for the energy transport related to the evaporation - which requires the most energy – and also for temperature profiles, crust formation, etc.

Industrial baking takes place in two types of continuous ovens (e.g., tunnel ovens), radiation and convection, of which the convection type is the most popular and the subject of this note. The global market for this type of ovens is approx. 4 billion USD per year [7] for new installations. A heat pump solution could be used for retrofits – in many units.

In contrast to other drying processes, e.g., spray dryers, the air is recirculated in the convection ovens, as illustrated in Figure 2-2. The air is circulated by the fan and heated in the heat exchanger on top of the ovens by gas firing [8] and distributed in the oven by perforated plates on top and at the bottom of the conveyor belt holding the product [9]. The air is typically cooled at 30 °C (while the humidity increases) and returned to the ventilator, reheated, and recirculated. A fraction of the air is bled into the atmosphere and replaced by fresh air for humidity control. The heating of the dough, the evaporation, and the color formation take place with baking temperature settings in the range of 170 to 250 °C, as mentioned, typically 25 to 40 °C above the actual baking temperature. The dough for bread products starts with 40 to 50% water content, which is reduced to 37-38 % for the final product. Similar numbers for cookies are typically 25 % water content at the start and 5 % for the final product.

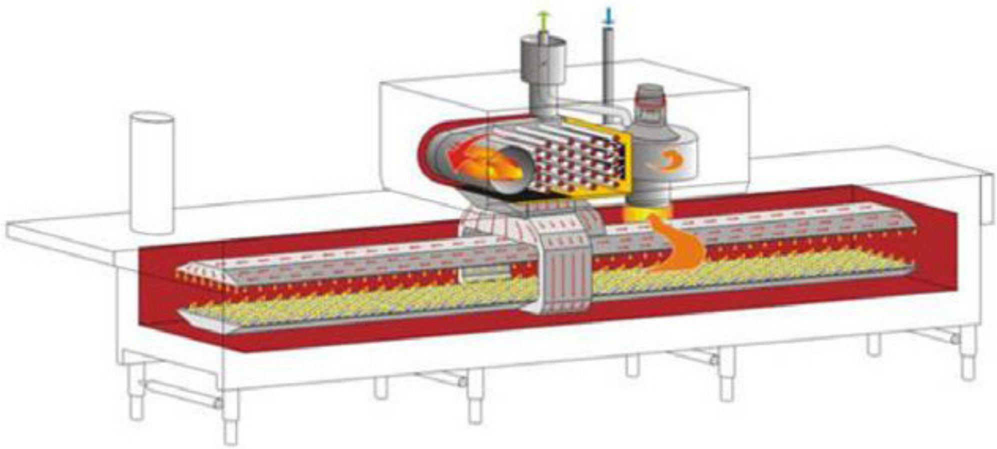


*Figure 2-1 - Continuous industrial convection baking oven, indirect gas fired type [1].*

The relative humidity – defined as the fraction of (superheated) steam compared to total air volume – can be as high as 35 to 40 % for bread baking and as low as 10 to 15 % for cookies, corresponding to dew points in the range 65 to 90 °C [10],[11].

A production line comprises 3 to 6 individual energy units with separated temperature zones (each 5 to 7 m long and 1.2 to 3 m wide) and increasing temperature settings that take care of the baking process. Each unit has capacities in the range of 100 to 200 kW. Figure 2-2 shows the flow diagram of a gas-fired continuous baking oven [12], [13].

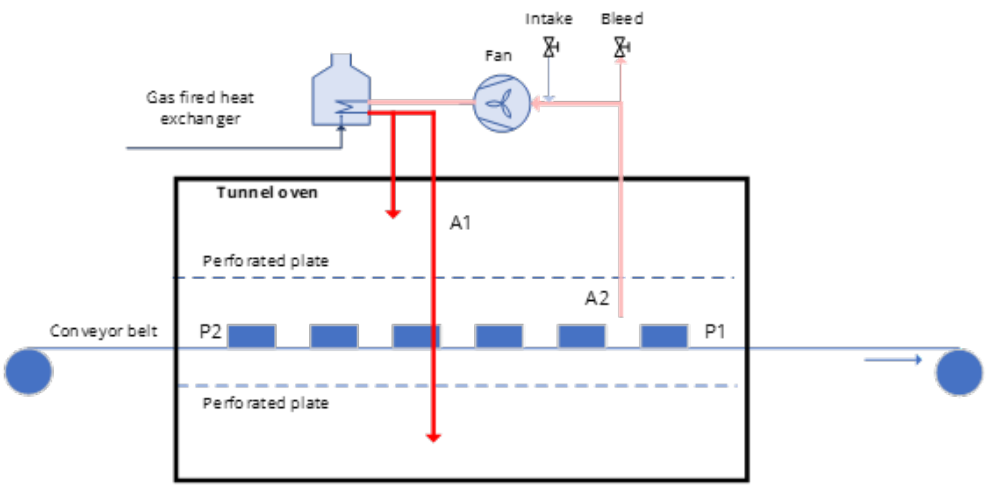



*Figure 2-2: Flow diagram of a gas-fired continuous baking oven. A1 and A2 refer to air in different state points, while P1 and P2 refer to the product*

Figure 2-3 shows a schematic of the baking process in the various zones with increasing setting temperatures (red lines) and plateaus for dough surface and center temperature when the evaporation takes place, for example [14]. The humidity in the oven is relatively high for a substantial fraction of the zones but decreases at the final temperature zones. The heating capacity is largest as the evaporation takes place, lower at the final stages.

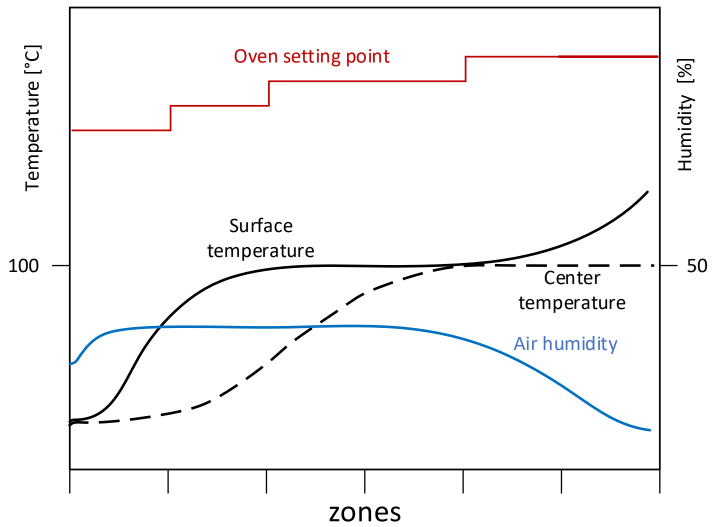



*Figure 2-3 - Schematic of baking process with setting temperature (red), product center (dotted black) and surface (solid black) temperature, and air humidity (blue) for a production line with several individual temperature zones.*

## Integration concepts

Due to the modular structure of the baking process line, the integration concepts suggest a separate heat pump for each energy unit to allow for different temperature zones, capacity settings etc. Two other concepts are depending on the nature of the heat source. It can either be condensation of the humid air – like the dehumidifier application – or cooling of the conveyor belt and the product after the last energy unit in the production line.

The details of the baking process and the product in question will determine which of the two configurations will be preferred. In most cases, the front and mid sections will likely use the humid air as a heat source, while the last one or two sections will use the cooling as a heat source.

The dew point of the humid air is relatively high, typically in the range of 65 to 90 °C and can thus serve as the heat source temperature, while set points are in the lower range of the baking interval, typically set points in the range 180 to 220 °C, and the capacity in the order of 200 kW. A separate heat exchanger is necessary for heat pump integration; otherwise, the capacity requirements would be much larger, in line with spray dryer applications.

The mass of the steel conveyor belt is significant [15], and the steel temperature will be close to the final baking temperature of the last energy unit, typically above 200 °C, while the average temperature of the product is somewhat above 100 °C. The center temperature is close to 100 °C as water is still evaporating. The surface temperature can be slightly higher, 120 to 150 °C. The capacity requirements are typically lower at the baking zones, in the order of 100 kW. Calculations show that the cooling of the conveyor belt and the product can supply more than 50 kW by cooling to the 90 to 95 °C range, which will be the heat source temperatures in the second integration concept [15]. If two zones should use the cooling for a heat source, the cooling temperature will be approx. 60 °C.

*Integration concept A: Humid air as a heat source*

The flow diagrams of the first integration concept are shown in Figure 2-4, and the operating conditions are reported in the fact sheet in Table 2-1. The figur shows how the humid return air from the oven (A2) is used as a heat source for the heat pump. After passing through a heat exchanger, the return air is cooled to a temperature close to the dew point (A4), and in the evaporator the air is further cooled to the dew point and some of the water in the air is condensed (A3). The dry, cooled air is heated in the internal heat exchanger to a temperature level of around 150°C (A5), after which the condenser heats the dry air to the return air temperature level of typically 180°C (A1).

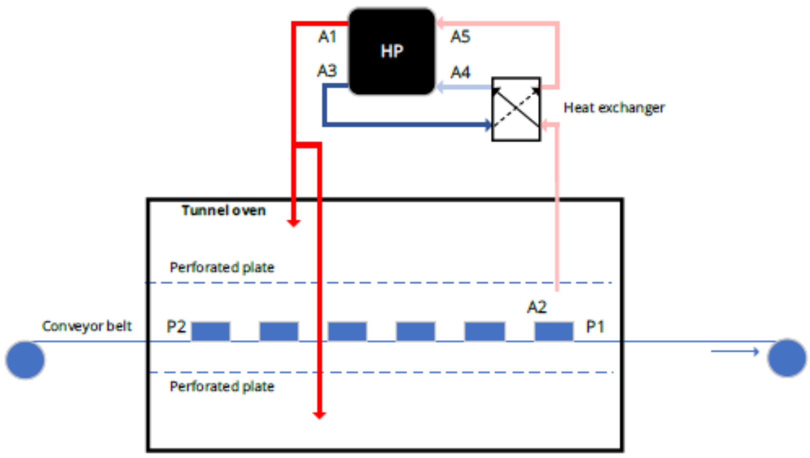



*Figure 2-4: Flow diagram of Integration Concept A (baking ovens). A1,..,A5 refer to air in different state points, while P1 and P2 refer to the product*

*Table 2-1: Overview of specifications for heat pump application in Integration concept A (baking ovens)*

| **Heat Pump Application A – humid air as a heat source** | |
|---|---|
| **Heat Sink** | • $T_{in}$ = 150 °C → $T_{out}$ = 180 °C (typically)<br>• Humid air due to recirculation operation<br>• 150-250 kW |
| **Heat Source** | • $T_{in}$ = $T_{out}$ = 65-90 °C (condensation)<br>• Condensation of humid air<br>• 75-125 kW |
| **Comments** | • Separate heat exchanger<br>• Capacity adjustment according to evaporation rate<br>• The supply temperature should typically be 180-250 °C. Steam or hydrocarbons are the most likely refrigerants. |

*Integration concept B*

Figure 2-5 shows the flow diagrams of the second integration concept, and Table 2-2: Overview of specifications for heat pump application in Integration concept B (baking ovens)shows the operating conditions in the fact sheet. If product and conveyor cooling is used as the heat source, the separate heat exchanger is not relevant and the evaporator is supplied directly by the cooling air, as shown in Figure 2-5.

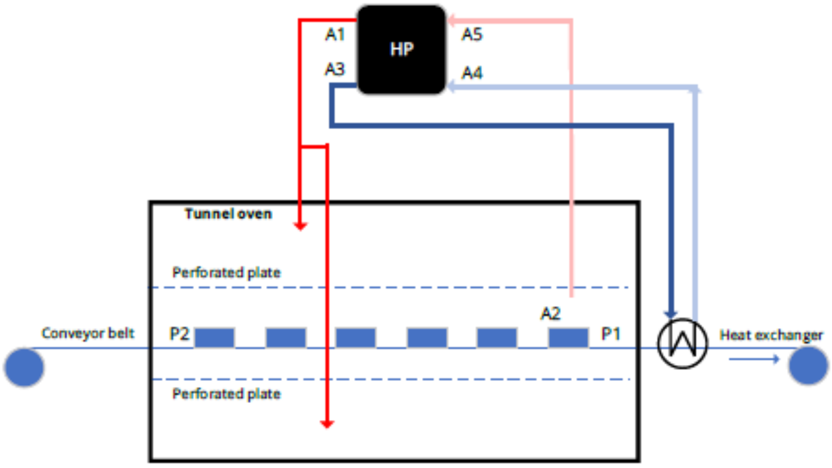



*Figure 2-5: Flow diagram of Integration Concept B (baking ovens)*

*Table 2-2: Overview of specifications for heat pump application in Integration concept B (baking ovens)*

| **Heat Pump Application B – cooling of product and conveyor belt as heat source** | |
|---|---|
| Heat Sink | • $T_{in}$ = 180 °C → $T_{out}$ = 220 °C (typically)<br>• Humid air<br>• 100 kW (it can vary greatly depending on the oven size and products) |
| Heat Source | • $T_{in}$ = 200 °C (belt), 110°C (product) → $T_{out}$ = 90-95 °C<br>• Cooling of conveyor belt and product (air)<br>• 50 kW (it can vary greatly depending on the oven size and products) |
| Comments | • High supply temperature for coloring, crust, taste, etc.<br>• Capacity adjustment according to evaporation rate<br>• Supply temperature should typically be 180-250 °C. Steam or hydrocarbons are most likely refrigerants. |

### 2.1.2. Distillation

#### Process description

Distillation is a widely used separation technology in the process industry and one of the largest energy consumers. Today, the chemical sector is responsible for about 1/3 of the industrial sector's total energy consumption and associated $CO_2$ emissions [16]. In particular, process heat generation in distillation processes dominates and consumes about 40 % of the energy in the chemical industry [17]. The combustion of fossil fuels, mainly natural gas, accounts for most of the thermal energy. Typically, distillation processes require steam above 100 °C.

Key suppliers of distillation systems include GEA (Germany), Alfa Laval (Sweden), SPX FLOW (US), Sulzer (Switzerland), Core Laboratories (Netherlands), PILODIST (Germany), Anton Paar (Austria), Praj Industries (India), L&T Hydrocarbon Engineering (India), EPIC Modular Process Systems (US), BÜFA Composite System (Germany), and Bosch Packaging Technology (Germany) [18]. In 2017, the distillation systems market was valued at USD 5.94 billion and was projected to grow at a CAGR of 5.1 % to reach USD 7.91 billion by 2023 [18].

The Chemtech division of Sulzer1 (Switzerland) introduced the world's first distillation plant with vapor recompression around 1985 and has carried out a lot of pioneering work [19]. Figure 2-6 shows a plant for separating fine chemicals (chlorobenzene isomers) with an evaporation capacity of about 2 MW. It started up in 1986 at a chemical company in the U.S.A. In 1987 a distillation plant for separating 1,2dichloroethane was installed. It had a pressure ratio of 2.2 and an electric drive power of 1.3 MW. A further vapor recompression distillation plant was built for the separation of styrene/ethylbenzene in 1987. Later, there were many more of these systems, for example in a propylene plant with an annual production of 125000 t. In case of corrosion and risk of explosion, closed-loop heat pumps are replacing vapor recompression [19].

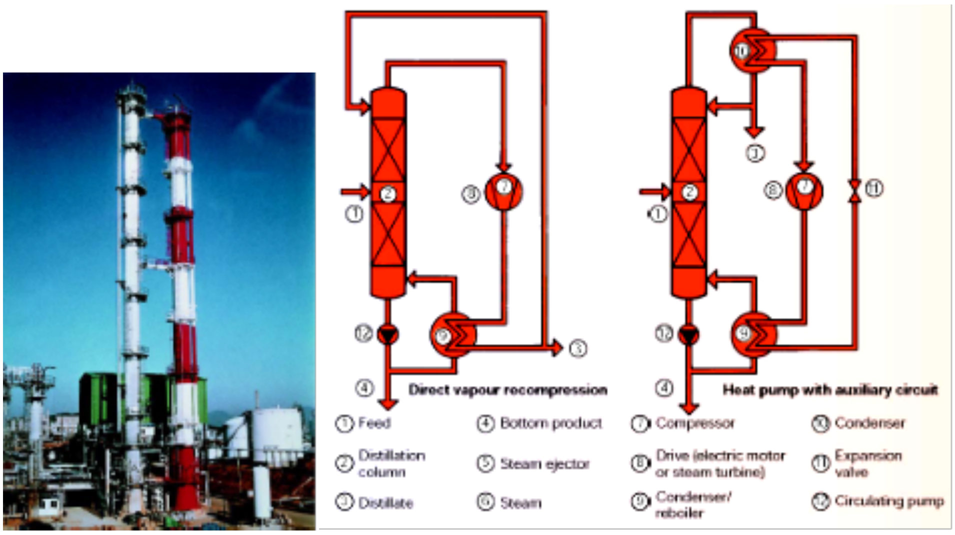



*Figure 2-6: Left: One of the first distillation plants with vapor recompression for the separation of fine chemicals with an evaporation capacity of about 2 MW (Sulzer Chemtech, 1986), Right: Principle of vapor recompression and closed-cycle heat pump integration in distillation (Source:* [19]*).*

Figure 2-7 shows a simplified flow diagram of a typical distillation process for bioethanol production from a fermentation liquid with a heat supply above 100 °C, typically low-pressure steam of around 120 °C. Here, the process of the bioethanol producer Hokkaido Bioethanol Co. [20] in Japan is used as a specific example to explain a possible HTHP integration [21]. Similar distillation processes are possible in other companies and countries with heat source temperatures of 20 to 45 °C, supplying low-pressure steam at about 110 to 120 °C and about 0.5 to 2.5 MW of heating capacity [22].

In principle, distillation uses steam to vaporize the more volatile substance (e.g., ethanol from the aqueous feed solution) and a condenser to liquefy (condense) the distillate, the main product (i.e., bioethanol). As an example, oil- or gas-fired boilers provide 120 °C steam. The installed heating capacity of distillation applications in the chemical industry is typically between 1 and 10 MW. The distillate is cooled by a cooling circuit, normally connected to a cooling tower. However, cooling can also be provided by river water, a chiller, or other cooling systems.

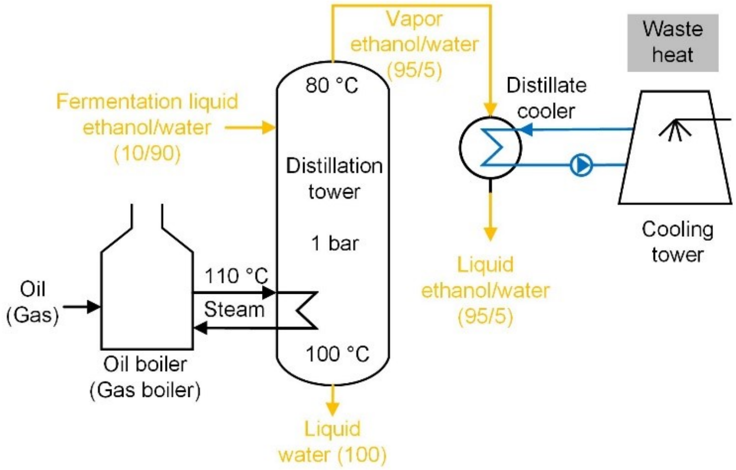



*Figure 2-7: Typical distillation process with a steam boiler and a cooling tower* [22]

### Integration concepts

Figure 2-8 shows the flow diagram of an integration concept based on a realized installation with the main components, i.e., a HTHP for the steam generation (possibly also with a flash tank). The waste heat from the distillation process is recovered in the distillate cooler as a heat source and converted from 65 °C to saturated steam at 110 °C (temperature lift 45 K). This way, the steam-generating heat pump (SGHP) simultaneously provides cooling for the condenser and heating for the reboiler at the bottom of the distillation tower. The heat source for the heat pump is continuously available for distillate cooling. The heat transfer media are a water circuit and steam in a flash tank. The heat pump capacity is approx. 1850 kW, and the operating pressure in the distillation column is at one atmosphere. Since this is a continuous process, no storage integration is required. However, this is an assumption and steam storage could be considered to handle peak loads and flatten the profiles.

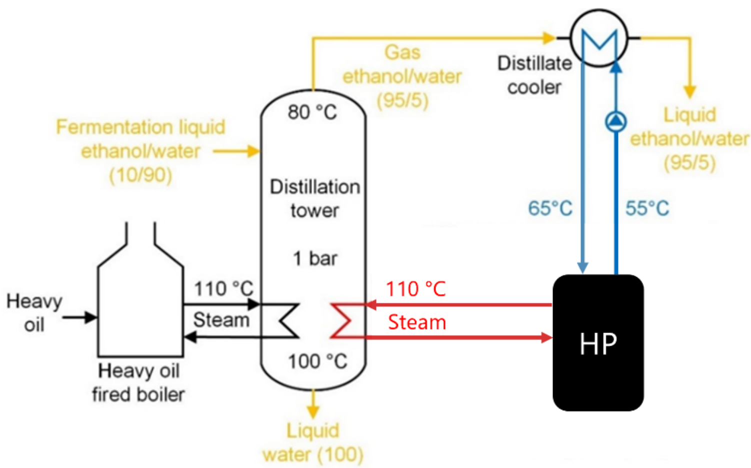



*Figure 2-8: Flow diagram of integration concept A (distillation process)*

The main advantages are:

- Utilization of waste heat improves overall efficiency (waste heat recovery)
- Both sides of the HTHP (hot and cold side) are used
- Process heat supply with a reduced $CO_2$ footprint
- Reduced dependence on natural gas (or oil)
- Reduced cooling demand
- Deep HTHP integration directly into the distillation process with multiplication potential

In this distillation example, the heat pump is considered a black-box unit. At the same time, the boundary conditions (temperatures and capacities) in other distillation processes may vary for each heat pump application depending on the substances (e.g., solvent mixture composition) and pressure in the distillation column (e.g., vacuum distillation reducing the boiling points).

The GCC from the pinch analysis of a distillation process typically indicates a pinch temperature near 60 to 100 °C [23], suggesting heat recovery and low-pressure steam generation by an HTHP. The operating schedule of a distillation process is typically continuous, with operating hours above 4,000 hours per year. The most important process parameters are the required heating capacities, steam mass flow (e.g., 2 t/h like in [20], [21]), and process temperatures (e.g., steam pressure).

The focus for distillation processes is on electrically driven SGHPs delivering low-pressure steam at about 110 to 120 °C, which is interesting for the chemical sector due to the existing steam pipeline infrastructure and heat exchangers.

Various integration concepts can be considered to integrate SGHPs. Figure 2-9 shows another typical distillation integration concept.

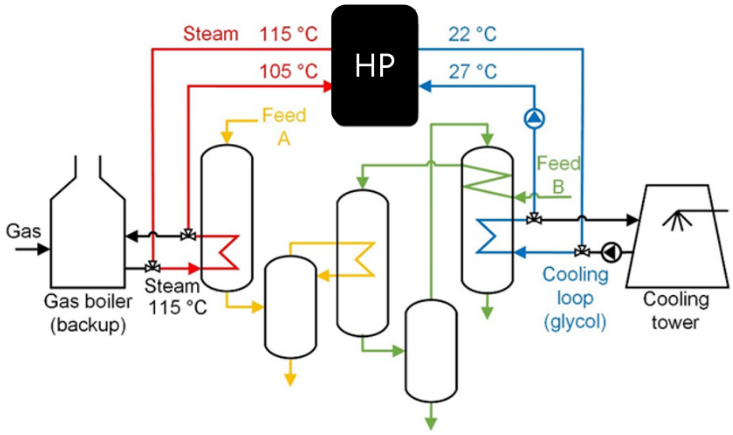



*Figure 2-9: Flow diagram of integration concept B (distillation process)*

Figure 2-10 shows another integration concept in distillation based on an additional thin film evaporator.

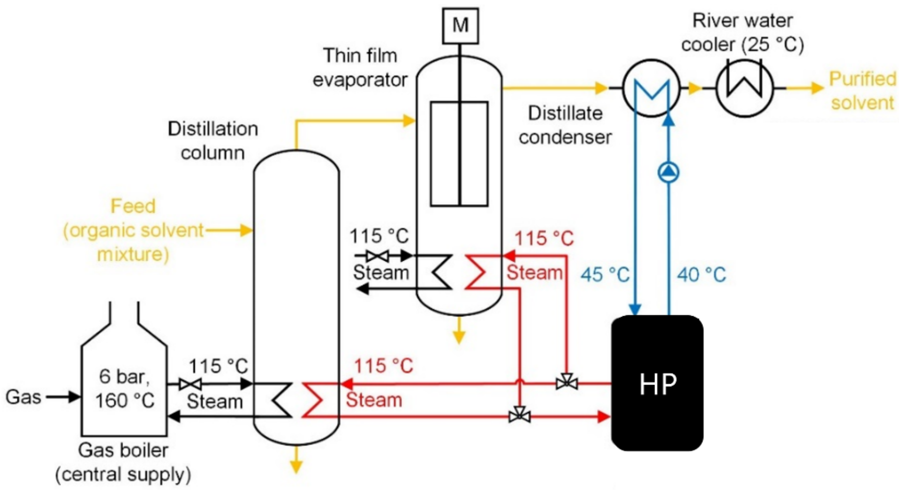



*Figure 2-10: Flow diagram of integration concept C (distillation process)*

Table 2-3 lists the boundary conditions for potential heat pump concepts, such as temperatures at the source and sink and heating capacities. The media are all low-pressure steam on the sink and water on the source side. The typical cycle design, refrigerant (R1234ze/R1233zd, R600a or R601 and R718), and compressor types (e.g., screw, piston, turbo) describe each heat pump concept. Each working fluid has a preferred working domain.

*Table 2-3: Overview of specifications for heat pump application for the Integration concepts(distillation)*

| **Heat Pump Application A** | |
|---|---|
| Heat Sink | • $T_{in}$ = 110 °C (water) → $T_{out}$ = 115 °C (steam)<br>• 1850 kW heating capacity |
| Heat Source | • $T_{in}$ = 65 °C → $T_{out}$ = 60 °C<br>• Water loop |
| Comments | • Steam-generating heat pumps with flash tank<br>• A specific example from Hokkaido Bioethanol Co. in Japan<br>• Continuous operation<br>• References: [20], [21] |
| **Heat Pump Application B** | |
| Heat Sink | • $T_{in}$ = 105 °C (water) → $T_{out}$ = 115 °C (steam)<br>• Water and steam<br>• 950 kW heating capacity (2 lines) |
| Heat Source | • $T_{in}$ = 27 °C → $T_{out}$ = 22 °C<br>• Water (cooling loop, glycol) |
| Comments | • Two-staged cascade cycle HP<br>• Continuous operation<br>• Reference: [22] |
| **Heat Pump Application C** | |
| Heat Sink | • $T_{in}$ = 100 °C → $T_{out}$ = 115 °C<br>• Water and steam<br>• 2'500 kW heating capacity |
| Heat Source | • $T_{in}$ = 45 °C → $T_{out}$ = 40 °C<br>• Water |
| Comments | • Open cycle with water and MVR or a closed-cycle SGHP + MVR<br>• Continuous operation<br>• Reference: [22] |

### 2.1.3. Spray drying

#### Process description

Drying is an extremely energy-intensive process with a wide range of applications and temperature requirements as well as a very high waste heat generation. A distinction is made between contact and convection dryers. The latter brings the material to be dried in contact with hot drying air, which leaves the process with high relative humidity. More than 85 % of all industrial dryers work according to the convective drying principle [24]. The most frequently used types of convection dryers are spray tower, belt, chamber, and tunnel drying [25]. In operational terms, there are continuous or batch dryers and fresh-air or circulating-air operated dryers.

Figure 2-11 shows hot (blue) and cold (red) streams of a typical spray tower drying process which needs external heating or cooling. In addition to the supply and exhaust air, the incoming product flow (P1 → P2), as long as it can be pumped through a heat exchanger, is suitable for heat recovery. In this illustration, the product is fed in at the top, but there are also other types of spray dryers where, for example, the product is fed in from the side at the bottom. In the following, the supply (A1 → A2) and exhaust air (A8) are considered as heat sinks and heat sources due to the lower complexity and reduced heat exchanger costs.

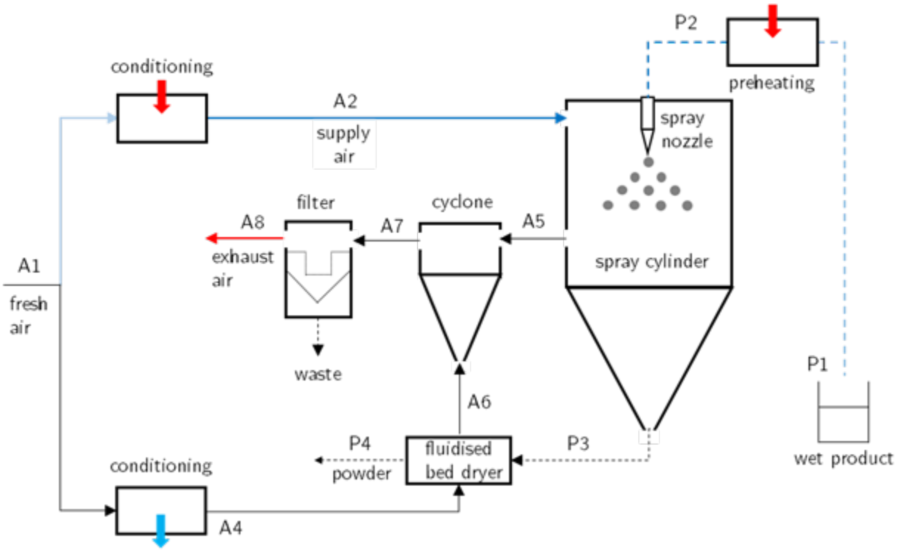



*Figure 2-11: Hot (blue) and cold (red) streams of a typical spray dryer process* [26]

In convective dryers, the reduction of moisture in a product takes place through evaporation. Figure 2-12 (a) shows the changes of state of the air in the Mollier h-x diagram and (b) in a schematic diagram. For this purpose, the supply air as fresh air from ambient temperature needs to be conditioned to dryer inlet temperature (1 → 2 analogous to A1 → A2 in Figure 2-11). This is usually done directly by natural gas-fired air heaters or by steam. Then, a hot and relatively dry air flow (state 2) heats the product to evaporation temperature and transfers the necessary enthalpy of evaporation (2 → 3).

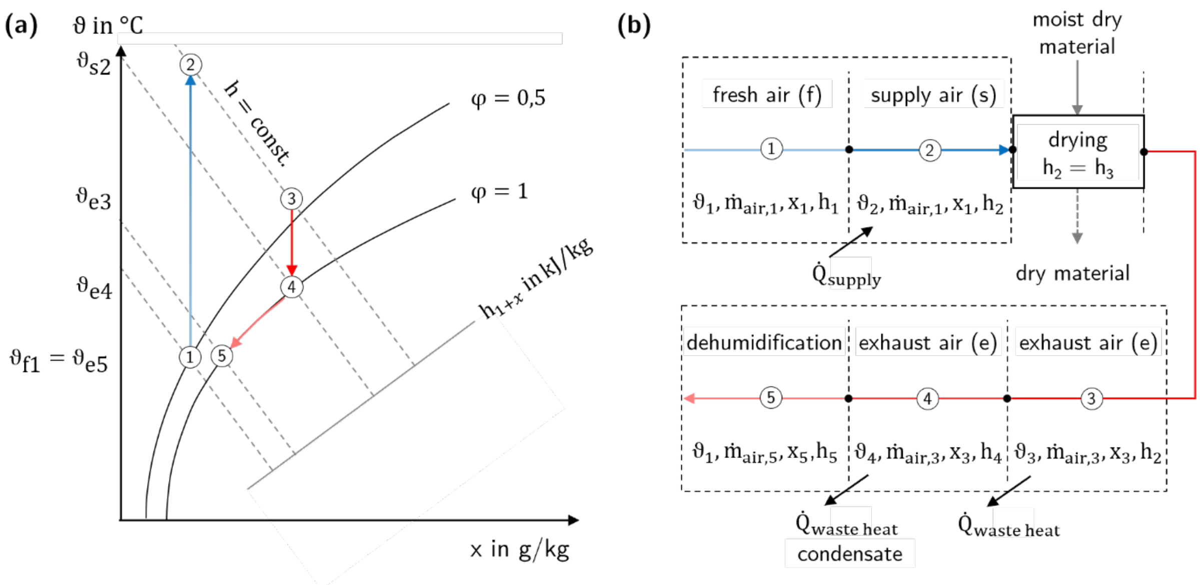



*Figure 2-12: Changes of the state of air in a convective drying process: conditioning of the supply air (1→2), drying according to the principle of adiabatic humidification (2→3) and cooling (3→4) and condensation of the humid exhaust air (4→5) in the Mollier h,x diagram (a) and in the schematic diagram (b)* [26]

In order to maintain the driving partial pressure gradient between dry air and moist product in the operation, the humid exhaust air (A8) must be continuously discharged and replaced by fresh air. For this purpose, parts of the sensible heat and latent evaporation enthalpy are recovered, by cooling (3→4) and dehumidifying (4→5) the moist exhaust air.

Milk, cheese and coffee powder are common drying products in spray towers [27]. In 2018, nearly 2,500 thousand tonnes of milk powder were produced worldwide [28]. Based on the states of drying air and drying product and their changes according to Figure 2-12, the thermal streams of the supply and exhaust air of the different products can be described as follows.

*Table 2-4: Stream table for spray dryer of milk powder according to* [29] *based on case study data by* [30]

| Stream | $\vartheta_{in}$ in °C | $\vartheta_t$ in °C | $CP$ in kW/K |
|---|---|---|---|
| A1-A2 | 11 | 210 | 57.9 |
| $A8_3$ -$A8_4$ | 73 | 31.0 | 70.1 |
| $A8_4$-$A8_5$ | 31.0 | 11 | 237.2 |
| P1-P2 | 52 | 75 | 10.2 |

*Table 2-5: Stream table for spray dryer of cheese powder according to* [29] *based on case study data by* [31]

| Stream | $\vartheta_{in}$ in °C | $\vartheta_t$ in °C | $CP$ in kW/K |
|---|---|---|---|
| A1-A2 | 11 | 200 | 54.7 |
| $A8_3$ -$A8_4$ | 80 | 34.9 | 71.7 |
| $A8_4$-$A8_5$ | 34.9 | 11 | 263.5 |

*Table 2-6: Stream table for spray dryer of coffee powder according to* [29] *based on case study data by* [25]

| Stream | $\vartheta_{in}$ in °C | $\vartheta_t$ in °C | $CP$ in kW/K |
|---|---|---|---|
| A1-A2 | 11 | 210 | 57.9 |
| $A8_3$ -$A8_4$ | 110 | 35.7 | 69.0 |
| $A8_4$-$A8_5$ | 35.7 | 11 | 267.2 |

*Table 2-7: Stream table for spray dryer of starch according to* [32]

| Stream | $\vartheta_{in}$ in °C | $\vartheta_t$ in °C | $CP$ in kW/K |
|---|---|---|---|
| A1-A2 | 13 | 160 | 54.4 |
| $A8_3$ -$A8_4$ | 52 | 37.8 | 58.3 |
| $A8_4$-$A8_5$ | 37.8 | 13 | 240.3 |

In the following, the process requirements for milk and starch spray drying are shown as an example. Different modelling depths can be used for the representation. The GCCs shown in Figure 2-13 (a) and Figure 2-14 (a) represent the process requirements assuming all heat recovery potential is tapped. If product preheating or dry air preheating is not considered for technical or economic reasons, the thermal profiles of the heat sinks and sources are shown in Figure 2-13 (b) and Figure 2-14 (b).

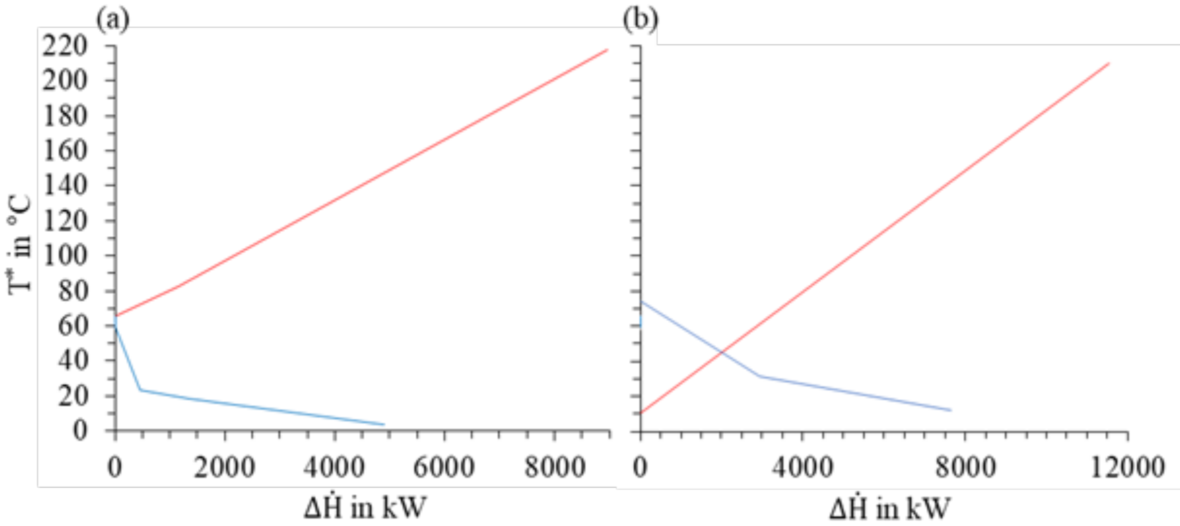



*Figure 2-13: (a) GCC and (b) sink and source profiles of milk spray drying based on case study data by* [30]

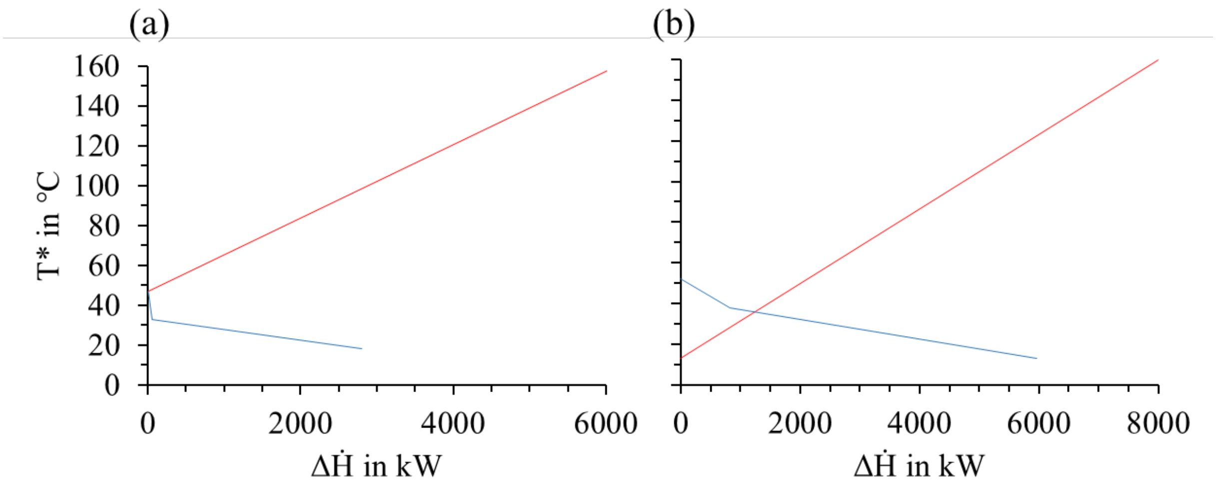



*Figure 2-14: (a) GCC and (b) sink and source profiles of starch spray drying based on* [32]

#### Integration concepts

Wilk et al. [32] shows how heat pumps, as a classic waste heat utilisation technology, uses the latent heat of the water in the humid exhaust air to preheat drying air (A1-A2) in continuous drying applications. The humid exhaust air (A8) from the drying processes, as shown in Figure 2-11, is suitable as a heat source for the evaporator of the heat pump. It can be integrated directly (Integration Concept A) into the process or indirectly via an intermediate cooling water cycle (Integration Concept B). Air as a heat transfer medium has a low heating capacity and density. In the temperature-load-diagram of industrial drying applications, these properties lead to large temperature changes with small net enthalpy flow changes. For these reasons, heat pump with a temperature glide are particularly suitable for supplying energy to drying processes. Three concepts are therefore suitable for heat pump applications and are described below: Cascade, transcritical, and Reversed Brayton heat pump cycles.

*Integration concept A: Air-to-air heat pump integration*

Due to the low overlapping temperature range of the heat source and heat sink as well as the low heating capacity of air, a heat recovery with additional heat exchangers reduces the economic efficiency of the heat pump. Therefore, Walmsley et al. [33] recommend operating an air-to-air heat pump as a sole waste heat recovery technology. The flow diagram of the concept is shown in Figure 2-15, and the specifications are reported in Table 2-8.

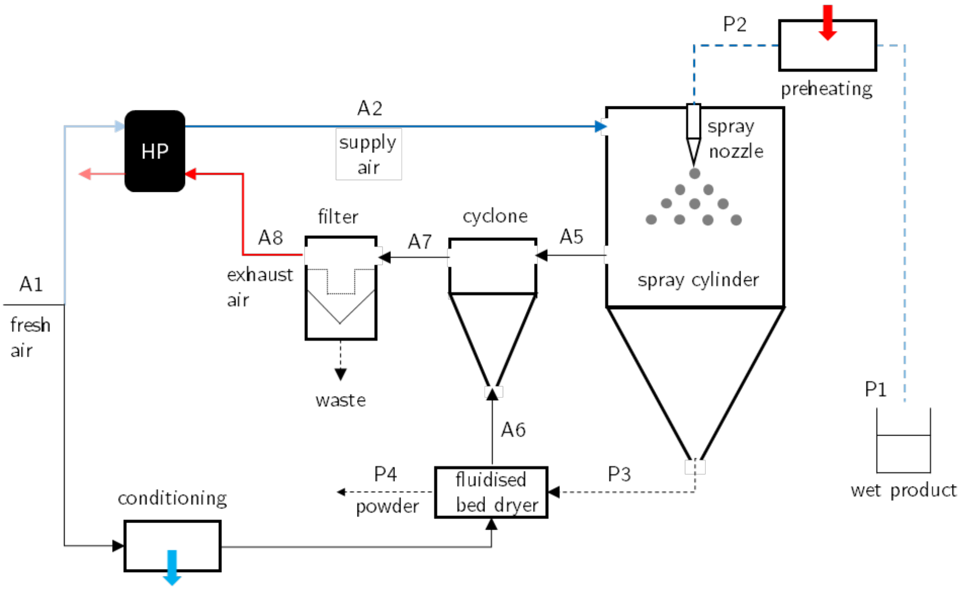



*Figure 2-15: Flow diagram of integration concept A (spray drying)* [26]

*Table 2-8: Overview of specifications for heat pump applications in Integration concept A (spray drying)*

| | |
|---|---|
| **Heat pump application I: Cascade heat pump cycle** | |
| **Heat Sink** | • $T_{in}$ = 64.3 °C → $T_{out}$ = 210 °C<br>• Air<br>• 1 – 10 MW |
| **Heat Source** | • $T_{in}$ = 50 °C → $T_{out}$ = 19.9 °C<br>• Air |
| **Comments** | • High performances possible (optimal selection of working fluids for different temperature ranges)<br>• No additional heat exchanger or intermediate cycle for clearer separation of the refrigerant cycle from the air flow.<br>• Flexible design offering optimal integration of heat recovery and supply at multiple temperatures.<br>• More expensive (depending on the complexity)<br>• More complex operability<br>• Maturity: Various commercial products up to 160 °C expected by 2023/2024, later up to 250 °C |
| **Heat Pump Application II: Transcritical cascade cycle** | |
| **Heat Sink** | • $T_{in}$ = 11 - 15 °C → $T_{out}$ = 200 – 210 °C<br>• Air<br>• 1 – 10 MW |
| **Heat Source** | • $T_{in}$ = 70 °C → $T_{out}$ = 11 - 15 °C<br>• Air |
| **Comments** | • Can utilize high-temperature glides efficiently.<br>• Limited performance for low temperature glides<br>• Compact and cost-effective installation |

| | |
|---|---|
| | • Fast regulating units<br>• Maturity:<br>  ○ R-744: Up to 120 °C demonstrated in MW scale.<br>  ○ R-744: Up to 150 °C above 10 MW demonstrated in the lab expected to be commercially available soon<br>  ○ Hydrocarbons/HFOs: Up to 200 °C demonstrated in lab expected to be commercially available by 2025 |
| **Heat Pump Application III: Reversed Brayton Cycle** | |
| **Heat Sink** | • $T_{in}$ = 64.3 °C → $T_{out}$ = 210 °C<br>• Air<br>• 1 – 10 MW |
| **Heat Source** | • $T_{in}$ = 50 °C → $T_{out}$ = 23 °C<br>• Air |
| **Comments** | • Natural refrigerant R-744<br>• Can utilize high temperature glides efficiently.<br>• Limited performance for low-temperature glides<br>• Includes use of expander technology |

*Integration concept B*

Kong et al. [34] proposed an intermediate cooling water circuit between the exhaust air stream and the fresh air intake or heat pump evaporator due to spatial distances. This can also be advantageous in the case of heavy contamination in the exhaust air.

Furthermore, depending on the type of heat pump available, a water intermediate circuit can also be provided on the sink side. This can be advantageous because the corresponding heat exchanger or condenser in the heat pump can be smaller and, in the event of a leak, no refrigerant can enter the airflow. However, an additional heat exchanger is then necessary. The flow diagram of the concept is shown in Figure 2-16, and the specifications are reported in Table 2-9.

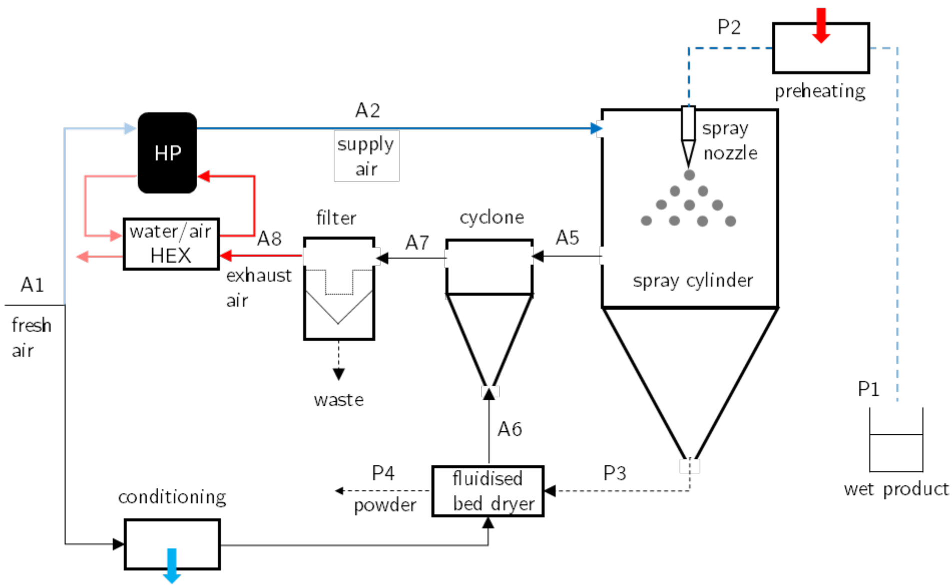



*Figure 2-16: Flow diagram of integration concept B (spray drying)* [35]

*Table 2-9: Overview of specifications for heat pump application in Integration concept B (spray drying)*

| **Heat pump application I: Cascade heat pump cycle** | |
|---|---|
| **Heat Sink** | • $T_{in}$ = 15 °C → $T_{out}$ = 200 - 210 °C<br>• Air<br>• 1 – 10 MW |
| **Heat Source** | • $T_{in}$ = 40 °C → $T_{out}$ = 12 °C<br>• Water |
| **Comments** | • High performances possible (optimal selection of working fluids for different temperature ranges)<br>• Also possible with an intermediate water cycle on the heat pump sink to separate the refrigerant cycle more clearly from the air flow<br>• Flexible design offering optimal integration of heat recovery and supply at multiple temperatures<br>• More expensive (depending on the complexity)<br>• More complex operability<br>• Maturity: Various commercial products up to 160 °C expected by 2023/2024, later up to 250 °C |
| **Heat Pump Application II: Transcritical cascade cycle** | |
| **Heat Sink** | • $T_{in}$ = 11- 15 °C → $T_{out}$ = 200 - 210 °C<br>• Air<br>• 1 – 10 MW |
| **Heat Source** | • $T_{in}$ = 40 °C → $T_{out}$ = 12 °C<br>• Water |
| **Comments** | • Can utilize high temperature glides efficiently<br>• Limited performance for low temperature glides<br>• Compact and cost-effective installation<br>• Fast regulating units<br>• Maturity:<br>  ○ R-744: Up to 120 °C demonstrated in MW scale<br>  ○ R-744: Up to 150 °C above 10 MW demonstrated in lab expected to be commercially available by 2023<br>  ○ Hydrocarbons/HFOs: Up to 200 °C demonstrated in lab expected to be commercially available by 2025 |
| **Heat Pump Application III: Reversed Brayton Cycle** | |
| **Heat Sink** | • $T_{in}$ = 64.3 °C → $T_{out}$ = 210 °C<br>• Air<br>• 1 – 10 MW |
| **Heat Source** | • $T_{in}$ = 40 °C → $T_{out}$ = 12 °C<br>• Water |
| **Comments** | • Natural refrigerant with R-744<br>• Can utilize high temperature glides efficiently |

| | |
|---|---|
| | • Limited performance for low temperature glides<br>• Includes use of expander technology |

### 2.1.4. Batch sterilization

#### Process description

Batch retort sterilization, or commercial sterilization in discontinuous retorts, has been the most used procedure in canning plants since the 1930s [36]. Its versatile thermal process allows the commercial sterilization of several products ranging from meats and sausages over baby food and ready-to-serve dishes to fruits and vegetables. Usually, the product is filled in metal cans or retortable pouches, whereas glass jars are less common.

Figure 2-17 presents a typical retort with a conventional energy supply. The retort is supplied with steam to achieve the necessary temperature for sterility and conservation. The processing temperature required to inactivate all forms of microorganisms ranges between 104 to 130 °C [36]. Processing temperature and time are individual for each product and the type of sterilizer used. After the holding time, the sterilized goods are cooled to less than 40 °C with cooling water. Process steam is the main thermal energy consumer, often produced with fossil-fired steam boilers [37].

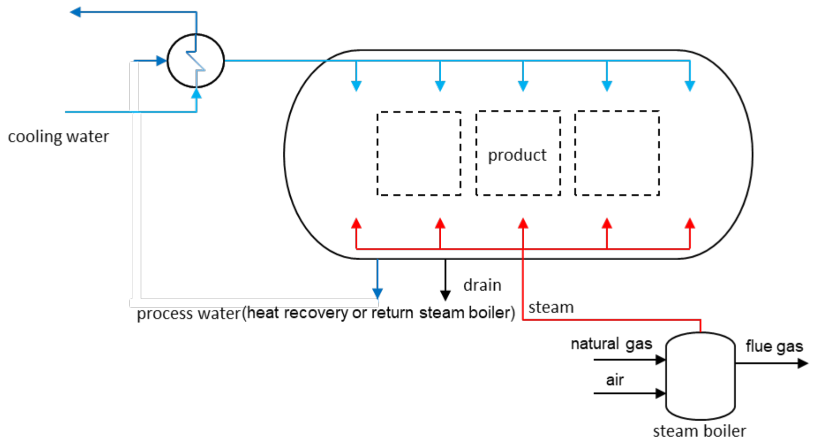



*Figure 2-17: Process flow diagram of a typical batch retort sterilization with a conventional energy supply, adapted from* [38]

As displayed in Figure 2, the highest energy/heating demand occurs during heating the retort and its contents to process temperature (~120 °C), also referred to as CUT (Come-Up-Time), which can range from 2 to 6 hours [39]. This requires injection of steam at about 130 °C. Steam demand is significantly lower during the holding phase, usually 20 to 60 minutes, according to [22]. During cooling, which takes 4 to 10 hours [39], the product temperature is reduced from sterilization to below 40 °C. Here, water is injected into the retort. Warm water of about 80 °C is obtained as a by-product of the cooling stage. This can be used as a heat source. As the process is not continuous but a batch process and heating and cooling demand are separated in time, the energy recovery potential can only be exploited by integrating thermal energy storage (TES) into the concept.

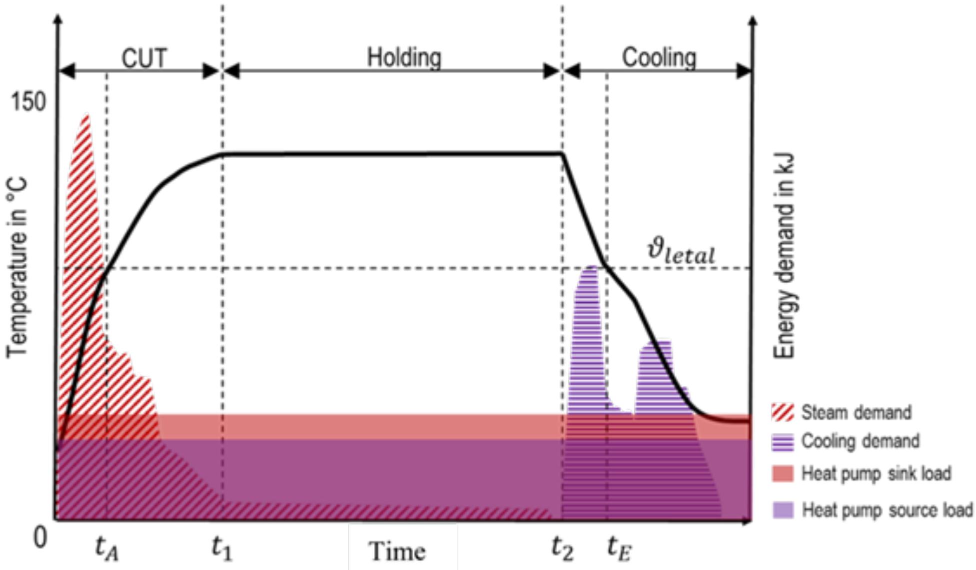



*Figure 2-18: Temperature-time-profile and corresponding energy demand for heat and cooling* [40]

The following are the process requirements of a batch retort sterilization process for pet food pouches. The GCC represents the process requirements, assuming that the cooling water obtained after cooling is the sole heat source. Steam is provided at a temperature of above 130 °C.

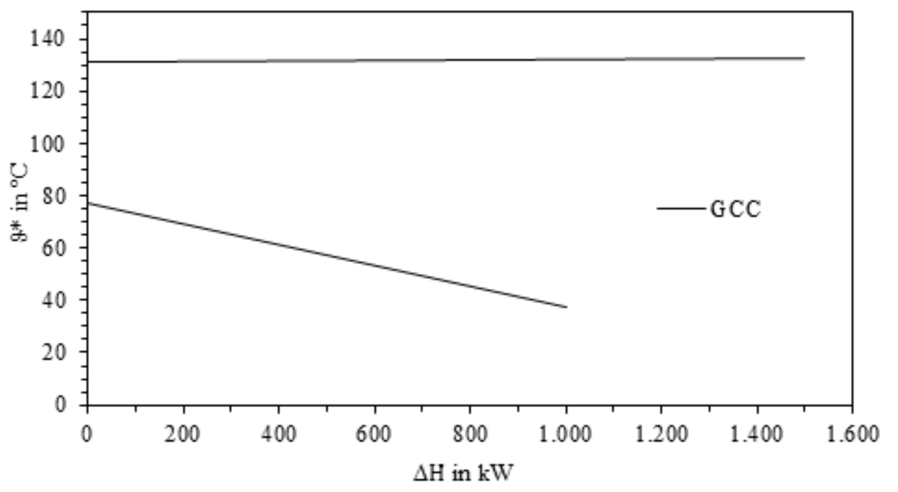



*Figure 2-19: GCC of batch Retort sterilization* [41]

### Integration concepts

Hot water is a suitable heat source after cooling mixed with condensate. Water can either be transferred directly to a flash tank or serve as a heat source for the heat pump's evaporator or the evaporator on its own. In each integration concept, a steam accumulator and/or two water storages need to be included due to the non-continuous nature of the process. Due to high flow rates and high temperature lift, several compression stages might be required.

For steam generation, MVRs or a combination of HTHP, flash tank/evaporator and MVR are predominantly used. CCHP applications are often less economically viable due to high-temperature differences between heat source and sink. Wilk et al. [42] state that steam recompression is the most efficient for generating steam between 2 and 5 bar. Conceivable heat pump applications are cascade, transcritical, reversed Brayton and MVR concepts.

*Integration concept A: High-pressure water production*

This integration concept revolves around the sterilization of dairy products in both glass bottles and aluminum cans. The project seeks to replace a gas burner with a HP and deliver high-pressure water at 150 °C, meaning no steam is generated.

Figure 2-20 illustrates that a hot buffer tank is placed between the HP and the retorts to deliver the high peak heat load seen during heating. A high mass flow is drawn from the buffer tank during the retort heating, while a continuous, low mass flow flows through the HP sink to provide a constant load on the HP and to fill the buffer tank for the next heating run. Similarly, on the source side, a large mass flow is drawn from the tank during cooling, and a smaller flow is continually fed to the HP source.

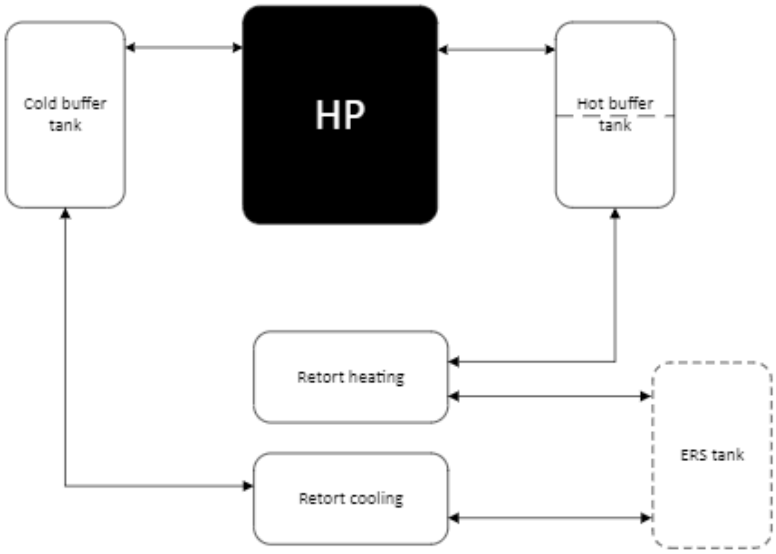



*Figure 2-20: Flow diagram of integration concept A (batch sterilization)*

To improve performance, the buffer tank on the hot side is separated into two tanks such that colder return water is not mixed with the 150 °C water. The best performance can be had when the return temperature on the hot side is as low as possible, which means the heat pump experiences the largest temperature glide in the sink.

Smaller improvements are made when increasing the cold buffer temperature, as $CO_2$ reaches its critical temperature at around 30 °C—going above this temperature on the source side results in a purely supercritical gas cycle (Reversed Brayton), which can be quite complex to deal with, especially concerning achieving the correct filling level.

Besides the HP, an energy recovery system (ERS) has been discussed, as this yields energy savings at no meaningful extra operating costs. The issue is that the ERS replaces the heating at the coldest temperatures, meaning that the hot buffer tank will receive higher average return temperatures. This results in the HP experiencing a smaller temperature glide and, thus, a worse COP. Adding an ERS thus depends on whether the reduced COP sufficiently makes up for energy savings.

The HP integration for this project is under-dimensioned, as the full demand for all autoclaves is around 4 times larger than what the HP will deliver. The existing gas burners will provide the rest of the heating.

*Table 2-10: Overview of specifications for heat pump application in Integration concept A (batch sterilization)*

| **Heat Pump Application A** | |
|---|---|
| Heat Sink | • $T_{in}$ = 90-100 °C → $T_{out}$ = 150 °C<br>• Water: 7 t/h<br>• 500 kW of heating |

| | |
|---|---|
| Heat Source | • $T_{in}$ = 40 °C → $T_{out}$ = 20 °C<br>• Water: 11 t/h |
| Comments | • Transcritical R744 HP<br>• 10 bar(a) hot buffer tank (liquid water at 150 °C)<br>• 1 bar(a) cold buffer tank |

*Integration concept B: Steam generation*

Steam is generated in the second integration concept (Figure 2-21).

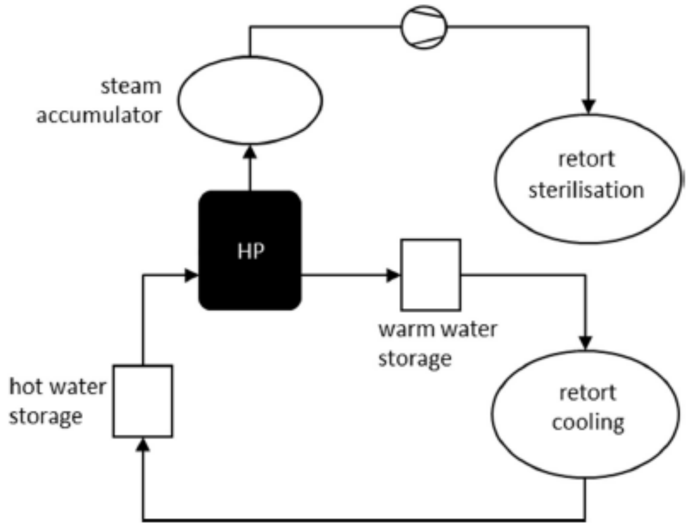



*Figure 2-21. Flow diagram of integration concept B (batch sterilization)*

During the cooling time of the first sterilization cycle, the cooling water is collected in the hot water storage at 80 °C. The 58 t/h of cooling water is divided in a low-pressure flash vessel to a share of 2.4 t/h of low-pressure vapor at a temperature of 52 °C and 55.6 t/h warm water at the same temperature level collected in the warm water storage for any other heat recovery purposes. The vapor gets compressed by several MVR units up to a suitable temperature level for sterilization. During the CUT, the filled steam accumulator is getting emptied. Additionally, the heat pump directly supplies the process. In the holding time, the heat pump supplies both the process and the steam accumulator until the steam accumulator is filled again. Afterward, the cooling period occurs again to collect the source in the hot water storage. In addition to reducing steam consumption, the steam generating HTHPs also reduce cooling water demand, decreasing the overall energy consumption on site.

*Table 2-11: Overview of specifications for heat pump application in Integration concept B (batch sterilization)*

| **Heat Pump Application B** | |
|---|---|
| Heat Sink | • $T_{in}$ = 80 °C → $T_{out}$ = 130 °C<br>• Steam: 2.4 t/h |
| Heat Source | • $T_{in}$ = 80 °C → $T_{out}$ = 52 °C<br>• Water: 58 (55.6) t/h |
| Comments | • Low-pressure flash tank + MVR<br>• Medium-pressure steam accumulator |

### 2.1.5. Anodizing

#### Process description

Electroplating processes are suitable for implementing heat recovery and integrating heat pumps due to the close temporal and spatial occurrence of heat sources and heat sinks with different temperature requirements. Similarly, energy costs account for a high proportion of turnover due to the high energy intensity. The widespread processes of zinc and CuNiCr coating have application potential but are not in the targeted temperature range > 100 °C. On the other hand, the anodizing process combines all requirements and offers the potential for heat recovery and heat pumps.

Galvanic processes consist of three steps shown in Figure 2-22: pre-treatment, main treatment (characteristic metal deposition), and post-treatment. Instead of metal deposition, the main process of the anodizing process is the anodic oxidation of the metal itself. As part of the pre-treatment, the workpieces are cleaned from grease, oil, and other residues of the manufacturing process in acidic or caustic degreasing baths. Subsequently, the workpiece is treated in a gloss bath, which increases the degree of reflection using strong acids. This process requires the setting of an electric field. The main process consists of the oxidation of the aluminum to strengthen the oxidation layer. The workpiece is immersed in a bath composed of a weak to strong acid, which acts as an electrolyte. At the same time, the workpiece serves as the anode and the bath as the cathode. By setting a weak electric current, oxygen formation on the workpiece's surface is caused. After the main process, dyeing is carried out as an additional protection against environmental influences by immersion in inorganic substances. The subsequent condensing process aims to prevent the inclusion of corrosion-promoting substances by closing the pores with hot water or steam. Between the treatments, the workpieces are rinsed and cleaned of residues in rinsing baths. The illustration shows an excerpt of the process schematic with a typical energy supply system. Typically, steam is the energy carrier medium in the inventory, which can hinder heat recovery and pumping due to the specific heat exchangers.

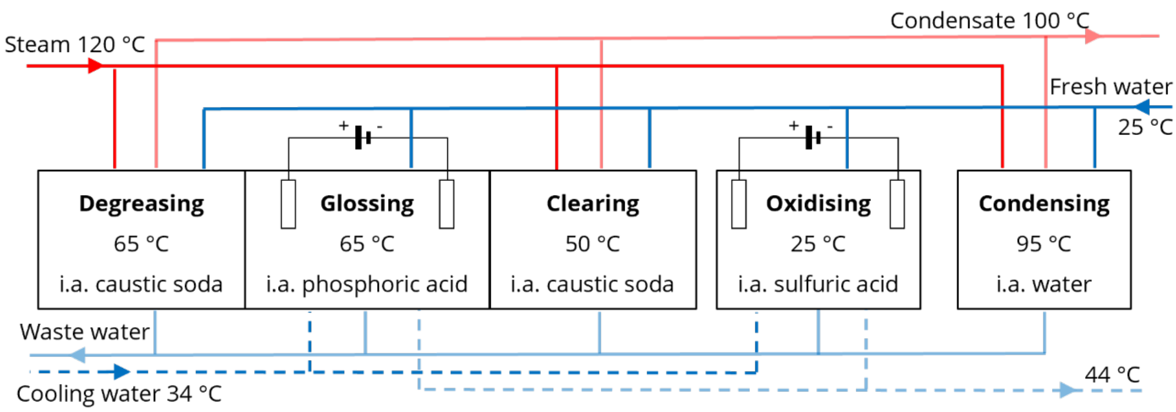



*Figure 2-22: Process flow diagram of a typical anodizing process* [43]

The existing process conditions, which are based on steam, among other things, are masked out for the energy demand modeling. The data come from an anodizing process of a medium-sized company. Several baths with the same process requirements are combined into one demand for simplification. In addition, the wastewater and freshwater supply flows are considered soft streams in the energy demand modeling.

The GCC in Figure 2-23 show the integration potential for smaller heat pumps to cover the demand for the degreasing bath. If a higher coverage rate needs to be achieved, the temperature lift increases, and the COP decreases.

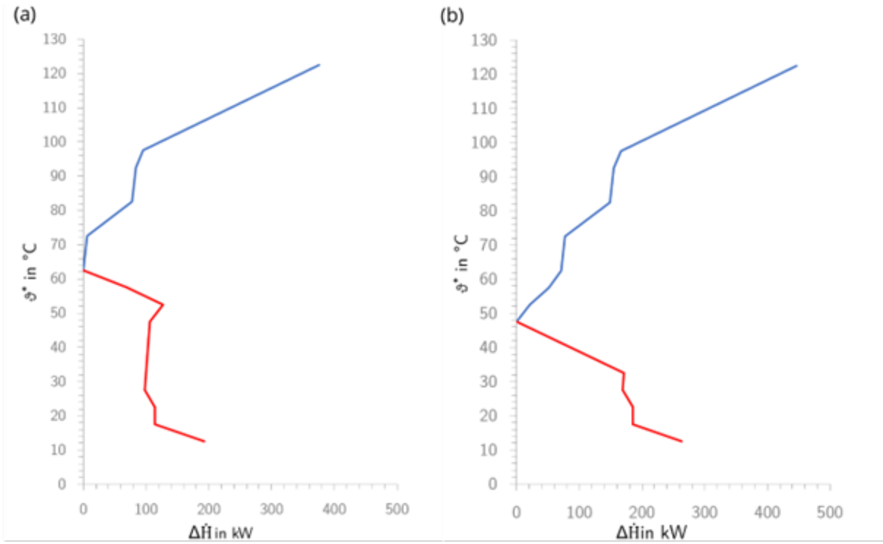



*Figure 2-23: GCC of anodizing process modeled by (a) white box approach and by (b) grey box approach* [44]

### Integration concepts

Two approaches are possible according to which heat recovery measure is used. The white box approach uses the acidic process medium to preheat the fresh water. In contrast, the grey box approach integrated it into the existing intermediate cycle to separate the systems for safety reasons. In both concepts, the discontinuously occurring wastewater from the condensing bath is collected in a thermal tank and is used for further freshwater heating if required. The heat source of the heat pump is the remaining wastewater, as well as, optionally, the cooling demand from the cooling of the glossing bath. Steam can be generated depending on the heat pump. This would have the advantage that the existing steam heat exchangers would not have to be replaced. In addition, cascaded heat pump concepts for supply of different temperature levels are also conceivable (cf. Figure 2-23).

Ultimately, the question of which concept to choose is an economic one. According to the white-box approach, the integration concept has a higher heat recovery potential and better heat pump efficiency. However, there may be higher costs for durable heat transfer equipment. In both concepts, the main process of oxidation is energetically irrelevant and, therefore, greyed out.

#### *Integration concept A: White-box (direct heat transfer)*

According to the white box model depicted in Figure 2-24, the heat recovery potential is higher due to the direct heat transfer between the process medium of the glossing bath and the fresh water. The pinch temperature is also higher in this example, which results in a lower temperature lift and better efficiency for the heat pump. Due to the direct heat recovery between the process medium of the glossing and the fresh water, the freshwater can be heated to 60 °C and later further to 82 °C using waste heat from the wastewater. The resulting temperature level of the heat source for the heat pump is then between 50 and 65 °C, depending on the demand.

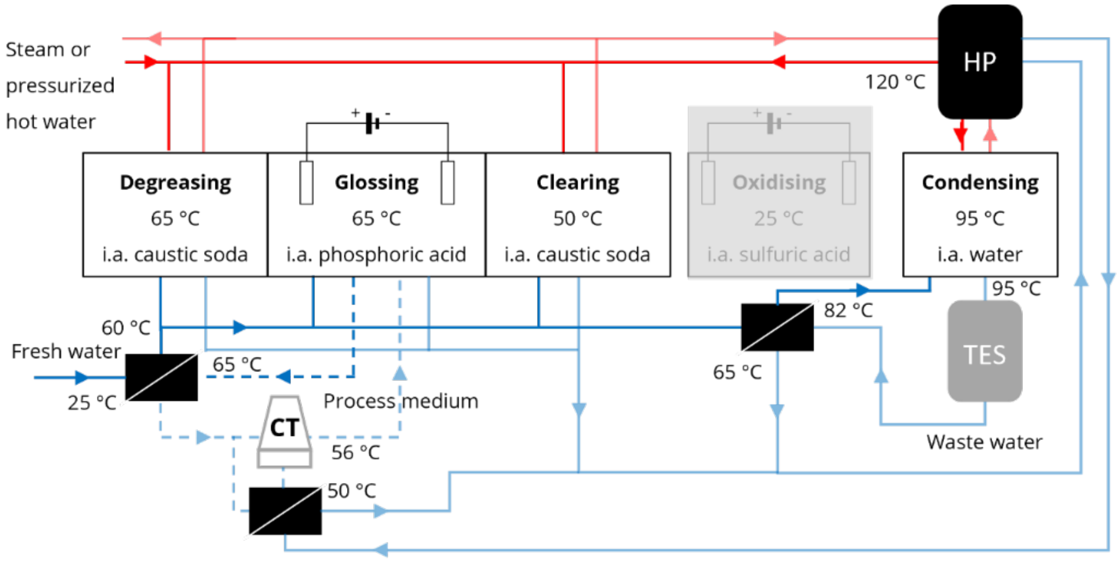



*Figure 2-24: Flow diagram of integration concept A (anodizing) [44]*

Each integration concept can include one or more heat pump applications. The fact box in Table 2-12 provides an overview of the main specifications of each heat pump application for integration concept A.

*Table 2-12: Overview of specifications for heat pump application in Integration concept A (anodizing)*

| **Heat Pump Application I** | |
|---|---|
| Heat Sink | • $T_{in}$ = 82 °C → $T_{out}$ = 95 °C<br>• Freshwater heating for condensing bath, hot water heating for degreasing and clearing bath<br>• 130 kW |
| Heat Source | • $T_{in}$ = 60 °C → $T_{out}$ = 50 °C<br>• Water from the cooling of glossing bath and wastewater<br>• 65 kW |
| Comments | • Single-stage HP<br>• Discontinuous wastewater occurrence requires TES.<br>• Freshwater is supplied continuously.<br>• Acid-resistant heat exchanger equipment<br>• Back-up boiler and cooling tower<br>• Optional space heating preheating |
| **Heat Pump Application II** | |
| Heat Sink | • $T_{in}$ = 110 °C → $T_{out}$ = 120 °C<br>• Steam for heating of condensing, degreasing and clearing bathes<br>• 330 kW |
| Heat Source | • $T_{in}$ = 20 °C → $T_{out}$ = 15 °C<br>• Water from the cooling of glossing and oxidising bath and wastewater<br>• 180 kW |
| Comments | • Cascade HP<br>• Discontinuous wastewater occurrence requires TES |

| | |
|---|---|
| | • Fresh water is supplied continuously<br>• Back-up boiler and cooling tower<br>• Optional space heating preheating |

*Integration concept B: Grey-box (intermediate circuit)*

Due to the lower heat recovery potential for the Grey-box approach, a larger heat pump for heating the degreasing tank below 100 °C is conceivable according to Figure 2-25.

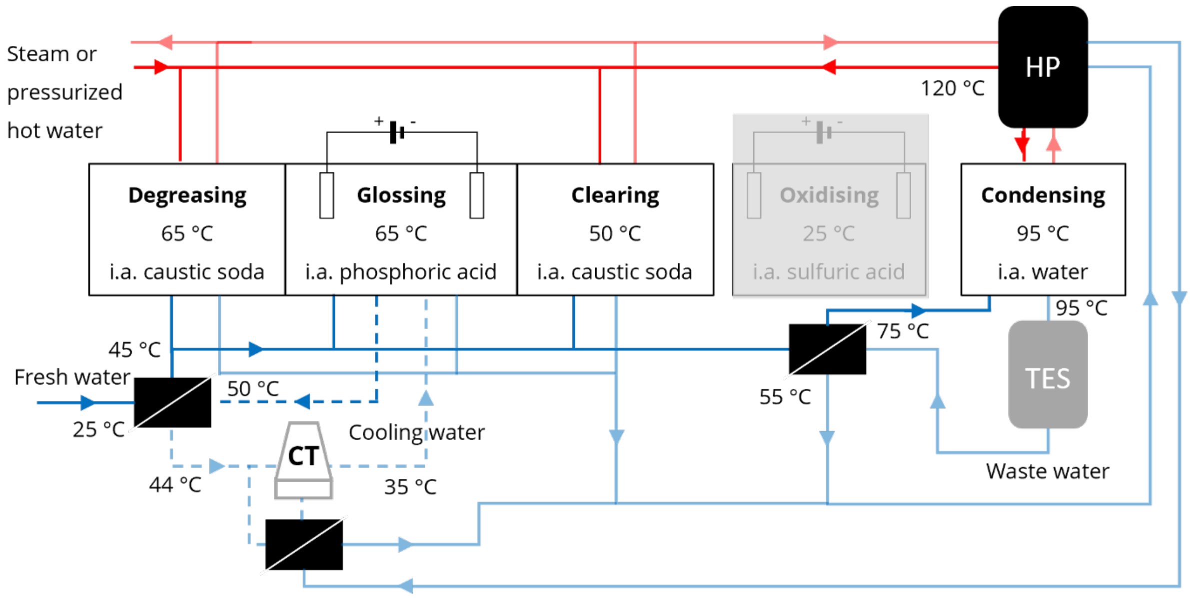



*Figure 2-25: Flow diagram of integration concept B (anodizing) [44]*

If the condensing process is added, the temperature lift increases due to the low pinch temperature, and the course of the GCC, and the COP is lower in comparison with concept A. The intermediate circuit reduces the achievable temperature level of the freshwater preheating due to the additional required driving temperature gradient. This slightly increases the usable potential of the wastewater heat recovery. However, the temperature level of the heat source of the heat pump decreases.

*Table 2-13: Overview of specifications for heat pump application in Integration concept B (anodizing)*

| **Heat Pump Application I** | |
|---|---|
| Heat Sink | • $T_{in}$ = 80 °C → $T_{out}$ = 85 °C<br>• Degreasing, clearing bath, fresh water heating<br>• 150 kW |
| Heat Source | • $T_{in}$ = 40 °C → $T_{out}$ = 35 °C<br>• water from cooling of glossing bath and wastewater<br>• 115 kW |
| Comments | • Single-stage HP<br>• Discontinuous wastewater occurrence requires TES<br>• Fresh water is supplied continuously.<br>• Acid-resistant heat exchanger equipment<br>• Back-up boiler and cooling tower<br>• Optional space heating preheating |

| Heat Pump Application II | |
|---|---|
| Heat Sink | • $T_{in}$ = 95 - 110 °C → $T_{out}$ = 110 – 120 °C<br>• Steam for heating of condensing, degreasing and clearing bathes<br>• 165 - 370 kW |
| Heat Source | • $T_{in}$ = 40 - 25 °C → $T_{out}$ = 35 - 20 °C<br>• Water from the cooling of glossing bath and wastewater<br>• 120 - 185 kW |
| Comments | • Cascade HP<br>• Discontinuous wastewater occurrence requires TES<br>• Fresh water is supplied continuously.<br>• Back-up boiler and cooling tower<br>• Optional space heating preheating |

### 2.1.6. Automotive paint drying

#### Process description

Modern car coatings consist of multiple paint layers applied to the car body via cathodic electrodeposition (CED or 'e-coating') or spraying. The multi-layer paint structure applied to cars is illustrated in Figure 2-26, which shows the structure of modern car coatings. After each paint layer is used, the car body is dried in specialized ovens. The temperature of these ovens can range from 60 to 200 °C, based on the specific composition of the paint. Once the drying process is complete, the car bodies are moved to cooling zones, allowing them to cool down before proceeding to the next production stage. The painting process is one of the most energy-intensive production steps during automotive production, accounting for over one-third of an automotive production plant's total energy demand [45].

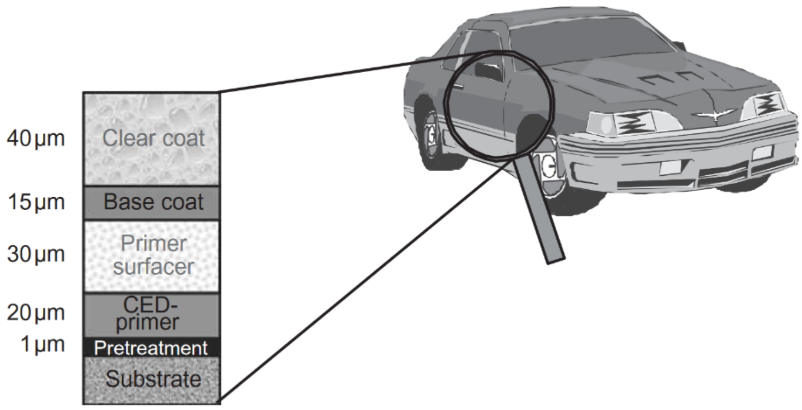



*Figure 2-26: Multilayer coating of cars* [46]

Figure 2-27 depicts the typical structure of an automotive paint drying process. The painted cars are transported to the drying ovens via conveyor belts. During the drying process, volatile organic compounds (VOC) are released into the drying air. Polluted air is collected from all drying ovens and routed to a thermal oxidizer where the VOC are removed from the air via gas-fired combustion. The thermal oxidizer exhaust gas reaches temperatures exceeding 200 °C, making it a significant source of heat within the paint shop. This heat source is also harnessed to support other processes in the paint shop, thereby reducing the overall energy consumption of the facility.

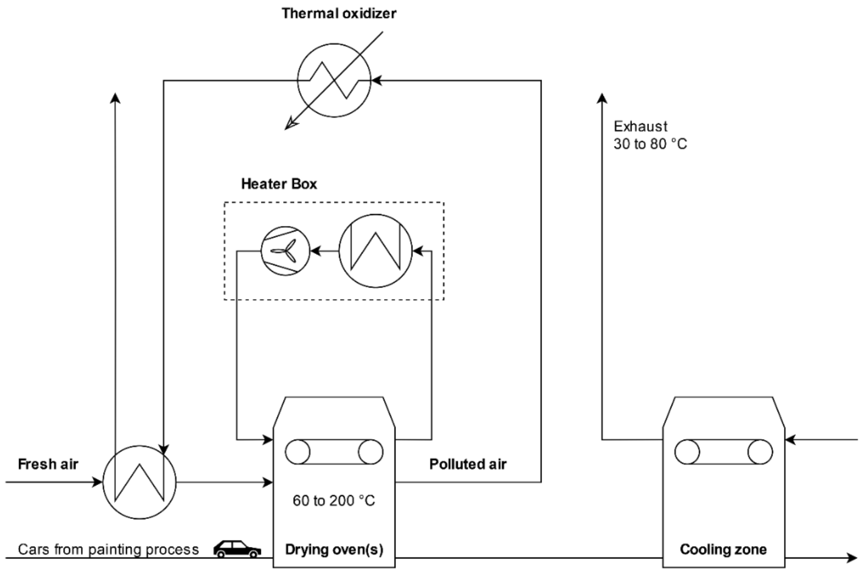



*Figure 2-27: Typical automotive drying oven setup.*

Figure 2-28 illustrates the composite curves of an automotive paint shop, including drying ovens, pretreatment, and heating and cooling demands of the HVAC systems. It is noteworthy that the ambient weather conditions highly influence the composite curves, as the HVAC systems play a crucial role in the overall energy consumption of the paint shop. From the data presented in Figure 2-28, it is evident that there are no significant heat sources within the paint shop to raise the temperature above 100 °C using heat pumps.

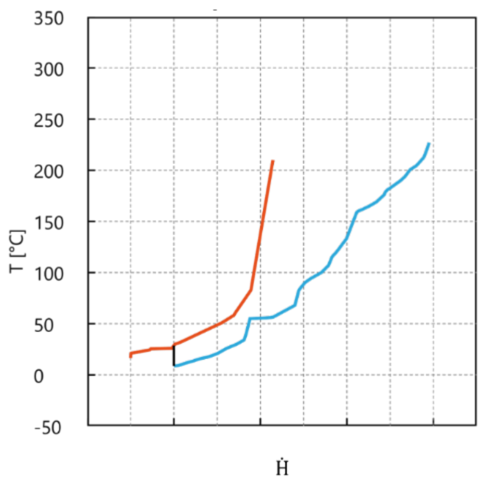



*Figure 2-28: Exemplary composite curves of an automotive paint shop*

An automotive paint shop typically operates for approximately 5000 to 7000 hours per year. Production downtimes are due to scheduled maintenance of the facility. Figure 2-29 shows a drying oven load profile over a week. The drying ovens have a load profile with an initial peak load during start-up and a lower working point for most of their operation. This presents a challenge to the heating system design as the system must be designed to handle the peak load.

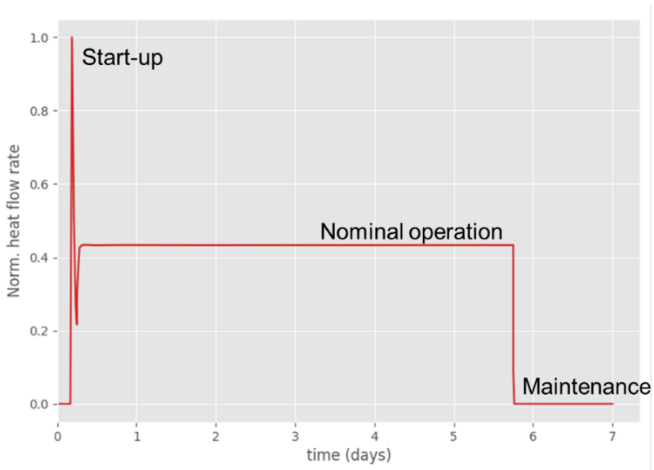



*Figure 2-29: Typical load profile of an automotive paint drying oven*

### Integration concept

This integration concept aims to supply a drying oven with heat using a high-temperature heat pump. Figure 2-30 shows a draft of the concept. The heat source consists of a constant airflow at 28 °C, which needs to be cooled down to a target temperature of 22 °C. The heat pump harnesses this heat source to generate temperatures exceeding 150 °C, which is necessary in a high-temperature drying oven. The heat pump is anticipated to fully meet the cooling requirement while providing much of the required heat.

The dryer is a multi-zone oven where each zone may have different temperatures and heat demands as the car bodies enter the zones in sequence. The drying ovens will have a load profile as shown in Figure 2-30. Consequently, the system will require either thermal energy storage or supplementary heaters to provide heat during plant start-up.

The working media and thermodynamic cycle of the heat pump are yet to be determined. Due to the high temperature at the heat sink, the heat pump will necessitate novel heat pump cycles or working media.

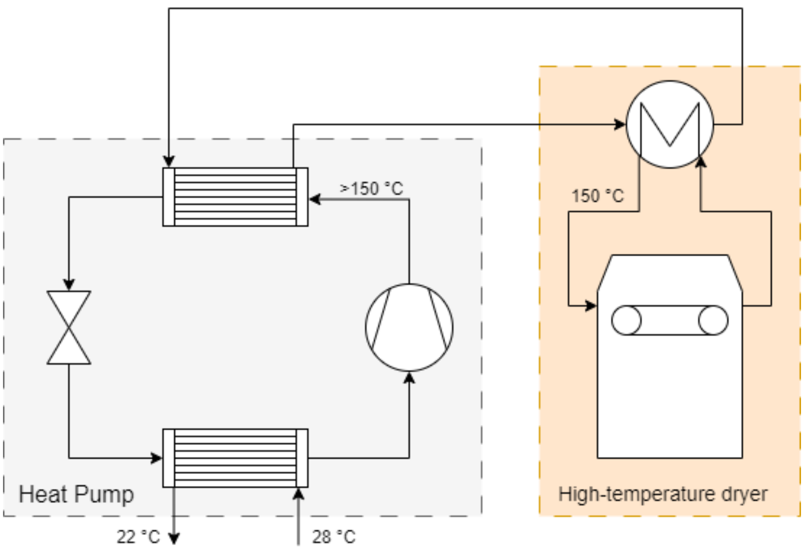



*Figure 2-30: Flow diagram of integration concept A (automotive paint drying)*

### Fact box

*Table 2-14: Overview of specifications for heat pump application in Integration concept A (automotive paint drying)*

| **Heat Pump Application I** | |
|---|---|
| **Heat Sink** | • High-temperature dryer:<br>• Multi-zone dryer: Each zone has similar temperatures, but different heat demands.<br>• $T_{in}$ = 130-140 °C → $T_{out}$ > 150 °C<br>• Liquid heat transfer medium |
| **Heat Source** | • $T_{in}$ = 28 °C → $T_{out}$ = 22 °C<br>• Moist air |
| **Comments** | • High peak heat demand is expected during start-up, usually 2-4 times the nominal load |

## 2.1.7. Brick drying

### Process description

Brick production is divided into six steps from raw material to the finished product as shown in Figure 2-31. The first three steps consist of raw material processing and forming of the so-called "green bricks". The fourth step is drying. Subsequently, the bricks are fired in step 5 before they are packed in the last step. Thermal energy is required for both drying and firing, with drying being the most energy-intensive process [47].

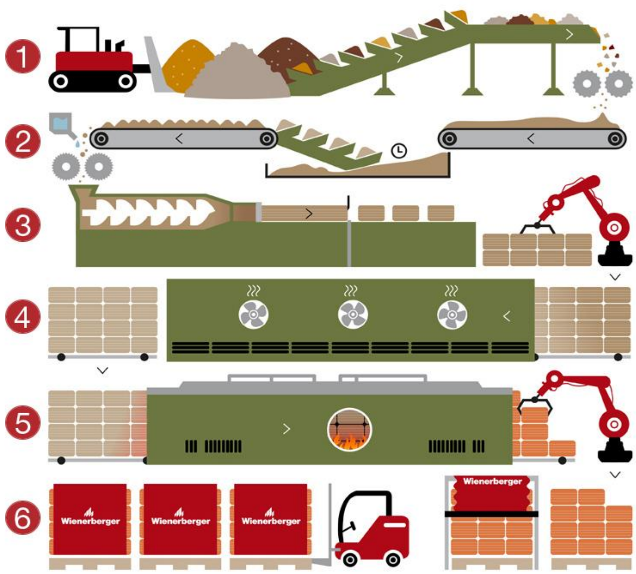



*Figure 2-31: Brick production at Wienerberger (1: Raw material mining, 2: Processing, 3: Forming, 4: Drying, 5: Firing, 6: Packing)* [48][47]

So far, mainly fossil-fired convective air dryers have been used for brick drying, with the evaporated water from the product being discharged via the exhaust air and often not being used for further energy recovery. The moist exhaust air from convective drying has dew points in the range of 30 to 65 °C. [49]

Figure 2-32 shows an example of a Wienerberger brick drying system as a combination of tunnel kiln and tunnel dryer. Air is used as drying agent that flows counter-currently to the bricks. Hot air from the kiln is used for the tunnel dryer and, if required, hot air produced by natural gas burning is added. The temperature in the tunnel dryer decreases over the length of the dryer. The tunnel dryer is continuously operated. Bricks enter the dryer with 28 % moisture and are dried to 2 %. By integrating a heat pump, the moist exhaust air can be used as a heat source and to recover the energy for drying. [50]

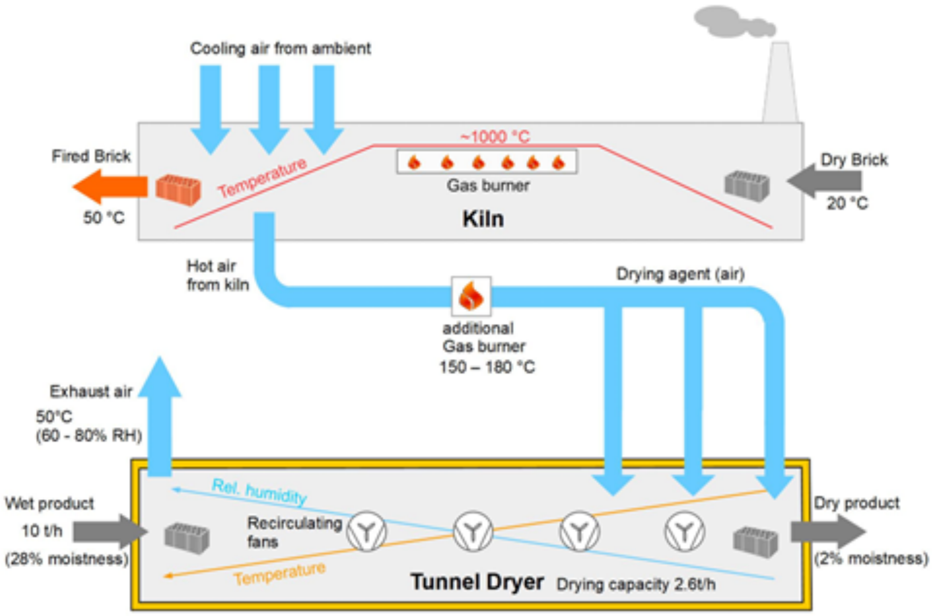



*Figure 2-32: Brick drying system as a combination between tunnel kiln and tunnel dryer, according to* [50], [51]

### Integration concepts

This document presents two heat pump integration concepts for supplying the tunnel dryer by using its waste heat. The drying process is a continuous process, whereby waste heat is generally available when the dryer is in operation and thus the heating requirement occurs. The required temperature level in the dryer depends on the product but also on the targeted drying rate and the length of the dryer. If the drying temperature is to be reduced, the length of the dryer must be extended accordingly, or the product rate reduced to achieve the same dehumidification. Currently, the exhaust air from the kiln is used to supply the dryer and, if necessary, the air is heated further. This additional heating is currently done using gas burners. It can be assumed that the kiln will also be decarbonized in the future and will influence the waste heat available for the dryer. This is considered in the integration concepts presented below.

*Integration concept A. Single heat pump application*

Figure 2-33 shows a schematic diagram of the heat pump integration concept A for the tunnel dryer. The heat pump recovers the energy from the exhaust air at approx. 50 °C and 60 – 80 % relative humidity (RH) and supplies the heat indirectly to the dryer by means of heating coils located inside the dryer [51]. In this concept, an intermediate circuit (water) is provided on both the source and sink sides. This concept allows to significantly reduce the air mass flow supplied to the dryer. The temperature of the supplied air mass flow can also be reduced compared to the current status, since it is no longer used solely for conditioning the entire dryer. This increases the efficiency of the dryer system. In this concept, the supply air can be provided by means of kiln waste heat or, if not sufficient, provided by external heat sources. A disadvantage of this concept is that the heating coils must be installed inside the dryer.

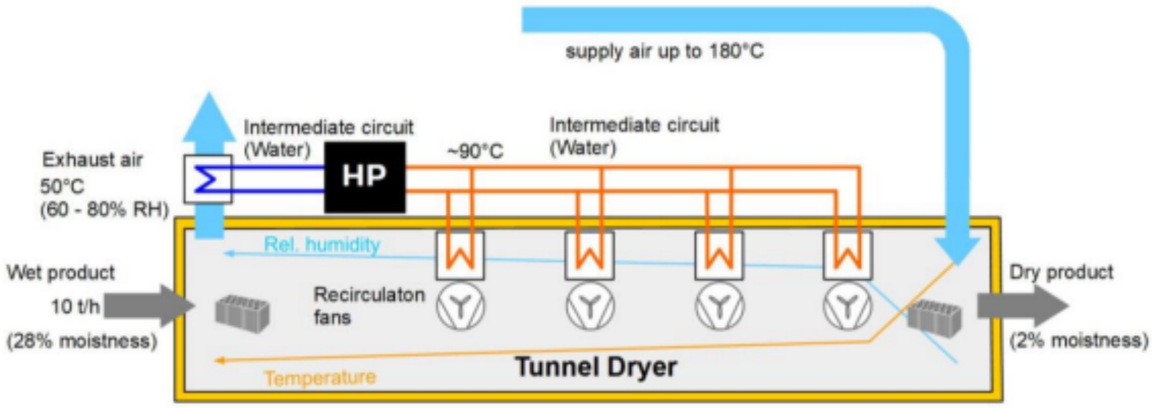



*Figure 2-33 Flow diagram of integration concept A (brick drying) (Source: AIT Austrian Institute of Technology GmbH)*

*Table 2-15: Overview of specifications for heat pump application in Integration concept A (brick drying)*

| **Heat Pump Application I** | |
|---|---|
| **Heat Sinks** | • $T_{out}$ = ~90 °C (depends on the targeted drying rate, actual dryer length and product throughput),<br>• Air (with water intermediate circuit ~90 °C) |
| **Heat Source** | • $T_{in}$ = ca. 50 °C and 60 – 80 % relative humidity (exhaust air),<br>• Exhaust air (with water intermediate circuit) |
| **Comments** | • The heating coils can be arranged both in parallel and in series depending on the required conditions inside the dryer |

*Integration concept B: Double heat pump application*

Figure 2-34 shows a schematic diagram of the heat pump integration concept B for the tunnel dryer. In this concept two heat pumps are applied. The first heat pump (HP 1) is integrated as described in integration concept A. The second heat pump (HP 2) is used to heat the supply air to the required temperature if there is not enough waste heat available from the kiln to ensure the supply air conditions. For this purpose, the second heat pump uses the intermediate circuit on the sink side of the first heat pump as a source. An intermediate circuit (water) can also be provided on the sink side of the second heat pump. This concept offers the possibility of providing the entire heating demand of the dryer by means of heat pumps. However, the COP of the heat pump decreases with increasing temperature level that must be provided by the heat pump to heat the supply air. In this concept, a lower COP of the entire heat pump concept is to be expected than in concept A.

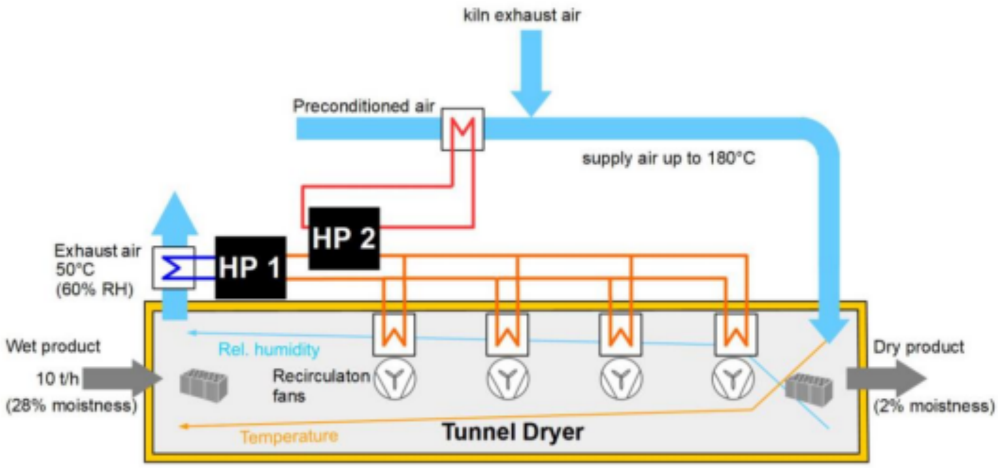



*Figure 2-34: Flow diagram of integration concept B (brick drying) (Source: AIT Austrian Institute of Technology GmbH)*

*Table 2-16: Overview of specifications for heat pump application in Integration concept B (brick drying)*

| **Heat Pump Application I: HP 1** | |
|---|---|
| **Heat Sink** | • $T_{out}$ = ~90 °C (depends on the targeted drying rate, actual dryer length and product throughput)<br>• Air (with water intermediate circuit ~90 °C) |
| **Heat Source** | • $T_{in}$ = ca. 50 °C and 60 – 80 % relative humidity (exhaust air)<br>• Exhaust air (with water intermediate circuit) |
| **Comments** | • The heating coils can be arranged both in parallel and in series depending on the required conditions inside the dryer |
| **Heat Pump Application II: HP 2** | |
| **Heat Sink** | • $T_{out}$ = up to 180 °C (drying agent)<br>• Air (with water intermediate circuit) |
| **Heat Source** | • $T_{in}$ = max. 90 °C<br>• Water (Intermediate circuit sink side HP 1) |
| **Comments** | • The sink outlet temperature of this heat pump is highly dependent on the required supply air parameters and the available furnace waste heat |

### 2.1.8. Oil and gas processing

#### Process description

Oil and gas production involves the entire process of producing the petroleum products "from well to wheel". There are many steps required before the final products are ready including exploration, drilling, production, processing, storage, refining, and so on. Oil and gas processing refers to the step where the newly produced fluids are processed such that the final products of are of a certain quality before storage and shipping or transportation through pipelines.

An important part of the processing is the separation stage. The separation stage often consists of a train of separators, where oil, gas and water are separated at various pressures and temperatures. Figure 2-35 illustrates the process. Separation is often performed through gravity separation in large horizontal tanks. This technique relies on gravity to separate components based on their densities. The temperature at which gravity separation occurs primarily depends on the nature of the fluids being processed.

In a typical offshore processing plant the separation stages require significant energy in the form of heat. The addition of heat reduces the oil viscosity and increases the settling velocities [52]. A major part of the heat demand for a typical platform in the North Sea can come from the processing and separation process, in particular [53]. After processing, the finished products in the form of crude oil and export gas, as well as by-products in the form of produced water typically need to be cooled down.

The overall energy demand in an oil and gas platform is traditionally covered by combusting a fraction of the produced gas in gas turbines, which produce electricity and heat through the waste heat recovery (WHR) units.

In Norway, there is a strong trend of electrification of oil and gas platforms aimed at reducing greenhouse gas emissions, increasing energy efficiency, and improving the overall environmental performance of offshore operations. One example where this has been implemented is the Johan Sverdrup Field, operated by Equinor [54]. One challenge with electrification is that the heat demand for processing needs to be covered through other sources than WHR from the exhaust from gas turbines. Electric or gas-fired boilers or heaters can be employed but are inefficient. Electrification has therefore opened the possibility of using high temperature heat pumps to cover the necessary heat demand for offshore processing, while the platforms cooling duties represent potential heat sources.

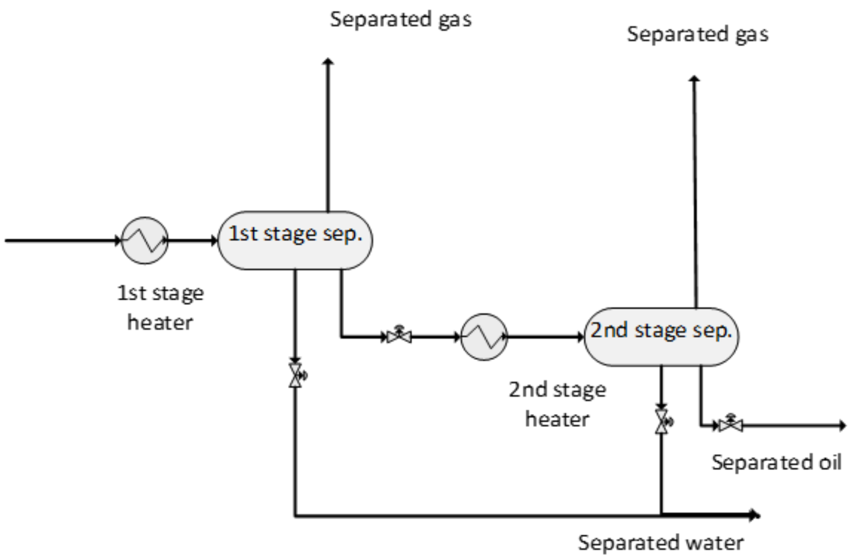



*Figure 2-35: Simplified diagram of a two-stage separation process*

*Heat sinks and heat sources*

The overall heat demand for such a processing facility capacity is often at a very high scale. In case studies performed within the HighEFF research centre by SINTEF, heat demand ranges between 5-40 MW, while the required processing temperatures can be up to 150 °C [55], [56]. Typical heat sinks and heat sources that can be expected for processing are given in Table 2-17, which includes capacities and inlet/outlet temperatures. Typical heating duties are heaters prior to separator trains, oil circulation heaters, and heater for test separators, which are used during individual oil and gas well testing. The table also includes a non-processing heating requirement, which is for living quarters (LQ). Options for integration of a heat pump to heat sinks include direct integration between heat pump condenser and individual heating duty (Integration concept A) and indirect integration via central heating system to multiple heating duties (Integration concept B).

The first option will give the highest COP due to reduced temperature lift. The second option is less efficient, but most likely easier to retrofit into existing platforms.

In addition to heating duties there are also substantial cooling duties. Processes that require cooling include crude oil and produced water cooling, cooling duties from export gas compressor trains e.g., suction coolers, after coolers and cooling duties from various pumps and motors. These duties are traditionally handled through use of a central cooling system based on a coolant such as a water-glycol mixture. Sea water is used to cool down the glycol mixture before returning to the heat exchangers. Alternatively, sea water can be used as coolant directly.

There are several options for integration with the heat source: direct integration between the heat pump evaporator and individual cooling duty (Integration concept A), indirect integration via central cooling system to multiple cooling duties (Integration concept B), integration of the heat pump evaporator to sea water as a heat source.

As with the heat sinks, direct integration is more efficient than indirect but could be more complex and difficult to retrofit into existing installations. These two options rely on the process heat to be available for the evaporator. This is typically the case as offshore oil and gas production is a continuous operation. However, during periods of transient operation, such as start-up or shut down, there might not be sufficient heat available for the heat pump. A third option is therefore to rely directly on sea water itself, which is a stable, but much colder heat source.

There is a high variation in both duties and temperature requirements, which is affected by many factors such as production rates, hydrocarbon composition, water production and the temperature of the fluids as they enter the processing facilities. The values in Table 2-17 are therefore general values based on experiences on case studies on the Norwegian continental shelf and do not by any means represent max-min values. Every case therefore needs to be evaluated individually to find the suitable integration concept.

*Table 2-17: Example heating and cooling duties found on offshore oil and gas platforms*

| **Heating duties** | **Duty [MW]** | **T inlet [°C]** | **T outlet [°C]** |
|---|---|---|---|
| **Oil circulation heater** | 2-10 | 10-25 | 60-80 |
| **1st stage separator inlet heaters** | 5-30 | 10-50 | 40-70 |
| **2nd stage separator inlet heaters** | 5-30 | 50-80 | 90-150 |
| **Test separator heater** | 1-5 | 10-50 | 40-70 |
| **Living Quarters (LQ)** | 2-10 | 60 | 80 |
| **Cooling duties** | **Duty [MW]** | **T inlet [°C]** | **T outlet [°C]** |
| **Crude oil cooler** | 5-15 | 60-80 | 40-50 |
| **Produced water cooler** | 1-15 | 60-80 | 40-60 |
| **Export gas compressor suction coolers** | 0.5-2 | 80-120 | 40-60 |
| **Export gas compressor after coolers** | 0.5-2 | 120-150 | 40-60 |
| **Water injection pump cooling** | 0.5-2 | - | - |
| **Sea water lift pump cooling** | 0.5-1 | - | - |
| **Gas export compressor motor and lube oil cooling** | 0.5-1 | - | - |

### *Variation in heating demand over time*

An important consideration when performing a case study for integration is the evaluation of required heat pump capacity when compared to the expected production profile as this is often closely related to the processing heating demand. An example production profile is given in Figure 2-36. It typically has the phase of ramp-up, plateau, decline and a tail-phase until it reaches a point where economic limit is reached and the field is abandoned. If the heat pump(s) is to cover all heating demands it needs to be scaled to the plateu heating requirements. However, this phase may only last a few years before the demand drops. Final heating demand in the tail-phase could be as low as 10-20 % of the plateau phase. The challenges of scaling to the pleateu demand could be:

- Need for multiple compressor units in order reduce minimum load capacity and maintain efficiency at reduced load
- Unused heat pump capacity in the decline and tail phase leading to: unnecessary space demand, increaed CAPEX and levelized cost of energy for heat (LCOE), long payback time

An alternative approach could be to reduce the scale the heat pump(s) heating capacity. Electric heaters could be used to cover the remaining demand during maximum load.

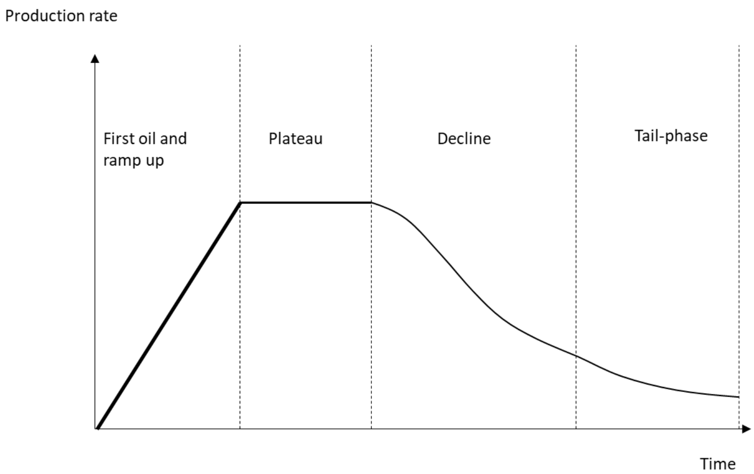



*Figure 2-36: Example of a production profile for an oil and gas installation*

### *Operating schedule and ATEX requirements*

The operating schedule for offshore oil and gas production is continuous. Therefore, heating demands of the processing facilities are also continuous 24/7. The exception would be test separators where part of the production is looped occasionally to test various production wells. Planned shutdown of production occurs during revision stops due to maintenance, modification or new installation which require the entire production to stop e.g. once annually. The revision stop is a window for service and maintenance activities for the high temperature heat pump as well.

Due to the operational environment in the processing facilities, with potential leakage of hydrocarbons, the area of installation for a high temperature heat pump will be hazardous. Any installed equipment both electrical and non-electrical needs to comply with the governing ATEX requirements.

## Integration concepts

### *Integration concept A: Direct integration with sink and source stream*

Integration concept A presents integration of a heat pump directly into the processing train. In this example the heat pump provides the required heating for the 2$^{nd}$ stage separator. The heat pumps condenser acts as the 2$^{nd}$ stage heater directly. The heat source is provided by cooling down the separated crude oil downstream of the separator. This is performed directly in the evaporator.

If there is a limited temperature glide of the heat sink and heat source using constant temperature condensing and evaporating refrigerant is beneficial. Case studies have shown that hydrocarbon refrigerants such as R600, R600a, or possibly R601 in case of high sink temperatures are beneficial in terms of the operating temperature range. R717/R718 zeotropic mixture could be favorable in case of high temperature glides. This integration concept is exposed to change in operating conditions: Reduced oil production over time can lead to significant load reduction. A change in composition between oil, gas and water over time could lead to reduced heat source availability to heat sink demand. It is therefore important to evaluate the expected operating parameters of pressure, temperature, flow rate and composition over time.

Potential advantages with concept A compared to B are reduced temperature lift and reduced maximum heat delivery temperature, reduced heating capacity, fewer compression stages, more choice in terms of refrigerants. Potential disadvantages are the need for heavy duty evaporators and condensers, load variations over time, less available space and more complex integration.

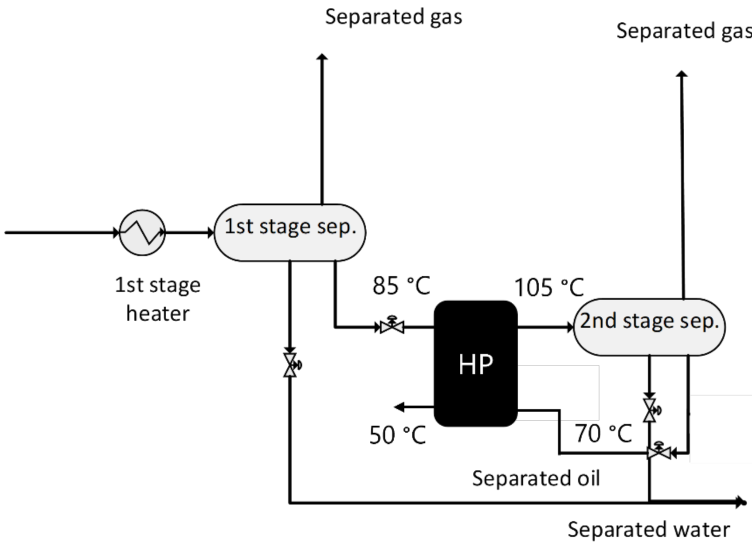



*Figure 2-37: Flow diagram of integration concept A (oil and gas processing)*

*Table 2-18: Overview of specifications for heat pump applications in integration concept A (oil and gas processing)*

| **Heat Pump Application I – n-Butane (R600) heat pump utilizing high-capacity turbo compressors** | |
|---|---|
| **Heat Sink** | • $T_{in}$ = 85 °C → $T_{out}$ = 105 °C<br>• Medium: Produced hydrocarbons (oil and gas) and water in 3 phases.<br>• Capacity: 5-30 MW |
| **Heat Source** | • $T_{in}$ = 70 °C → $T_{out}$ = 50 °C<br>• Medium: Separated crude oil<br>• Capacity: 3-15 MW |
| **Comments** | • Expected variations from 10-30 % to 100 % full load<br>• In case of increased water cut over time this will reduce the heat source capacity of the crude oil cooler relative to the heating demand of the second stage separator<br>• Suitable refrigerants: Hydrocarbons: R600, R600a, R601, ammonia-water (R717/R718) hybrid heat pump.<br>• Requires heavy duty condenser and evaporator capable of handling corrosive, acidic fluids with impurities such as sand and salts deposits etc. In case of retrofitting, increased heat exchange area could be |

| | |
|---|---|
| | required in order to reduce the minimum temperature difference between hot and cold fluid.<br>• Required capacities of > 5-10 MW: Use of turbo compressors may be beneficial in terms of oil free operation and compact size and reduced maintenance. Negatives are low pressure ratio, potentially requiring multiple compression stages. Could also require multiple parallel units or revamp modifications to handle low load scenarios.<br>• Required capacities of < 5-10 MW: Reciprocating compressors are beneficial in terms of handling large load variations while maintaining efficiency. But are larger in size and may require shorter maintenance intervals compared to turbo or screw compressors. High compressor discharge temperatures may cause issues to lubrication oil. |

*Integration concept B: Indirect integration*

Utilization of space in offshore production platforms is typically maximized in order to limit the overall size of the structure. Because of this, available space is often limited and is a key barrier for introducing large-scale heat pumps, especially in case of implementation into existing infrastructure. Moreover, the possibility of performing modifications to the existing processing plant can be both costly and technically challenging.

A central heating and cooling network using a dedicated heat transfer fluid, e.g. hot oil on the heating side and water-glycol mix or just sea water, on the cooling side is typically used to deliver the required heating and cooling for processes. In a traditional system waste heat recovery (WHR) units are used to supply the necessary heat for the central heating system. The supply temperature in the central heating system can be 50-150 °C above the required supply temperature of the heating duty with the highest temperature requirement. This is both because the waste heat from gas turbines can be recovered at these temperatures, but also because this allows to minimize the heat exchange area and thus the size of the various heat exchangers located in the processing facilities.

In integration concept B the heat pump is connected to a centralized heating and cooling system. Concept B is suited for cases involving existing infrastructure as it intends to minimize the need for modification of the existing processing facilities.

Since there is an intermediate heat exchange loop on the source and sink side, this allows for more flexibility for the installation site for the heat pump. A possibility is to utilize available space freed up by the removal of WHR units.

The condenser is connected to the central heating system, which supplies the required heat for multiple heaters. Existing heaters will be left as is or replaced with larger units to reduce the supply temperature of the hot oil. Alternatively, a heating system is split into two; a dedicated high temperature heating system for the hottest duties, which is covered by electric heaters, and a medium temperature heat system covered by the heat pump.

The evaporator can be connected to the central cooling system downstream of the individual coolers. The inlet temperature of the heat source will be based on mixing from the various coolers. Additional cooling is handled through heat exchange with sea water.

The advantage of concept B is an overall easier integration and the potential for using more standardized heat exchangers for condensers and evaporators since sink and source media are commonly used fluids. The disadvantage compared to concept A is a potentially high temperature lift, over 100 K, which may require the use of multiple refrigerants and thus a cascading type of heat pump with a bottom and top cycle unit.

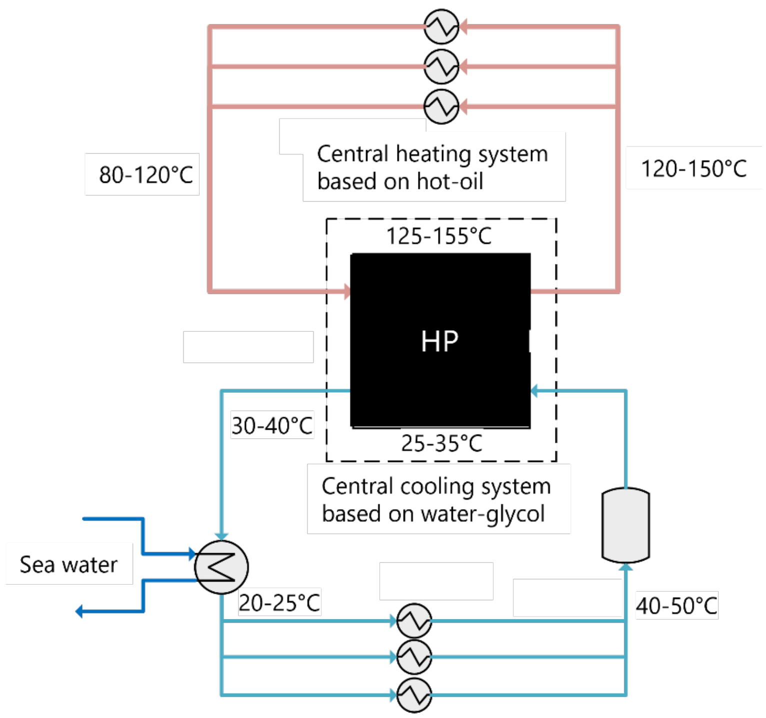



*Figure 2-38: Flow diagram of integration concept B (oil and gas processing)*

*Table 2-19: Overview of specifications for heat pump applications in integration concept B (oil and gas processing)*

| **Heat Pump Application I – Cascading heat pump cycle** | |
|---|---|
| **Heat Sink** | • $T_{in}$ = 100 °C → $T_{out}$ = 140 °C<br>• Medium: Hot oil, e.g. therminol 55<br>• Capacity: 20-50 MW |
| **Heat Source** | • $T_{in}$ = 45 °C → $T_{out}$ = 35 °C<br>• Medium: Water-glycol<br>• Capacity: 15-40 MW |
| **Comments** | • Expected high load variations, but improved heat source availability compared to concept A<br>• Suitable for high-capacity turbo compressors<br>• Suitable refrigerant combination could be:<br>• R-244-R-600 (T sink: 120 °C)<br>• R-600-R-601 (T sink > 120 °C):<br>• R-600a-R-601 (T sink > 120 °C, potential T source < 0 °C)<br>• R-717-R-718 (T sink > 120 °C)<br>• R-600a-R-718 (T sink > 120 °C)<br>• (R-717/R-718) hybrid heat pump.<br>• R-744 transcritical cycle |

### 2.1.9. Molded fiber dryers

#### Process description

Drying represents a highly energy-intensive process that is estimated to account for 15% of the total industrial energy consumption in the Netherlands [57], whilst some industries such as paper production use up to 70 % of their energy for drying. At present, the majority of this energy comes from non-renewable fuels. There's a substantial untapped potential in recovering and reusing waste heat, especially (latent) waste heat, which remains at too low a temperature for reuse in the drying process. Harnessing this potential could significantly contribute to energy conservation and subsequently reduce $CO_2$ emissions.

Drying is a crucial process in various industries where moisture removal is essential to achieve specific quality standards. Drying processes can be categorized by their heat transfer mechanism: convective drying and contact drying. Convective drying involves the use of a hot gas (usually air) to remove moisture from a product. This method relies on the principle of heat transfer, where the heated gas comes into contact with the wet material, causing the moisture to evaporate and be carried away by the gas flow. Molded fiber production exemplifies a drying process reliant on convective drying.

Molded fiber, created by molding pulp fibers into diverse shapes for packaging materials using a pulp molding machine, undergoes a drying process illustrated in Figure 2-39. The initial moisture content of the product entering the dryer post-molding typically ranges around 35 wt %. For instance, egg cartons are dried to a final moisture content of about 4 %, while egg trays to around 6 %. During drying, the product directly interfaces with a moving stream of hot air. This air, combined with natural gas, undergoes combustion in a chamber, and the resultant heated combustion products mix with recirculated, cooled air. In convective dryers, the hot drying air is blown from the dryer's top through perforated plates in the first layer. To maintain moisture levels, a portion of the air (usually 10-20 %) is exhausted to the atmosphere, while some heat is extracted from this stream to heat process water. Additional air drawn into the combustion chamber compensates for the volume exhausted to the atmosphere and other losses or for heating other processes.

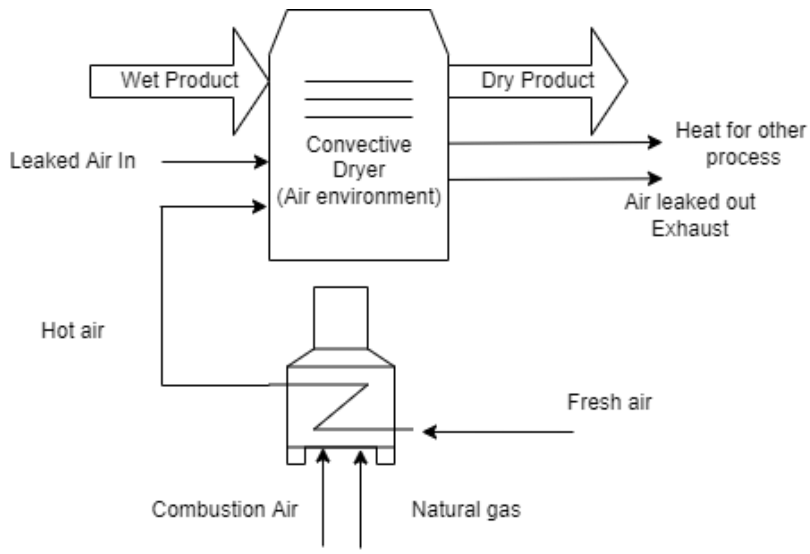



*Figure 2-39: Convectional convective dryer*

*Current drying process (Brownfield)*

The drying process currently in place (Brownfield) heavily relies on drying temperatures. Three major drying stages are outlined in the drying curve depicted in Figure 2-40:

- **Initial heating period**: Characterized by intense heat transfer due to a substantial temperature difference between the drying air and the wet product, resulting in a rapid increase in product temperature until reaching the wet bulb temperature.

- **Constant rate /product temperature period, CRP**: The bulk of free moisture is eliminated after the first drying stage maintaining a constant product temperature. The drying rate is primarily controlled by the external heat and mass transfer, along with the physical properties of the drying medium, its velocity, and temperature, reaching a critical moisture content by the conclusion of the second drying stage.
- **Falling rate period, FRP**: Follows a significant reduction in moisture evaporation from the second drying stage. The drying rate is now governed by the rate of moisture transfer inside the solid. Product temperature continues to rise until drying ceases upon reaching equilibrium moisture content.

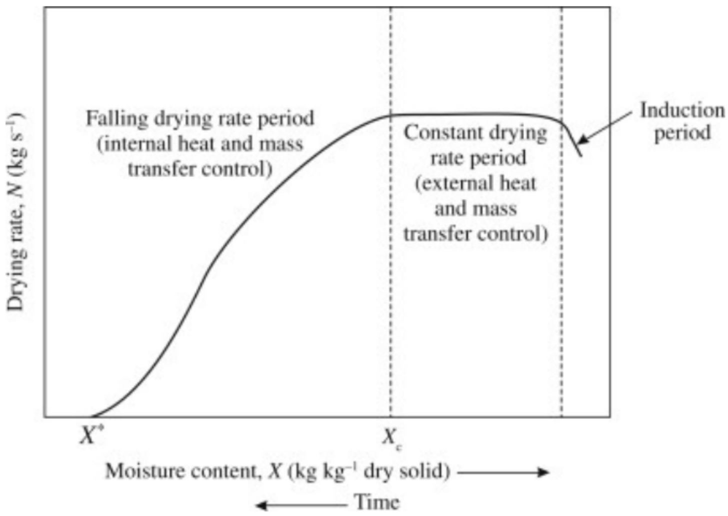



*Figure 2-40: Drying rate curve* [58]

*Superheated steam dryers (Greenfield)*

Superheated steam dryers (Greenfield) replace conventional convective drying methods by using superheated steam for heat supply, aiming to reduce energy consumption during drying [59]. Superior drying kinetics are achieved in both CRP and FRP due to the enhanced thermal conductivity and heat capacity of superheated steam compared to air drying, as demonstrated in Figure 2-41 presented below.

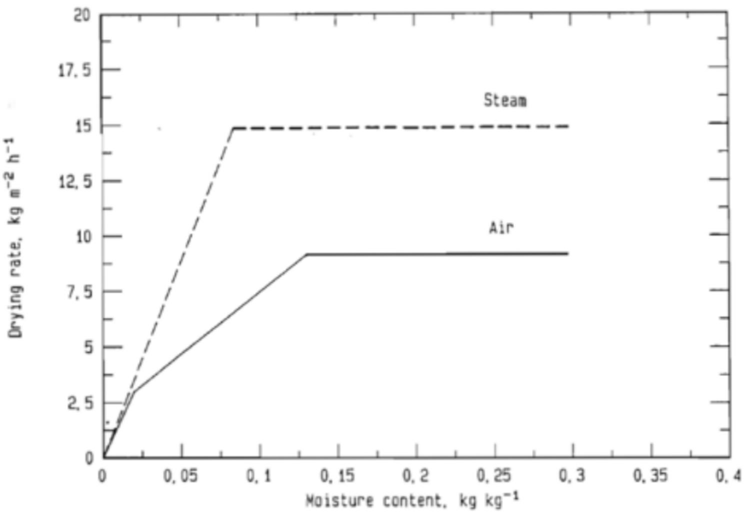



*Figure 2-41: Drying rate curves comparison between superheated steam and air* [60]

The primary advantage of superheated steam drying lies in the exhaust, which comprises steam with lower enthalpy than the incoming superheated steam. The energy equivalent to the evaporated moisture can ideally be recovered by condensation, especially in a heat pump integrated drying process [24]. This addresses the challenges associated with recovering latent heat in the exhausted air in air drying, which is typically costly.

Despite its advantages, superheated steam drying is a complex system. Control over air infiltration is crucial for higher drying efficiencies, necessitating meticulous engineering in dryer design. Ideally, a superior superheated steam dryer would feature a robust air lock system to minimize air leakage into the system [24].

### Integration concepts

*Integration concept A*

The integration concept of convective drying utilizing hot air to dry the product with a heat pump is shown schematically in Figure 2-42. The main idea is to utilize the exhaust moist air (with the moisture taken from the product) as a source for the heat pump in order to heat the recirculated air to the convective dryer temperature.

Given that both source and sink media consist of air, the heat pump needs to adapt to the large temperature glides in order to have an adequate performance. Two options arise: a Reverse Brayton cycle heat pump or a vapor compression heat pump with a zeotropic mixture.

Main advantages:

- Current convective dryers are maintained the same.
- Product quality will be maintained.

Main disadvantages:

- Large temperature glides in the source of the heat pump, resulting in large temperature lifts and therefore lower performance.
- The heat exchanger within the heat pump will have a large temperature area (or large pinch temperature difference) given the sink and source media consist of a hot gas.

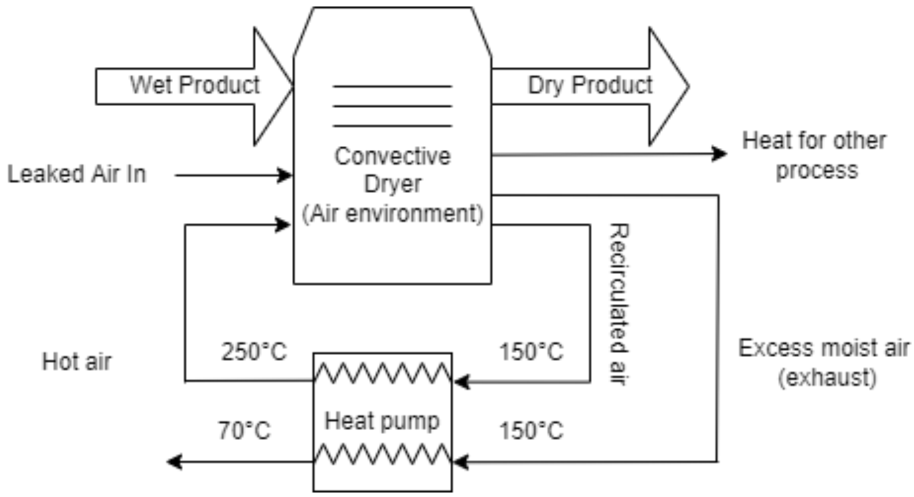



*Figure 2-42: Flow diagram of integration concept A (molded fiber drying)*

**Fact box**

*Table 2-20: Overview of specifications for heat pump applications in integration concept A (molded fiber drying)*

| Heat Pump Application I: Brownfield Dryer |
|---|

| | |
|---|---|
| Heat Sink | • $T_{in}$ = 150 °C → $T_{out}$ = 210-250 °C<br>• Media: Air (with 20 wt % of water)<br>• 1 MW |
| Heat Source | • $T_{in}$ = 150 °C → $T_{out,dew\ point}$ = 70-90 °C<br>• Media: Moist Air<br>• Capacity: 1000 kg/h |
| Comments | • Reverse Brayton cycle heat pump or a vapor compression heat pump with a zeotropic mixture due to the large temperature glides<br>• The conditions highly depend on the dryer design. |

*Integration concept B*

In the Greenfield scenario for the heat pump integration concept, the assumption is that the convective dryer contains mainly steam. The main advantages of this integration compared to the Brownfield scenario are:

- High source temperature for the heat pump, condensation of the steam at 100 °C
- Lower temperature at the sink given the better drying rates with superheated steam than with air (see Figure 2-41)

On the other hand, the main disadvantages of the Greenfield scenario are:

- Re-design of the convective dryer is necessary for the steam environment and to limit the leakage of air
- Product quality needs to be investigated given the new drying conditions/mechanism.

In terms of the heat pump design, two options arise. (1) Simple vapor compression heat pump with a pure refrigerant (e.g., pentane) capable of upgrading the heat from 100 °C to 165 °C. (2) The other alternative is utilizing steam compression: compressing the exhaust air to a pressure of 8 bar(a) (saturation temperature of 170 °C). The main challenge with the second option, steam compression, is that the convective dryer needs to be well sealed from the environment so there is no air in the exhaust stream; this is a practical matter that needs to be investigated.

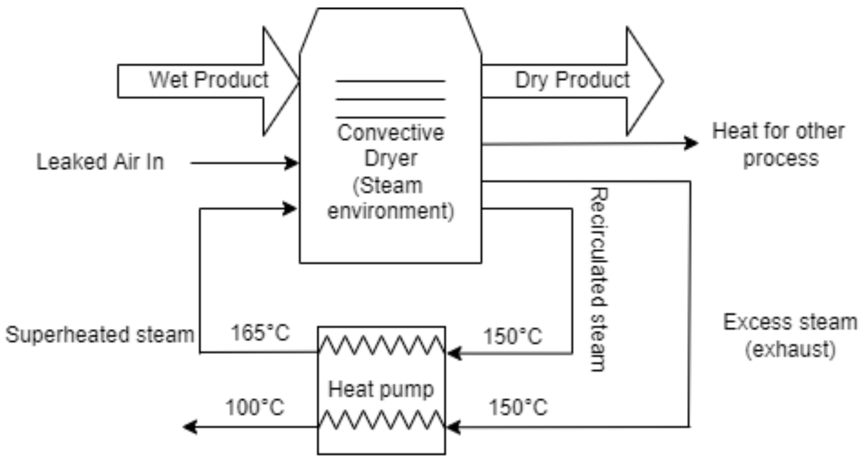



*Figure 2-43: Flow diagram of integration concept B (molded fiber drying)*

*Table 2-21: Overview of specifications for heat pump applications in integration concept B (molded fiber drying)*

| **Heat Pump Application II Greenfield Dryer** |
|---|

| | |
|---|---|
| Heat Sink | • $T_{in}$ = 150 °C → $T_{out}$ = 165 °C<br>• Steam<br>• 1 MW |
| Heat Source | • $T_{in}$ = 150 °C → $T_{out}$ = 100 °C<br>• Steam<br>• Capacity: 800 kg/h |
| Comments | • Vapor compression heat pump or steam compression.<br>• The conditions highly depend on the dryer design |

### 2.1.10. Extrusion cooking

#### Process description

Fellows [61] describes extrusion as a continuous process that combines several unit operations including mixing, cooking, kneading, shearing, shaping and forming. Figure 2-44 shows a schematic depiction of a single-screw food extruder in which foodstuff is worked by a screw inside a barrel, pressed through a die and then cut by a rotating knife. Extrusion cooking covers processes with products being heated to temperatures above 100 °C by frictional heat and additional heating of the barrel through heating jackets utilizing oil, water, steam or direct electric heating. According to [62], barrel temperatures can reach up to 180 °C depending on the product.

Typically, more than 2/3 of the energy is input as mechanical energy via the screw, characterized as specific mechanical energy (SME) in the range of 20 to 160 Wh/kg at production capacities of up to several t/h. [62], [63] state 30 Wh/kg as a magnitude for the specific thermal energy (STE). Combined with the production capacities listed by [64], this leads to thermal capacities in the range of a few kW up to the MW scale.

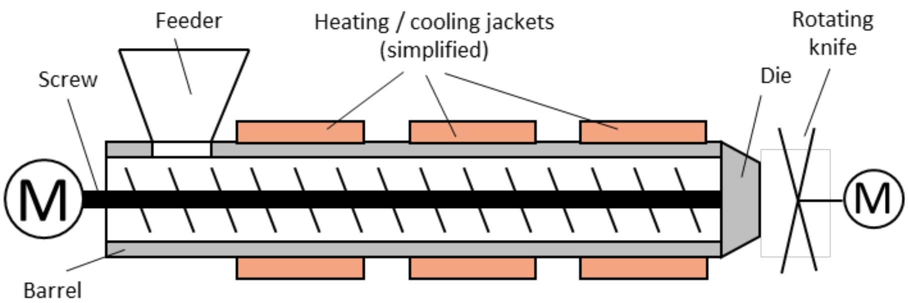



*Figure 2-44: Schematic depiction of a food extruder based on* [62],[65]

According to [64], foodstuffs manufactured through extrusion cooking range from simplest expanded snacks to highly processed meat analogues. Examples of extrusion-cooked products include cereal flakes, half products destined for fried or hot air expanded snacks, pre-cooked pasta, baby food, pet food, crispbread, and different kinds of confectionery.

Further processing steps can include drying (typically with air temperatures just above 100 °C) and cooling of the final product [64]. Both processes can potentially be integrated in the heat sink and source circuits of a heat pump.

#### Integration concept

Depending on the wide range of possible products, their properties and the needed temperatures can vary considerably. In the following integration concept (see Figure 2-45), the production of crispbread according to [66] is used as the reference process to integrate a heat pump (HP). Working the dough in the extruder leads to a temperature of approximately 90 °C, the additional heat input to heat the dough to the required temperature of 150 °C is supplied by a heat pump. After extruding the crispbread, it is dried in a belt dryer to adjust the crispy texture and to reduce the moisture content from 10 % to 6 %. Humid exhaust air from the dryer passes through a spray condenser constituting the heat source for the HTHP with the possibility to include thermal energy storage.

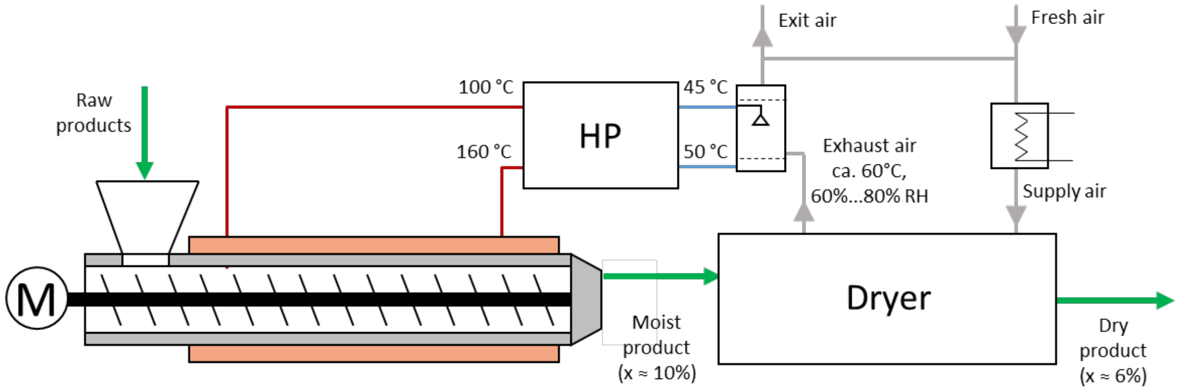



*Figure 2-45: Flow diagram of integration concept A (extrusion cooking)*

The production itself is a continuous process, operating 24 hours a day. Shutdowns for cleanups do not occur except for required sanitation when meat ingredients are used. The average life of major wear components is given in a magnitude of 5000 operating hours [66].

**Fact box**

*Table 2-22: Overview of specifications for the heat pump application applications in integration concept (extrusion cooking)*

| **Heat Pump Application** | |
|---|---|
| Heat Sink | • $T_{in}$ = 100 °C → $T_{out}$ = 160 °C<br>• Medium: Product (Dough, $c_p$ = 2.7 kJ/(kgK)) with intermediate water circuit at given temperatures<br>• Capacity: Approx. 45 Wh/kg, leading to 45 kW at a production capacity of 1000 kg/h |
| Heat Source | • $T_{in}$ = ca. 50 °C → $T_{out}$ = ca. 45 °C<br>• Moist Air (60 °C, 60…80% RH) with intermediate water circuit at given temperatures<br>• Capacity |
| Comments | • Continuous process<br>• Heat sink temperature depends on the product, values for crisp bread given in Figure 2-45 |

## 2.1.11. Plastic granules drying

### Process description

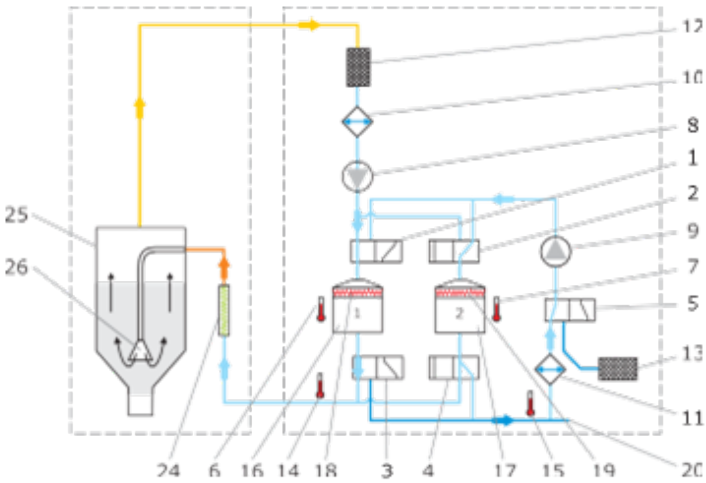
The drying of plastics raw materials is crucial in the manufacturing of a high-quality product. This integration concept is based on work in the project “Development of heat pump for drying plastic granules” supported by the Danish Energy Agency’s Energy Development and Demonstration Program in which DTU Technical University of Denmark, Labotek, Grundfos and Danish Technological Institute collaborate to demonstrate Labotek's drying equipment in combination with a heat pump-based heating/cooling concept.

Labotek is manufacturing a wide range of dry air-drying systems depending of the product being dried. The range of desiccant drying units is starting from 100 m³/h and extends up to 8500 m³/h. Drying hoppers are sized from 15 litres up to 12000 litres.

The Desiccant Flex Dryer (DFD) 600-1700 range caters for larger drying requirements. There are 4 sizes in this DFD range: 600, 1000, 1500 & 1700 m³/h. The desiccant dryer is combined with one or several drying hoppers (DH), depending on application.

In order to ensure the most stable high-quality drying of plastics raw materials, the DFD comprises two separate systems as standard. Two desiccant beds containing molecular sieves are engaged alternately in a closed drying system. One of the beds will always be operative in the drying process, while the other bed will be in regeneration or in stand-by mode, ready to be activated into the process upon next bed change.

The system incorporates twin built-in air/water heat exchangers, for process air & regeneration system. The DFD 600-1700 range is capable of supplying dew point down to 50 °C. The drying temperature is up to 180 °C depending on the type of plastic.




| Pos. | Description |
|---|---|
| 1 | Inlet slide valve desiccant bed 1 |
| 2 | Inlet slide valve desiccant bed 2 |
| 3 | Outlet slide valve desiccant bed 1 |
| 4 | Outlet slide valve desiccant bed 2 |
| 5 | Fresh air valve |
| 6 | Thermostat regeneration air, desiccant bed 1 |
| 7 | Thermostat regeneration air, desiccant bed 2 |
| 8 | Dry air blower |
| 9 | Regeneration blower |
| 10 | Return air cooler |
| 11 | Regeneration air cooler |
| 12 | Return air filter |
| 13 | Regeneration filter |
| 14 | Thermostat for dry air |
| 15 | Thermostat for regeneration air |
| 16 | Desiccant bed 1 |
| 17 | Desiccant bed 2 |
| 18 | Heating element for regeneration, desiccant bed 1 |
| 19 | Heating element for regeneration, desiccant bed 2 |
| 20 | Air outlet pipe |
| 21 | Control cabinet |
| 22 | PLC control |
| 23 | Operator panel |
| 24 | Heating element |
| 25 | Drying hopper |
| 26 | Air distributor |

*Figure 2-46: Plastic dryer*

#### Integration concepts

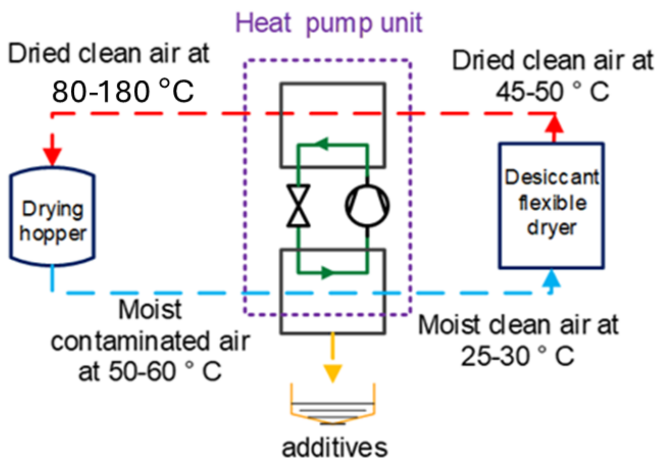



*Figure 2-47: Flow diagram of integration concept A (plastic drying)*

The heat pump integration provides hot air of up to 180 °C for the drying hopper and uses the excess moist air as heat source. Hereby, the integrated solution lowers both the heat input provided by electric heating and the cooling demand.

#### Fact box

*Table 2-23: Overview of specifications for heat pump applications in integration concept A (plastic drying)*

| **Heat Pump Application I** | |
|---|---|
| Heat Sink | • $T_{in}$ = 45 °C - 50 °C → $T_{out}$ = 80 °C - 180 °C<br>• Dry air<br>• 30 kW to 100 kW |
| Heat Source | • $T_{in}$ = 50 °C - 60 °C °C → $T_{out}$ = 25 °C - 30 °C<br>• Moist air |
| Comments | • The intended solution uses R-744 as refrigerant and market-ready components. |

### 2.1.12. Bio sludge drying

#### Process description

Drying is one of the oldest preservation processes and an essential part in many industrial sectors such as food, paper, metal processing, textile, wood and more. Air is commonly used as drying agent in convective drying processes where heat and mass transfer between the dried product and drying agent occur due pressure and temperature gradients [67].

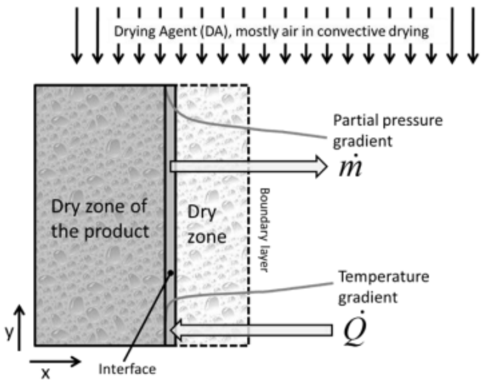



*Figure 2-48: Heat and mass transfer in convective drying of products* [67]

*Bio sludge drying*

Bio sludge is a form of organic matter which is treated as part of wastewater treatment plants. Typical sources for biological waste are food waste, sewage, garden waste and compost, sludge from septic tanks, waste wood, and digestates from feeds. Bio sludge needs to be treated before disposal in order to align with environmental regulations and remove potential health risks. Previous methods such as incineration, composting, and landfill are no longer suitable both economically and environmentally [68]. The treatment involves dewatering, drying, and disinfection. This is a costly and energy-intensive series of processes. Sludge drying is commonly performed using hot air and fluidized bed dryers or rotary drums, reaching a solid content of over 90 % [68].

*Superheated Steam Drying (SHS)*

In order to reduce the energy consumption in drying processes it may be appropriate to switch from air to superheated steam (SHS), as this is a more effective drying agent than air. Steam exhibits better heat and mass transfer properties, reduced viscosity and has a heat transfer coefficient twice as high as air. This allows for faster drying times, reduced energy consumption by 20-30 % and smaller dryers to name a few advantages compared to air [67]. Substitution from air to steam requires a dedicated compatible dryer [69]. Figure 2-49 shows a concept of bio sludge drying based on SHS. The raw and wet sludge enters the dryer. As the sludge moves through the dryer steam flows counter-flow to the sludge and evaporates the moisture from the sludge. The steam finally leaves the dryer in a slightly superheated state. Due to the evaporation of moisture, the mass flow of steam leaving the dryer is higher than when it enters. The excess steam is therefore vented to the ambient unless it can be used for other heat demanding processes. The remaining steam is then heated in an electric or gas-fired heater before re-entering the dryer.

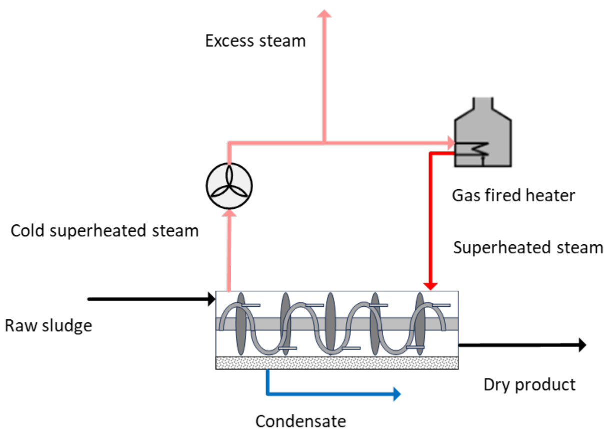



*Figure 2-49: Paddle dryer using superheated steam as a drying agent. The steam is heated using a conventional heat source, based on schematics from* [69]

*Mechanical Vapor Recompression*

Mechanical Vapor Recompression is a heat pump application utilizing steam (R718) as a refrigerant. Unlike a conventional heat pump where a dedicated evaporator is used to evaporate the refrigerant, the evaporation of steam occurs in the core process, which in this case is the bio sludge drying process. This allows the MVR compressors to utilize the excess steam directly from the dryer. The low-pressure excess steam compressed and condensed at a higher temperature to supply heat back to the recirculated low-pressure steam before re-entering the dryer. This is done via a heat exchanger. MVR heat pumps are therefore regarded as open loop heat pumps. The benefit of MVR heat pumps are reduced investment costs since an evaporator is not needed and improved efficiency due to no evaporator heat transfer losses.

### Integration concepts

A concept for Superheated steam drying (SHS) of bio sludge using MVR was developed and tested in the In the DryFiciency project [70]. The open loop MVR heat pump dryer concept was a cooperation between SINTEF, Epcon (heat pump rig), Rotrex (Turbo compressors) and Scanship (Drying system). For this purpose, a batch paddle dryer was used which works with SHS. The schematic diagram of the drying concept is given in Figure 2-50. The aim was to reduce the dryer's energy demand by up to 75 %, compared to traditional systems. The dryer operates with steam at ambient pressure between 100-120 °C. The surplus steam is routed via a compact two-stage turbo compressor system, which compresses the steam up to 4.2 $bar_a$, hence a saturation temperature of 146 °C, with a thermal capacity of 500 kW. Water injection after each compression stage is used for de-superheating. The medium pressure steam from the compressors provides energy to the low-pressure recirculated steam, which is superheated in a plate heat exchanger just before re-entry into the drying chamber. The capacity of the dryer was about 250 kg/h of feedstock and was tested with feedstock such as compost, garden waste and woodchips. At maximum temperature lift, the performance was a COP of 4.5 and a Carnot efficiency of 49 % [71].

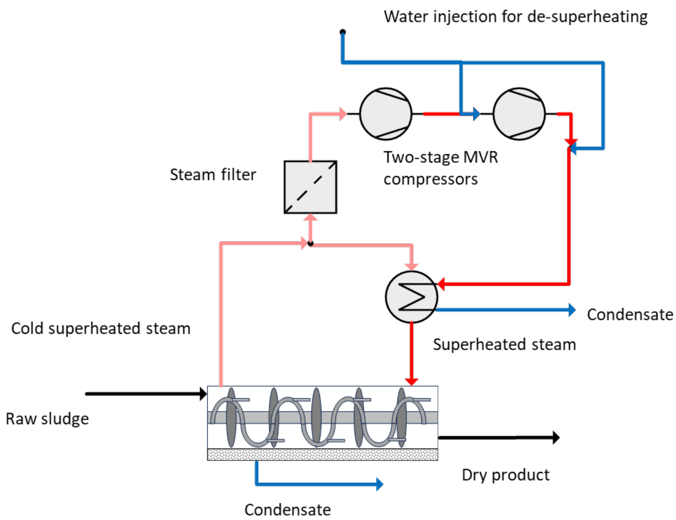



*Figure 2-50: SHS drying with MVR, based on schematics* [69]

### Fact box

*Table 2-24: Overview of specifications for heat pump applications in the integration concept*

| **Heat Pump Application I** | |
|---|---|
| Heat Sink | • $T_{in}$ = 100 °C → $T_{out}$ = 125-146 °C<br>• Steam<br>• 225-500 kW |

| | |
|---|---|
| Heat Source | • $T_{in}$ = 100 °C → $T_{out}$ = 120 °C<br>• steam |
| Comments | • Control of the steam saturation level at the dryer outlet is required to avoid saturated steam (wet steam) entering the compressors. It may also be avoided by using a flash tank between the dryer and the compressors.<br>• Closed loop internal regeneration of the compressed steam in the MVR loop or using an electric heater could be beneficial to provide sufficient heat in start-up situations. |

## 2.2. Literature review of examples with HTHP integration concepts

The integration of HTHPs into industrial processes is a challenging task for planners and engineers [72]. Tailor-made concepts are required to find an optimal integration point.

At the 14th Annex 58 Workshop Meeting in Aarhus on April 24, 2023, a first literature review on HTHP integration concepts was presented. A more detailed summary of different integration concepts with literature references was presented in the workshop at the ICR2023 conference in Paris (August 24, 2023) [73].

Publications from specialist journals and conference reports on the integration of HTHP were collected. The search terms were integration, heat pump and high temperature. Over 90 examples were found. The literature search and collection of studies will continue with a focus on further conference contributions from recent years.

Table 2-25 summarizes different studies on integration concepts with the corresponding literature references. It is categorized by process/example like distillation, drying, steam production, dairy, food and beverage, paper, district heating, wellness sauna, etc. A PowerPoint presentation in the Appendix illustrates the different HTHP integration concepts.

The reviewed HTHP integration concepts show that adaptation and precise matching to the process are necessary. MVR solutions differ from closed-cycle heat pumps. The range of applications is wide. Several papers have been published on integrating HTHPs into various processes, such as drying, steam, dairy, food, paper, district heating, and others.

HTHP integration is a complex task, and the integration concept is individual from case to case and depends on the availability of the heat source and the heat sink. Combinations with electric heating or other heating technologies are rather rare. Combinations with thermal energy storage are more often applied. The optimal integration of HTHPs into district heating networks depends mainly on the location, connection, and operation modes. A good HTHP integration concept includes the right dimensioning of the HTHP and the right control strategy to convince installers, manufacturers, and end users.

An energy analysis, ideally a pinch analysis, is recommended at the beginning to ensure that the integration of a heat pump contributes to the optimization of the overall system. Pinch analysis is applied in several cases for proper process integration. The heat pump is integrated across the Pinch temperature. Most studies from the literature are feasibility and concept studies and consider the heat pump to be a black box, independent of the heat pump technology. The HTHP is integrated into the process, unit, or supply level.

There is a lack of realized HTHP integration examples into industrial processes [72]. The main barriers are lack of knowledge and complex integration. Thus, several authors developed methodologies and tools to help integration:

- Heat Pump Integration by Pinch Analysis for Industrial Applications: A Review [41]

- Heat pump integration in non-continuous industrial processes by Dynamic Pinch Analysis Targeting [74]
- A Graphical Method for Combined Heat Pump and Indirect Heat Recovery Integration [75]
- Heat pump and thermal energy storage integration in non-continuous processes – an application to the food industry [76]
- Practical heat pump and storage integration into non-continuous processes: A hybrid approach utilizing insight-based and nonlinear programming techniques [77]
- Optimal heat pump integration in industrial processes [78]

*Table 2-25: Examples of studies with HTHP integration concepts for distillation, drying, steam generation, dairy, food, paper, district heating and other applications (extended from* [73]*).*

| | Process / Example | Reference |
|---|---|---|
| **Distillation** | Distillation processes bioethanol | Arpagaus et al. (2022) [22] |
| | Schnapps distillation | Arpagaus et al. (2023) [79] |
| | Whisky distillation | Längauer and Adler (2022) [80] |
| | Heat pump-assisted distillation | Yang et al. (2015) [81] |
| | 5-stage MVR-HP with water in a closed loop in two distillation columns | Gotaas et al. (2022) [82] |
| | MVR-HP system with several-stage compressions | Gotaas et al. (2022) [82] |
| **Drying** | Spray dryer for protein-rich fish food production. | Andersen et al. (2023) [83] |
| | Spray drying process with HTHP, recuperator and electric heater | Arpagaus et al. (2023) [79] |
| | Integration of $CO_2$ HTHPs and conventional heaters for spray dryers | Bellemo and Bergamini (2022) [84] |
| | Milk powder production with spray drying | Bühler et al. (2019) [85] |
| | Tixotherm Process for drying milk permeate powder | Arpagaus et al. (2023) [86] |
| | Drying of fish food pellets at BioMar | Petersen and Zühlsdorf (2022) [87] |
| | Industrial dryer | Holder and Schlehuber (2022) [88] |
| | Brick drying | Wilk et al. (2022, 2023) [89], [90] |
| | Starch drying | Wilk et al. (2022, 2023) [89], [90] |
| | Electronic coil drying | Schlosser (2022) [91] |
| | Industrial laundry (tunnel washer, tumble dryer) | Bühler et al. (2020) [92] |
| | Laminate drying | Jakobs (2017) [93] |
| **Steam** | Steam generation by ammonia bottom cycle and MVR-HP top cycle | Gotaas et al. (2022) [82] |
| | Steam generation via MVR and flash tank (alcoholic distillation) | Schlosser (2022) [91] |
| | Steam generation via MVR and flash tank (sludge drying, thermal separation) | Schlosser (2022) [91] |
| | Steam generation via MVR and heat exchanger (pharma recooling) | Schlosser (2022) [91] |

| | | |
|---|---|---|
| | Steam production with Rotation Heat Pump | Längauer and Adler (2022) [80] |
| **Dairy** | Cheese factory hot water generation in combination with a storage tank | Arpagaus and Bertsch (2019) [94] [95] |
| | Dairy culture production from district heating with natural refrigerants | Andersen et al. (2023) [83] |
| | Dairy steam generation for the CIP process | Arpagaus et al. (2023) [86] |
| | Upgrading exhaust gas and process waste heat streams in the dairy industry | Corrales et al. (2022) [96] |
| | HTHP integration in a dairy TINE Bergen | Ahrens et al. (2020), Brækken et al. (2022), Schlemminger (2022) [97]–[99] |
| | Milk sterilization with steam | Corrales et al. (2022) [96] |
| **Food** | Brewery hot water | Andersen et al. (2023) [83] |
| | Sausage cooking | Arpagaus et al. (2023) [86] |
| | Pasteurisation | Längauer and Adler (2022) [80] |
| | Meat processing (rendering) | Klinac et al. (2023) [100] |
| **Paper** | Pulp and paper industry | Pellegrini et al. (2023) [101] |
| | Pulp and paper | Schnabel et al. (2023) [102] |
| | Upgrading exhausted air waste heat in the paper industry | Corrales et al. (2022) [96] |
| | Upgrading cogeneration waste heat streams in the paper industry | Corrales et al. (2022) [96] |
| **Other processes** | Electrolysis | Längauer and Adler (2022) [80] |
| | Extrusion process | Zauner et al. (2020) [103] |
| | $CO_2$ HTHP for wellness sauna applications | Seitz et al. (2018) [104] |
| | Heat recovery and process cooling | Kukkola (2022) [105] |
| | Solar thermal and Rotation Heat Pump | ECOP (2023) [106] |
| | Ammonia plant | Flórez-Orrego et al. (2023) [107] |
| **District heating** | Upgrading district heating at DIN Forsyning | Petersen and Zühlsdorf (2022) [87] |
| | Heat from the cooling of the steelmaking process for district heating | Barbon (2022) [108] |
| | District heating and booster | Längauer and Adler (2022) [80] |
| | District heating | Mateu-Royo et al. (2020) [109] |
| | District heating and cooling networks | Barco-Burgos et al. (2022) [110] |
| | Geothermal systems | Jeßberger et al. (2022, 2023) [111], [112] |

# 3. Heat pump concepts

## 3.1. Summary of heat pump concepts

This chapter provides an overview of heat pump concepts that can be developed for different heat pump applications. The heat pump applications covered in this report are:

- Hot water production (Section 3.1.1),
- Steam generation (Section 3.1.2),
- Applications with large temperature glides (Section 3.1.3).

According to the template described in Section 1.3**Fel! Hittar inte referenskälla.**, every section includes a brief description of the heat pump application followed by a detailed description of the heat pump concepts.

### 3.1.1. Hot water production

Many industrial processes are supplied from a utility system that is based on pressurized hot water. The hot water is typically heated by a boiler using natural gas or another fossil fuel, as shown in Figure 1.

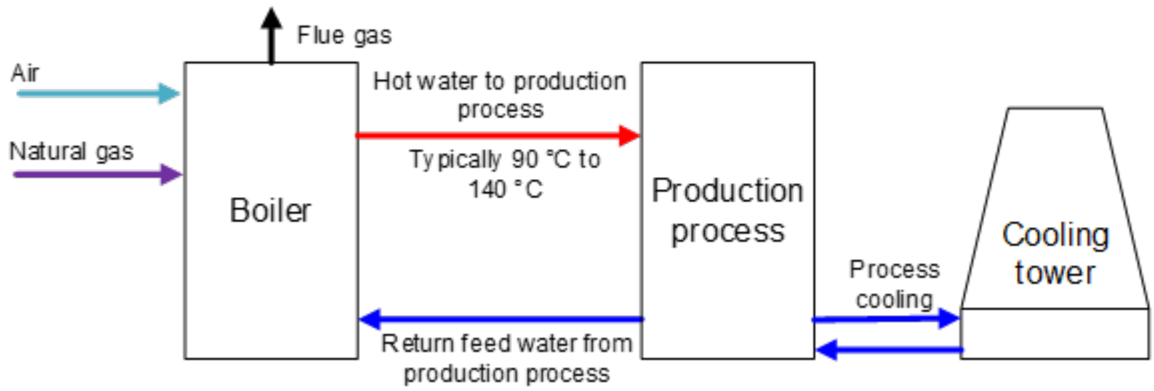



*Figure 3-1: Diagram of typical process heat supply based on pressurized hot water.*

Heat supply with hot water is used in several applications and industries for production purposes, e.g., in the pharma and food industries. Typical forward temperatures are in the range of 90 °C to 140 °C, with a corresponding pressure that ensures the water to be on liquid form. A stream of hot water is returned to the boiler at a lower temperature before it is heated up again and used in production. The return temperatures from the industrial processes to the heating utility is often in the range of 60 °C to 90 °C and are strongly dependent on the local configurations and heat demands. The operating schedule can either be continuous operation or batch production, while the capacities can range from a few hundred kW to several MW. The heat that is provided to the production process is often emitted as an excess stream, such as hot air, or by using a cooling tower.

Heat pumps can be used to provide heat to the hot water system and thereby replace the boiler. The heat source for the heat pump can be excess heat from the process, resulting in a reduced load of the cooling system, or another internal or external heat source. To ensure the highest possible performance, it is crucial to lower the supply temperature as much as possible and recover the heat for the heat source at the highest possible temperatures. The operation of hot water utilities is often continuous, alternatively it can be balanced by storage tanks, ensuring constant operation of the heat pump system.

The application potential for these systems is considerable, as hot water loops are one of the most frequently used process heating utilities and more effective than steam networks.

**Detailed description of each heat pump concept**

For hot water production, there are various potential concepts with promising thermodynamic and economic performances for a variety of applications. The obtainable performance, and thereby the competitiveness of each concept, depends on the specific boundary conditions, such as the temperature profile of the heat source and the heat sink. Each concept describes a cycle layout with different configurations of working fluids, compressors, lubrication systems and expansion devices. Each concept accordingly has different advantages and constraints. The three concepts introduced are:

- Heat pump concept A: Single-stage, multi-stage and cascade heat pump cycle
- Heat pump concept B: Transcritical single stage cycle with gas bypass, ejector or expander using R-744
- Heat pump concept C: Hybrid absorption compression HP

Each of these concepts is referring the “HTHP system” for hot water production as seen in Figure 3-2.

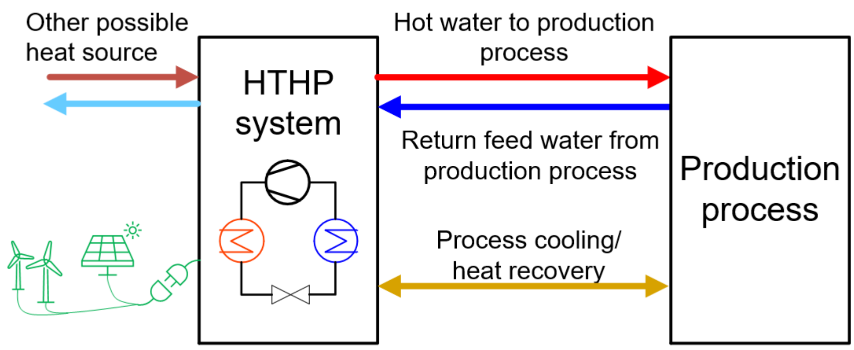



*Figure 3-2: Hot water production with HTHP concepts*

*Heat pump concept A: Single-stage, multi-stage, and cascade heat pump cycle*

The single-stage heat pump cycle is the simplest configuration of a vapor compression heat pump and can be operated with a range of refrigerants, e.g. such as R-600, R-600a, R-601, R-601a, or HFOs. These systems can utilize different compression technologies, such as piston and screw compressors, or turbo compressors. The temperature lift is limited to the maximum pressure ratio of the compressor. The single-stage systems consist of a cycle with one compression stage and one working fluid as shown in Figure 3-3.

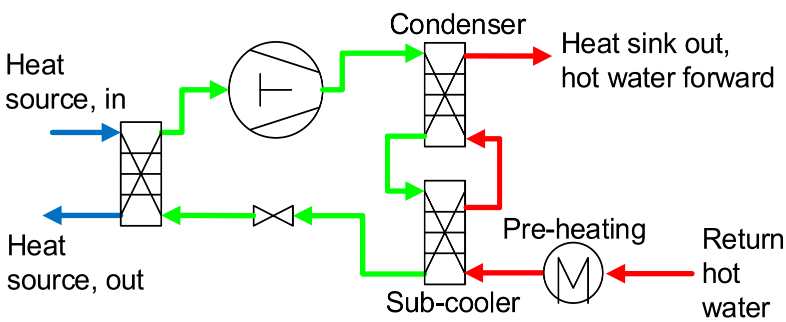



*Figure 3-3. Flow diagram of a single-state cycle*

Single-stage systems are typically relatively compact – both in terms of construction and footprint as well as controllability and operability. This results in relatively high performances and low investment costs. The temperature lift that can be achieved depends on the working fluid and the compressor, but temperature lifts in the range of up to 60 K to 70 K seem reasonable.

For larger temperature differences, the systems can be designed with multiple compression stages for the same refrigerant or as cascade arrangements that combine multiple closed cycles with different working fluids. This increases the performance as well as the investment cost. The multi-stage systems work with one working fluid being compressed in several stages while interstage cooling might be applied to optimize the compression process and keep the temperatures low.

The use of cascade cycles allows using refrigerants in their optimal working domains and thereby high performances. For HTHP applications, this approach enables utilizing commercially available solutions for the bottom cycle, while various candidates are being developed and expected to be commercially available for the top cycle within the next 2 to 3 years, depending on temperature and capacity. Figure 3-4 shows an example of a cascade heat pump cycle.

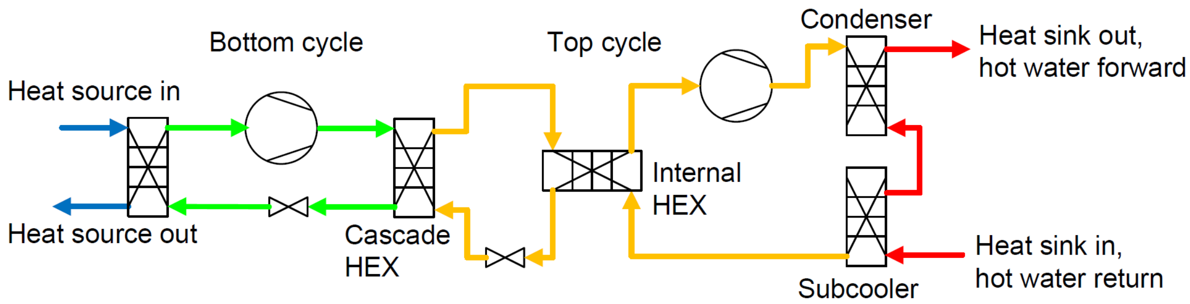



*Figure 3-4: Flow diagram of a cascade cycle*

Since each working fluid has an optimal working domain, it becomes advantageous to work with several closed cycles with separate working fluids instead of a multi-stage system for too large temperature lifts. The bottom cycles can e.g. be realized with R-290 or commercially available technologies, such as ammonia (R-717) systems while the top cycle could e.g. be operated with R-600, R-600a, R-601, R-601a, R-1233zd(E), or R1234ze(E). Cascade systems are more complex in construction and operability, but in turn offer the optimal selection of working fluids and lubrication systems for certain temperature regions.

These systems can be optimized by various measures, such as optimizing the cycle or optimal application integration. Depending on the working fluid and the application, it is typically advantageous to integrate an internal heat exchanger and maximize subcooling by additional heat exchangers. Furthermore, the concept is relatively flexible concerning heat recovery and heat supply at various temperature levels. The performance can often be improved considerably by allowing sufficient subcooling or integrating the oil cooling from the compressors in the heat supply, possibly by pre-heating the hot water return water.

These cycles are typically based on experiences from refrigeration systems and can be built with a wide range of compressor types from different technology suppliers. The heating capacities are estimated to be between 100 kW and more than 10 MW.

*Table 3-1: Fact box with detailed heat pump concept A description.*

| **System type/name** | Single, multistage and cascade HP |
|---|---|
| **Short description** | • Piston, screw and turbo compressors<br>• Working fluid depending on temperature domain: Hydrocarbons (R-600, R-600a, R-601, R-601a,) or hydrofluoroolefins (R-1233zd(E) or R-1234ze(E))<br>• Various cycle arrangements possible, including internal heat exchangers and subcooling<br>• High design flexibility |
| **Capacity ranges** | 0.1 MW to above 10 MW – depending on compressor type |

| | |
|---|---|
| **Expected performance** | Example for a single stage with internal HEX,<br>R-600, and with source temp. from 55 °C → 45 °C and sink from 90 °C → 120 °C:<br>COP = 3.2 (incl. estimated losses) and pressure ratio = 5.3. |
| **System complexity and estimated cost level** | Complexity depends on a number of different stages and cycles. Overall, a specific investment cost for the installed system without integration is expected to be between 200 €/kW and 800 €/kW. |
| **Main advantages** | • Flexible design offering optimal integration of heat recovery and supply at multiple temperatures<br>• Equipment based on refrigeration systems, building on broad knowledge and distribution channels<br>• Natural refrigerants are possible |
| **Main challenges** | • Lubrication of compressors for screw and piston<br>• ATEX measures for flammable refrigerants<br>• Efficiency for very large temperature lifts |
| **Maturity** | By 2021, the first prototypes were demonstrated in the laboratory and industry, corresponding to TRL 6-7.<br>Larger availability from various component and system suppliers with an increasing number of demonstrations in the industry is expected by 2024, corresponding to TRL 7-9.<br>Various commercial products up to 160 °C expected by 2024. |
| **Possible technology suppliers** | There are several compressor suppliers for hydrocarbon compressors, e.g., Mayekawa, JCI, BOCK, Frascold, GEA, Bitzer, Dorin |

*Heat pump concept B: Transcritical single-stage cycle with gas bypass, ejector or expander using R-744*

This concept uses $CO_2$ (R-744) as a working fluid. The evaporation process is subcritical, while the heat rejection is realized in the transcritical region. In this region, the working fluid experiences a large temperature glide, resulting in high performance if the temperature profile matches well with the heat sink. Maximum supply temperatures of up to 120 °C below 10 MW and 150 °C above 10 MW can be achieved.

$CO_2$ is a working fluid with a relatively low critical temperature, resulting in high operating pressures and transcritical heat rejection. This implies certain characteristics that make it a high-performing working fluid for certain operating conditions but limits its range of applications to certain boundary conditions.

The transcritical operation at pressure of above 100 bar causes that the working fluid experiences a large temperature glide during heat rejection while considerable inefficiencies are occurring during the expansion process. It may accordingly be concluded that reaching high performances requires addressing these two aspects. The losses during heat exchange are kept at a minimum if the temperature profile of the heat sink matches well with the temperature profile of the working fluid, which is the case for a process that requires a large temperature increase, such as heating water from 20 °C to 120 °C. The losses during the expansion process can be minimized by employing expansion devices or reducing the return temperature from the process, meaning the sink inlet temperature, and thereby maximizing the subcooling of the working fluid. This means that $CO_2$ systems are showing highest performances with large temperature glides on the sink side and low sink inlet temperatures. The concept is best suited for heat sources below 30 °C to keep the evaporation process subcritical. Figure 3-5 shows an example of a flow sheet for a R-744 cycle with expander.

Due to the high operating pressures of above 100 bar, $CO_2$ systems are designed as relatively compact systems with a small footprint and fast regulation times.

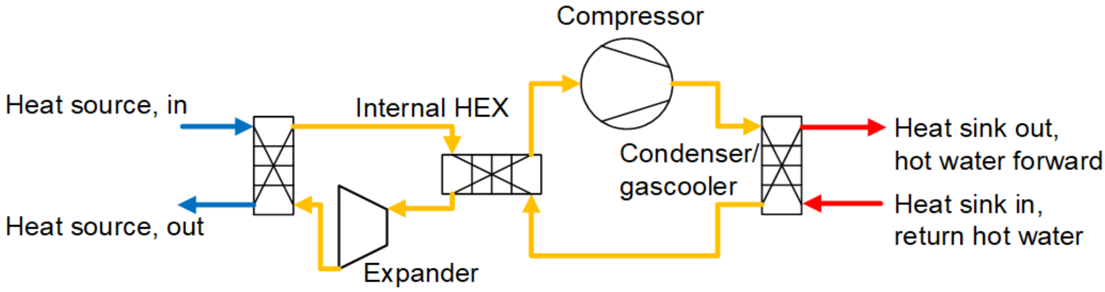



*Figure 3-5: Diagram flow of a R-744 cycle*

*Table 3-2: Fact box with detailed description of heat pump concept B.*

| | |
|---|---|
| **System type/name** | Transcritical single stage cycle with gas bypass, ejector or expander using R-744 |
| **Short description** | • Piston compressors for 50 kW to MW range and turbo compressors for > 5 MW<br>• R-744 ($CO_2$) as working fluid.<br>• High potential in applications with large temperature glides (over 40 K)<br>• Internal HEX and expanders can increase the performance |
| **Capacity ranges** | 0.1 MW to 50 MW |
| **Expected performance** | Example with single stage R-744 cycle with liquid separator and both IT and MT compressor in an application with source temp. glide from 30 °C to 15 °C and sink from 40 °C to 120 °C:<br>COP = 2.7 (incl. estimated losses) and pressure ratio = 3.9. |
| **System complexity and estimated cost level** | Cost increase with the use of expander and ejector. Specific investment cost for installed system without integration estimated to be: 250 €/kW-500 €/kW. |
| **Main advantages** | • Compact and cost-effective installation<br>• Fast regulating systems<br>• Natural refrigerant |
| **Main challenges** | • Low process return temperatures required<br>• Limited performance for low temperature glides<br>• Expanders can improve performance and increase range of application to higher process return temperatures, but limited number of technologies available for lower capacities |
| **Maturity** | First systems in 100 kW to 1 MW capacity range are operating with temperatures up to 120 °C. Higher supply temperatures are in the development phase at TRL 6-7.<br>For large capacities above 5 MW, a system by MAN ES has been demonstrated in lab. Full-scale demonstration expected by 2024. |
| **Possible technology** | Suppliers: GEA Refrigeration Netherland, Fenagy, ENGIE Refrigeration and MAN Energy Solutions (however centrifugal turbo- |

| | |
|---|---|
| **suppliers** | compressor available from minimum 10 MW) |

*Heat pump concept C: Hybrid absorption compression heat pump*

This hybrid absorption compression heat pump is based on the Osenbrück cycle and working with a working fluid mixture of the natural refrigerants R-717 and R718. The working fluid mixture experiences temperature glides during evaporation and condensation and is therefore most suited for applications with temperature glides. The cycle configuration includes both a pump and a compressor, working in parallel. This allows to control the mass fraction at the outlet of the evaporator and thereby the temperature glide. Figure 3-6 show an example of a flow sheet for a hybrid absorption heat pump.

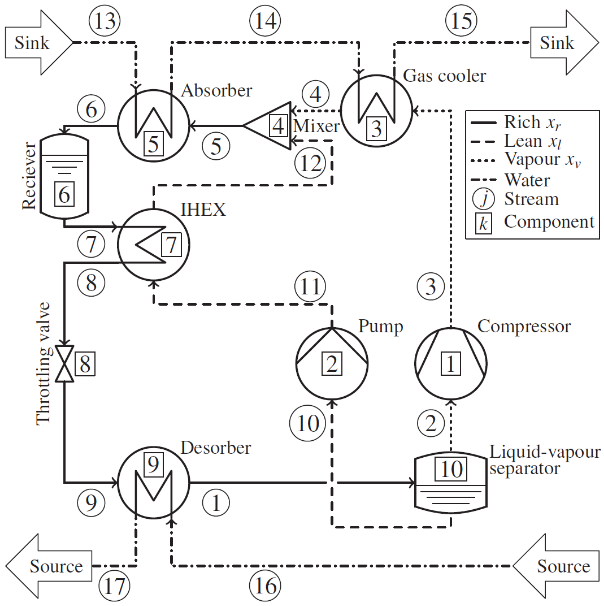



*Figure 3-6: Flow diagram of an example of hybrid absorption compression heat pump using R-717/R-718* [113]

The cycle is slightly more complex than standard systems but offers higher flexibility. The number of suppliers is rather limited, and the capacity range is from 500 kW to multiple MW with supply temperatures of up to 120 °C. It is furthermore expected that higher supply temperatures can be reached in close future.

The use of the zeotropic mixture as working fluid offers the potential to reach relatively high supply temperatures with standard equipment as well as the flexibility to design highly efficient systems for given applications by varying the refrigerant mixture composition. By mixing the two refrigerants it is possible to reach a high temperature at a moderate pressure.

Compared to a conventional vapor compression cycle the evaporator is replaced by a desorber, and the condenser is replaced by an absorber. In the desorber heat is transferred from the heat source to the refrigerant, at low temperature (waste energy). In a conventional vapor compression cycle the refrigerant experiences a phase change at constant temperature. The temperature glide during phase change can be utilized to match the sink temperature profile for hot water production.

*Table 3-3: Fact box with detailed description of heat pump concept C.*

| | |
|---|---|
| **System type/name** | Hybrid absorption compression HP using R-717/R-718 |
| **Short description** | • Piston or screw compressors<br>• Zeotropic mixture of ammonia (R-717) and water (R-718)<br>• Liquid pump operating in parallel to compressor |

| | |
|---|---|
| | • Maximum supply temperatures of up to 120 °C were demonstrated while higher temperatures may be reached during coming years. Most promising for applications with a certain temperature glide in source and sink |
| **Capacity ranges** | 500 kW to 5 MW |
| **Expected performance** | Case study in application with source temp. glide from 90 °C → 70 °C and sink glide from 90 °C to 120 °C: COP = 5.6. |
| **System complexity and estimated cost level** | More complex system compared to conventional vapor compression system. Specific investment cost for installed system without integration: From 200 €/kW up to 600 €/kW depending on the type and the number of compressors. |
| **Main advantages** | • Able to match temperature glides enabling high performances<br>• Natural refrigerants |
| **Main challenges** | • Limited number of suppliers<br>• Maturity of systems at high temperatures |
| **Maturity** | Multiple units in operation and forward temperatures up to 120 °C available.<br>Higher forward temperatures under development. |
| **Possible technology suppliers** | Hybrid Energy |

### 3.1.2. Steam generation

Steam is one of the most important heat transfer and process media used in industrial processes and is often generated with steam boilers by burning natural gas as shown in Figure 3-7.

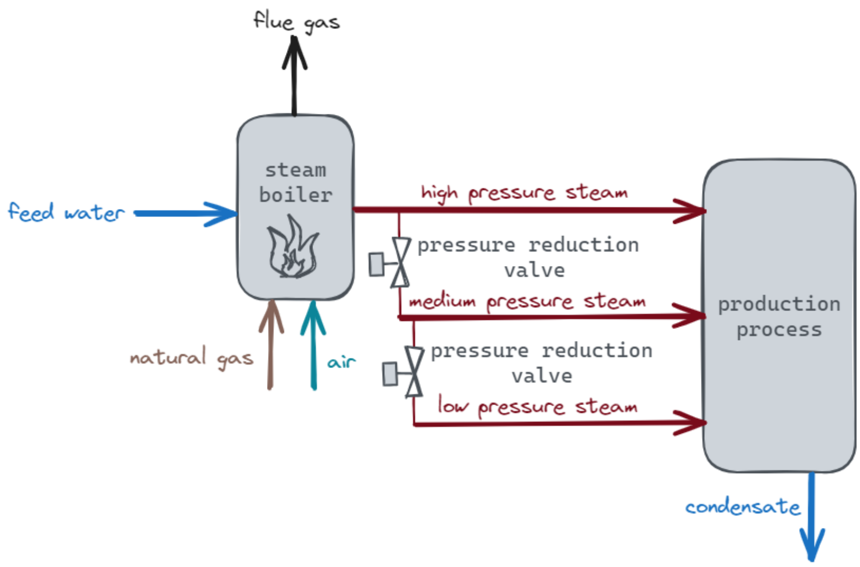



*Figure 3-7: Scheme of a typical steam supply system of a production process (Source: AIT Austrian Institute of Technology GmbH).*

A benefit of steam as heat transfer is its beneficial heat transfer properties during condensation which allows for smaller sized heat exchangers. Steam is also used as a reactant when it is brought into direct contact with the product, such as pasteurization with steam injection. Another possible application is steam drying, for example in the textile, food or paper industries.

Depending on the quality requirements of the steam and the plant layout, either fresh water of the desired purity is evaporated in the boiler, or the condensate of the production process is evaporated again. In closed loop applications the condensate usually enters the boiler subcooled, where it is evaporated again. The subcooling can be achieved during the utilization of the steam and condensation, respectively, or also through targeted cooling, e.g.: during heat recovery. Typical steam applications are operated above atmospheric pressures, but vacuum designs can also be found, for example in distillation columns or paper machines.

If heat pumps are used for steam generation, a heat source is required in contrast to steam generation based on fossil fuels. This can be either waste heat from a process that may also have a cooling requirement or ambient heat (fresh air, groundwater, or geothermal energy). If there is a cooling demand for the waste heat flow, the heat pump can fulfill both tasks, cooling and steam generation. Heat pumps for steam generation are required in a wide power range from approx. 300 kW to more than 10 MW.

As shown in Figure 3-7, in steam generators based on fossil fuels, steam is generally provided at the highest required pressure level and then expanded to the other required pressure levels. The coefficient of performance of a heat pump (COP, ratio between the heating capacity and electrical power consumption) is strongly dependent on the temperature lift (temperature difference between the utilization temperature and the source outlet temperature). The lower the temperature lift, the higher the COP of the heat pump. Thus, when using a heat pump system, it is important to provide the steam at the appropriate pressure level that is needed. Figure 3-8 shows this procedure by means of a combination of closed loop heat pump and steam compression.

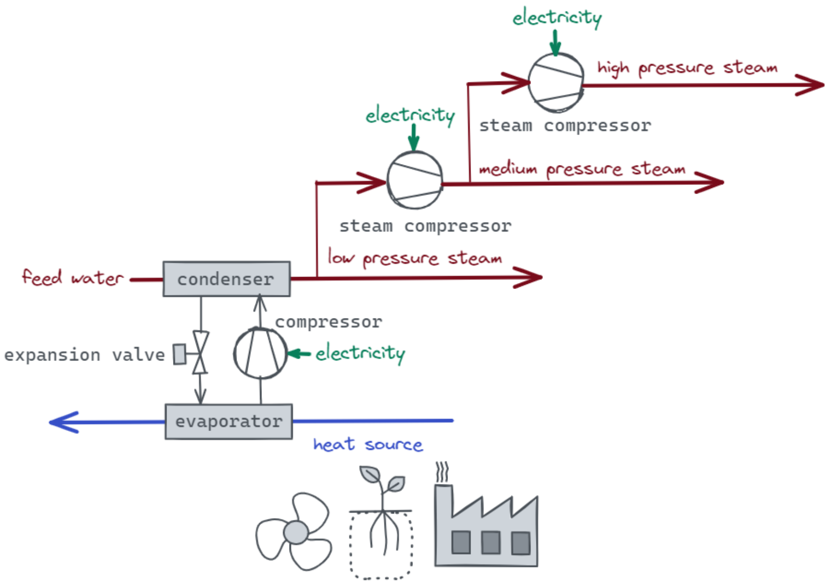



*Figure 3-8: Steam supply with a heat pump system consisting of a closed heat pump and two steam compressors (Source: AIT Austrian Institute of Technology GmbH).*

Moreover, for heat pump integration, a storage device can be included both on the steam side and on the source side of the heat pump. This is especially important when the steam demand does not coincide with the availability of the waste heat source. On the steam side, the use of so-called steam accumulators is suitable. However, these require either very large volumes and are characterized by a high pressure decrease when steam is discharged. Nevertheless, the application of a storage device in the heat pump system can increase the flexibility of the steam production process and support a more continuous operation of the heat pump.

### Detailed description of each heat pump concept

There are several concepts for steam generation with heat pumps. There will be no extensive discussion on the internal cycle design and refrigerant of closed heat pumps. It should be noted, however, that through the selection of refrigerant and cycle design adapted to the application, increases in the COP can still be achieved.

The focus of this document lies on how the steam is produced in or outside the heat pump and how its pressure and temperature can further be increased. Various heat pump cycles and heat pump types are described in more detail in the document on hot water generation and are in principle also applicable to steam generation. However, concepts in which large temperature differences on the sink side are advantageous (for example transcritical heat pumps) are disadvantageous in steam generation. Among others, three concepts are particularly important:

- Concept A: Direct steam generating compression heat pumps.
- Concept B: Heat pump for hot water production using a flash tank for steam generation.
- Concept C: Steam compression.

*Heat pump concept A: Direct steam generating heat pumps*

In direct steam-generating heat pumps, a so-called plate and shell heat exchanger is typically used as a condenser. The feed water is directly evaporated in this heat exchanger. Figure 3-9 schematically shows a classic heat pump cycle with a direct steam generating condenser. The internal working principle of a direct steam generating heat pump does not differ from that of a heat pump for hot water production.

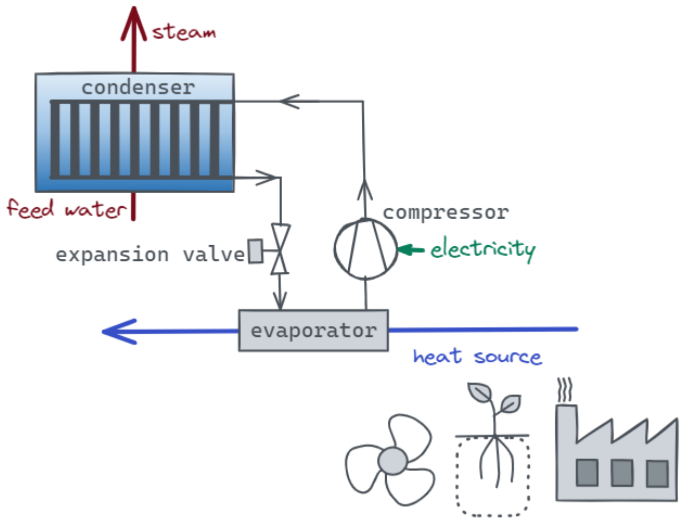



*Figure 3-9: Direct steam generating heat pump e.g. by using a shell and plate heat exchanger as a condenser (Source: AIT Austrian Institute of Technology GmbH).*

It is also possible to use the steam generating heat exchangers (plate and shell heat exchanger) externally, i.e. with an intermediate cycle between the condenser of the heat pump and the steam generator. Here, the refrigerant cycle of the heat pump is not modified, hot water is generated in the condenser and steam is generated in the external heat exchanger.

Heat pumps employing a refrigeration cycle operating in the subcritical range are particularly suitable for this application. Therefore, when selecting a refrigerant, consideration is given to ensuring that the critical point of the refrigerant is well above the required steam temperature. Figure 4 shows the steam temperatures that can be generated for different refrigerants.

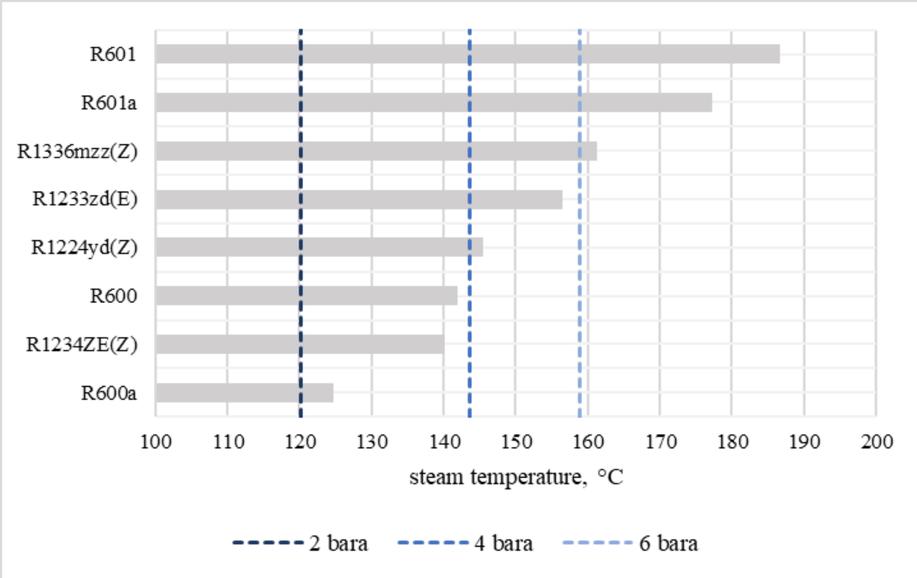



*Figure 3-10: Suitable steam temperatures for different refrigerants (assumption: 10 K minimum temperature difference between critical temperature and steam temperature).* [114]

Direct steam generating heat pumps are compact and are most efficient in terms of heat transfer, as there is no extra equipment needed apart from the refrigerant cycle. This also results in a smaller footprint and decreased investment costs.

*Table 3-4: Fact box with detailed description of heat pump concept A*

| | |
|---|---|
| System type/name | Direct steam-generating heat pumps |
| Short description | • Heat pump cycle equipped with a condenser that allows to evaporate feed water directly (for example plate and shell heat exchanger).<br>• Piston, screw and turbo compressors applicable.<br>• Refrigerant selection depends on the steam temperature to be generated and other aspects like safety, etc..<br>• Various refrigeration cycle configurations (internal heat exchanger, subcooler, etc.) applicable.<br>• Coupling with storage on the source and sink side possible. |
| Capacity ranges | 0.03 MW to 70 MW |
| Expected performance | Strongly dependent on the operating point.<br>Theoretical example: Cooling waste water from 85 °C to 80 °C, 200 kg/h steam generation at 4 $bar_a$ (feed water temperature 80 °C) → COP 2.6 |
| System complexity and estimated cost level | Complexity depends on the number of different stages and cycles.<br>Specific investment cost for an installed system without integration is estimated to be 200 – 1000 €/kW (see IEA HPT Annex 58 Task 1 Technology Supplier). |
| Main advantages | The advantages are given compared to the other concepts of steam generation with heat pump:<br>• More compact design<br>• Smallest footprint |
| Main challenges | • High temperature lifts largely affect the COP. |

| | |
|---|---|
| Maturity | TRL 5-9 |
| Possible technology suppliers | Sustainable Process Heat, Mayekawa Europe, Heaten, Turboden, Siemens Energy, Aneo Industry AS (see IEA HPT Annex 58 Task 1 Technology Suppliers). |

*Heat pump concept B: Heat pump for hot water production using a flash tank for steam generation*

The heat pump in this concept could be any heat pump for hot water production. The pressurized hot water from the heat sink outlet is then fed through a flash valve into the flash tank, where the pressure drops cause a part of the stream to evaporate. The proportion that evaporates depends on the temperature of the pressurized water before expansion and the pressure after the valve, it is typically in the range of 10 %. The steam can then be extracted from the flash tank and the appropriate amount of feed water is added to the system to keep the filling level or mass constant. To close the cycle, liquid water is pumped from the flash tank back to the condenser of the heat pump, where it is heated again.

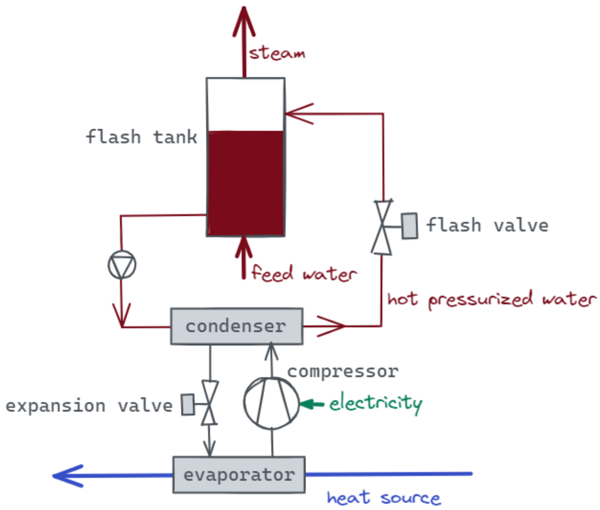



*Figure 3-11: Heat pump for hot water production using a flash tank for steam generation (Source: AIT Austrian Institute of Technology GmbH).*

Furthermore, it is possible to replace the forced circulation with a natural circulation that is strongly density-induced and buoyancy-driven. In the natural circulation, a fraction of water can be evaporated throughout the condenser leading to wet steam (two-phase medium). The following drum enhances the heat transfer by separating the steam area from the water region due to temperature and density differences. The pressure drop across the natural circulation system plays a role in defining the amount of steam produced over the condenser.

In contrast to concept A, further components are required in this concept. This concept has therefore a larger footprint and investment costs.

*Table 3-5: Fact box with a detailed description of heat pump concept B.*

| | |
|---|---|
| System type/name | Heat pump for hot water production using a flash tank for steam generation |
| Short description | • Classic heat pump for hot water production is combined with a flash tank system for steam generation.<br>• Piston, screw and turbo compressors applicable.<br>• Refrigerant selection depending on the steam temperature to be generated and other aspects like safety, etc...<br>• Various refrigeration cycle configurations (internal heat |

| | |
|---|---|
| | exchanger, subcooler, etc.) applicable. |
| Capacity ranges | Heat pump capacity: 0.3 MW to above 70 MW (see IEA HPT Annex 58 Task 1 Technology Suppliers). |
| Expected performance | • Strongly dependent on the operating point.<br>• Theoretical example: Cooling wastewater from 85 °C to 80 °C, 200 kg/h steam generation at 4 $bar_a$ (feed water temperature 80 °C) → COP 2.3 |
| System complexity and estimated cost level | • Complexity depends on the number of different stages and cycles.<br>• The costs are in a wide range, especially at high temperature lifts it can result in higher costs because here multi-stage heat pump systems are used.<br>• Specific investment cost for the heat pump (without flash tank system) estimated to 200 – 800 €/kW<br>• Specific investment cost for flash tank estimated to be 300 – 800 €/kW |
| Main advantages | • Retrofitting of heat pumps for hot water production |
| Main challenges | • Additional components are required (flash tank system)<br>• Lower COP due to the higher sink outlet temperature of the heat pump which is required due to the pressure loss during expansion and the electrical power required for the pump.<br>• Larger footprint |
| Maturity | Heat pump for hot water production: TRL 6-9 |
| Possible technology suppliers | The following manufacturers, for example, offer heat pumps in combination with a flash tank (or separator) for steam generation: Fuji Electric, Kobelco Compressors Corporation, Mitsubishi, Enertime.<br>There are several manufacturers available for heat pumps for hot water production. |

*Heat pump concept C: Steam compression*

In this concept, steam compression is used to increase the pressure and temperature of an existing steam mass flow by using a dedicated steam compressor. During compression of a steam mass flow, superheating of the steam occurs. In order to obtain saturated steam again, the steam compressors can be equipped with a water injection in which liquid water is injected to bring the steam mass flow to the saturation state. Depending on the type of steam compressor, only a certain increase in temperature can be realized per stage or compressor. If higher temperature differences are required, multi-stage systems are applied with several compressors connected in series. Steam compressors can be combined with any steam-generating heat pump as presented in Concepts A and B. Figure 3-12 shows the combination with concept A (direct steam-generating heat pump).

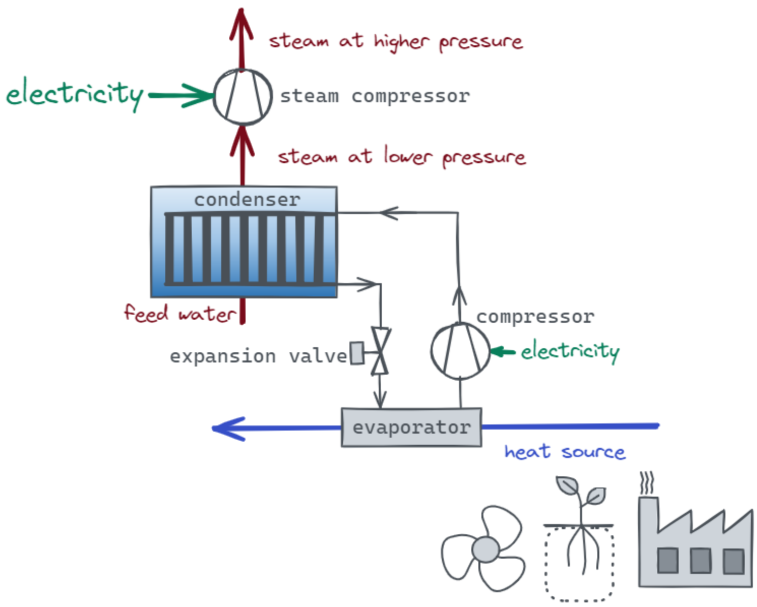



*Figure 3-12: Direct steam generating heat pump in combination with downstream steam compressor (Source: AIT Austrian Institute of Technology GmbH)*

Figure 3-13 shows another application of steam compressors. Here, industrial waste heat is used in a heat exchanger to evaporate feed water. If the waste heat temperature is below 100°C, feed water is evaporated at vacuum conditions. The temperature and pressure of the steam is then increased through steam compression. This system is often called an open loop heat pump.

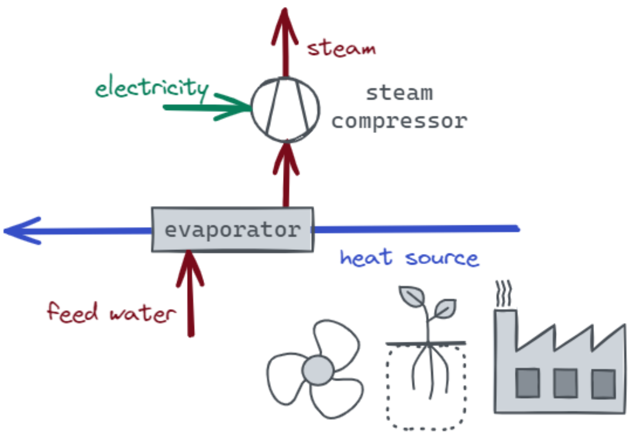



*Figure 3-13: Steam compression in combination with heat exchanger for steam generation (Source: AIT Austrian Institute of Technology GmbH)*

*Table 3-6: Fact box with detailed description of heat pump concept C.*

| | |
|---|---|
| System type/name | Steam compression |
| Short description | • Compressor for increasing the steam pressure with the use of electrical energy. Superheated steam is brought to saturation condition by water injection.<br>• Piston, screw, turbo compressors and centrifugal fans applicable. |
| Capacity ranges | Heat supply capacity of steam compressor: 0.5 MW to 100 MW |
| Expected performance | Strongly dependent on the operating point.<br>Theoretical example: Cooling wastewater from 85 °C to 80 °C, 200 kg/h steam generation at 1.5 $bar_a$ and following steam compression to 4 $bar_a$ |

| | |
|---|---|
| | (feed water temperature 80 °C) → COP 3.2 (entire system) [42] |
| System complexity and estimated cost level | • Complexity depends on the system with which the steam compressor is combined. (see Concept A and Concept B).<br>• Depending on the steam compressor type, the maximum possible temperature lift that can be achieved in one stage is limited. Max reachable lift per stage at 2 bar inlet: 10 to 20 K Centrifugal compressor, 40 K Piston compressor, 60 K Screw compressor.<br>• Estimated cost: 100 – 430 €/k |
| Main advantages | • Higher overall COP in combination with a steam-generating heat pump at high temperature lift compared to the use of a steam generating heat pump alone.<br>• Higher achievable steam pressures. |
| Main challenges | • Increased footprint for high temperature lifts depending on technology. |
| Maturity | TRL 4-9 |
| Possible technology suppliers | Spilling, Piller, Kobelco Compressors Co., ToCircle, Weel &Sandvig, Epcon, SRM |

### 3.1.3. Applications with large temperature glide

The heat pump concepts described in the following are particularly suitable for heating process streams over a large temperature glide. Heat pump concepts can exploit efficiency advantages by matching the $T, \dot{H}$-profile of a heat sink closely as it can be done by sensible gas cooling in contrast to an isothermal heat transfer during condensation of a subcritical heat pump.

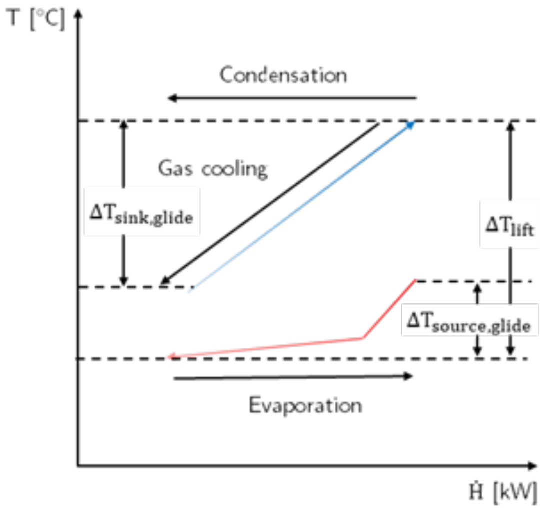



*Figure 3-14: $T, \dot{H}$-diagram of heat sink with large temperature glide*

Relevant examples are domestic and process hot water heating and drying processes.

Hot water at a temperature level between 60 °C and up to 90 °C is used in processes like washing, rinsing, cleaning and degreasing. These are widespread processes with high water consumption and a high temperature spread between the low temperature level of groundwater or well water and the respective target temperature.

Drying is an energy-intensive process with a wide range of applications and temperature requirements as well as a very high level of waste heat in the form of hot humid exhaust air, see Figure 3-15. By incorporating a heat pump into this setup, the aim is to capture and recycle the thermal energy present in the expelled hot gases (mostly the water vapor expelled by the product), thereby reducing energy waste and improving the dryer energy efficiency. The primary objective of integrating a heat pump with a convective dryer is to optimize energy usage, enhance drying efficiency, and potentially reduce operational costs. This innovative approach allows for better utilization of available heat energy, minimizes environmental impact by lowering energy consumption, and contributes to sustainability efforts within industrial drying processes.

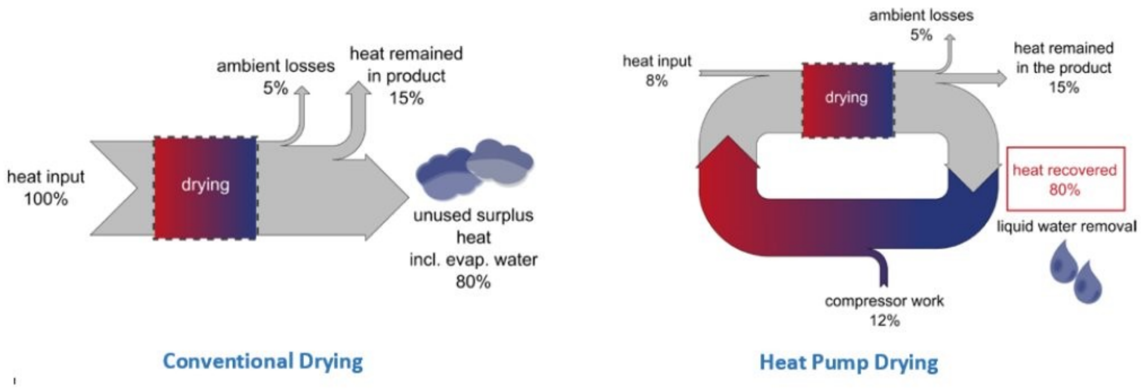



*Figure 3-15: Energy flow diagram of a convectional and a heat pump integrated dryer* [115]

In conventional, fresh air operating dryers ambient air is heated to a target drying temperature range between 120 and 200 °C. In spray dryers, for example, the product feed to be dried is sprayed finely dispersed into the the drying air. The necessary heating enthalpy usually comes from natural gas-fired boilers like shown in Figure 3-16.

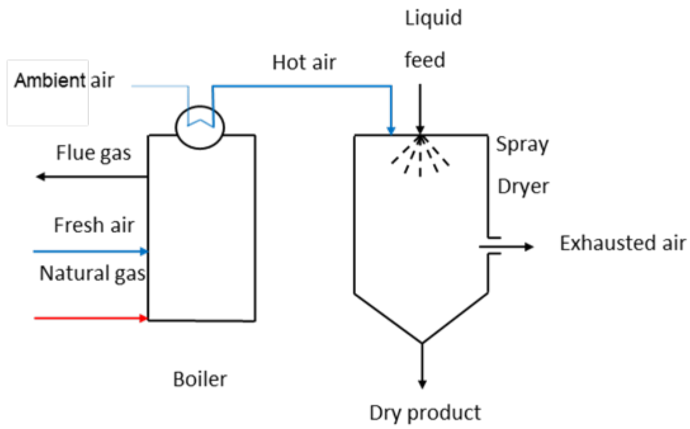



*Figure 3-16: Conventional energy supply system of a drying process*

In continuous drying applications, heat pumps can utilise the latent enthalpy of evaporation in humid exhaust air to preheat drying air like shown in Figure 3-17. Some of the sensible heat and evaporation enthalpy is recovered by cooling and dehumidifying the humid exhaust air. After upgrading to a usable temperature level by the heat pump, the incoming supply air can be (pre-) heated before the actual drying. In terms of hot water heating the medium is water and the heat source is ambient or waste heat from various site-specific heat sources.

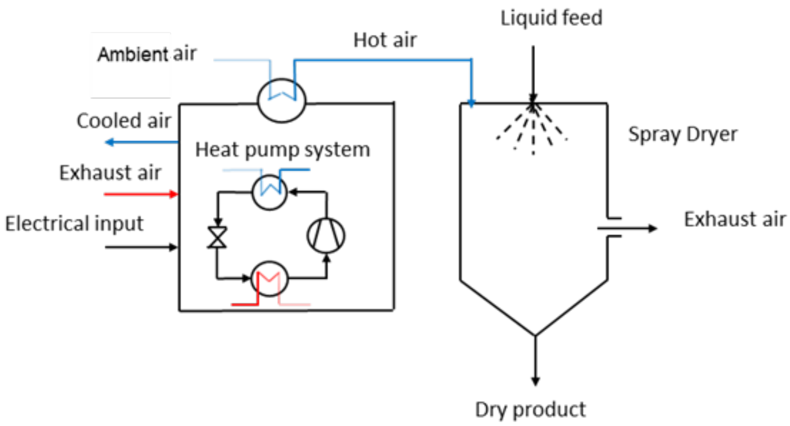



*Figure 3-17: Integration of a heat pump into a drying process*

**Detailed description of heat pump concepts**

*Heat pump concept A: Transcritical single-stage cycle with gas bypass, ejector, or expander*

This concept uses $CO_2$ (R-744) as a working fluid (see Section 3.1.1). The evaporation process is subcritical while the heat rejection is realized in the transcritical region. In this region, the working fluid experiences a large temperature glide, which can result in high performances, if the temperature profile matches well with the heat sink as shown by Figure 3-18 with an exemplary flow sheet for an R-744 cycle with expander. The detailed description of the concept is reported in Table 3-2.

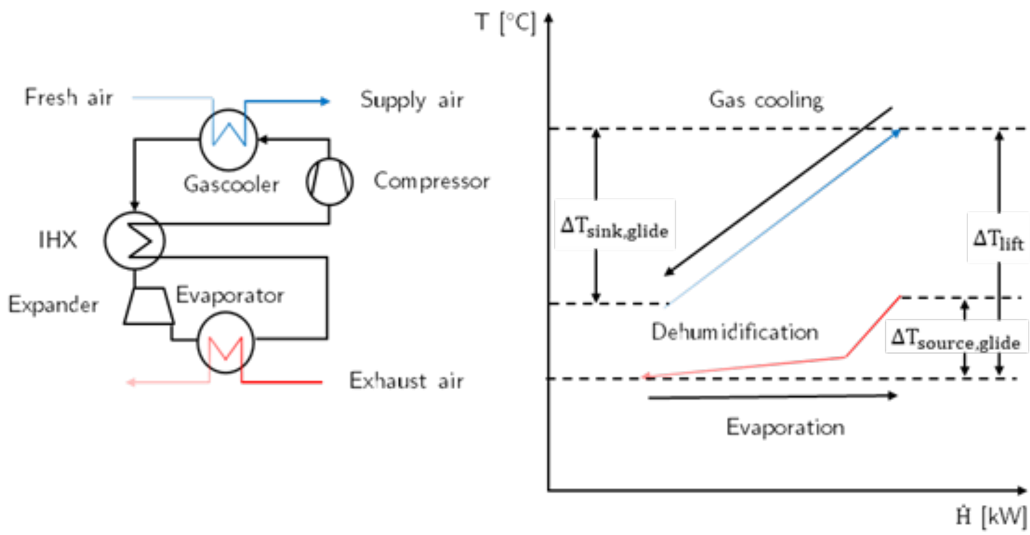



*Figure 3-18:* Example of flow sheet for R-744 cycle and T-H.-diagram for transcritical cycle

*Heat pump concept B: Transcritical, cascaded cycles with gas coolers, gas bypass, ejector, or expander*

The cascade cycle in Figure 3-19 consists of two refrigeration circuits (low-temperature and high-temperature/pressure refrigeration circuit) that are connected by a heat exchanger. The refrigerant of the low temperature circuit condenses in this heat exchanger, while the refrigerant of the high temperature circuit evaporates at the same time. In this configuration, each individual refrigerant circuit has to overcome a lower pressure ratio than in the single-stage configuration, which leads to an increase in efficiency, especially at high temperatures. However, the additional heat exchanger increases the overall temperature lift. Figure 3-19 shows an example of a cascade heat pump cycle (see Section 3.1.1).

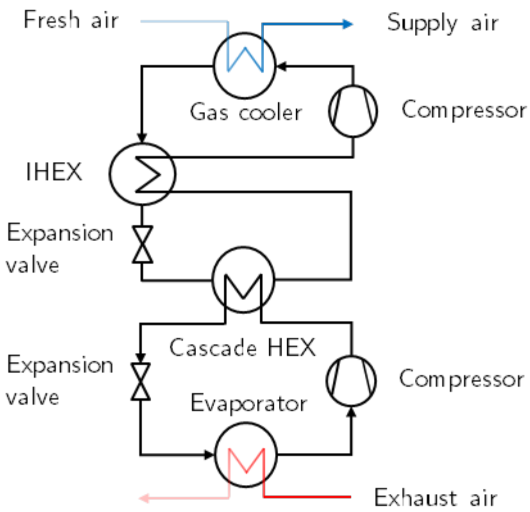



*Figure 3-19: Transcritical cascaded CO2 heat pump with IHX*

*Table 3-7: Fact box with detailed description of heat pump concepts*

| | |
|---|---|
| System type/name | Transcritical, cascaded cycles with gas coolers, gas bypass, ejector, or expander |
| Short description | • Piston, screw and turbo compressors<br>• Working fluid depending on temperature domain: Hydrocarbons (R-600, R-600a, R-601, R-601a,) or hydrofluoroolefins (R-1233zd(E) or R1234ze(E)), R-744 ($CO_2$), zeotropic mixtures<br>• Various cycle arrangements possible, including internal heat exchangers and subcooling.<br>• High design flexibility<br>• High potential in applications with large temperature glides (over 40 K)<br>• Internal HEX and expanders can increase the performance |
| Capacity ranges | 0.1 MW to above 50 MW – depending on compressor type |
| Expected performance | |
| System complexity and estimated cost level | Complexity depends on number of different stages and cycles. Overall, a specific investment cost for the installed system without integration is expected between 200 €/kW to 800 €/kW. |
| Main advantages | • Can utilize high temperature glides efficiently<br>• Flexible design offering optimal integration of heat recovery and supply at multiple temperatures<br>• Equipment based on refrigeration systems, building on broad knowledge and distribution channels<br>• Fast regulating units<br>• Compact and cost-effective installation<br>• Natural refrigerants possible. |
| Main challenges | • Lubrication of compressors for screw and piston<br>• ATEX measures for flammable refrigerants<br>• Limited performance for low temperature glides |

| | |
|---|---|
| Maturity | • By 2021, the first prototypes were demonstrated in laboratory and industry, corresponding to TRL 6-7.<br>• Larger availability from various component and system suppliers with an increasing number of demonstrations in the industry expected by 2023 to 2024, corresponding to TRL 7-9.<br>• Various commercial products up to 160 °C expected by 2023/2024.<br>• R744: Up to 120 °C demonstrated in MW scale<br>• R744: Up to 150 °C above 10 MW demonstrated in lab expected commercially available soon<br>• Hydrocarbons/HFOs: Up to 200 °C demonstrated in lab expected commercially available by 2025 |
| Possible technology suppliers | There are several compressor suppliers for hydrocarbon compressors, e.g: Mayekawa, JCI, BOCK, Frascold, GEA, Bitzer, Dorin |

*Heat pump concept C: Stirling heat pump*

The Stirling process consists of two isochoric and two isothermal changes of state and is realised in a machine with two chambers connected by two pistons. As a heat pump, the Stirling cycle works in reverse and is particularly suitable for very high temperature lifts. As can be seen in Figure 3-20, an isothermal compression of a gas such as helium takes place in the first chamber. To keep the gas at a constant temperature during the volume change, work is done, and heat is transferred to the heat sink. The gas is then transferred to the second chamber at a constant volume, the regenerator is heated, and the gas is cooled. To achieve a constant volume, the movement of the two pistons is mechanically synchronised. Finally, the gas is expanded isothermally, the work of volume change is released, and the piston is moved to heat the gas by the heat source to keep the temperature constant. The gas is returned to the first chamber at constant volume, and the gas is heated by the regenerator.

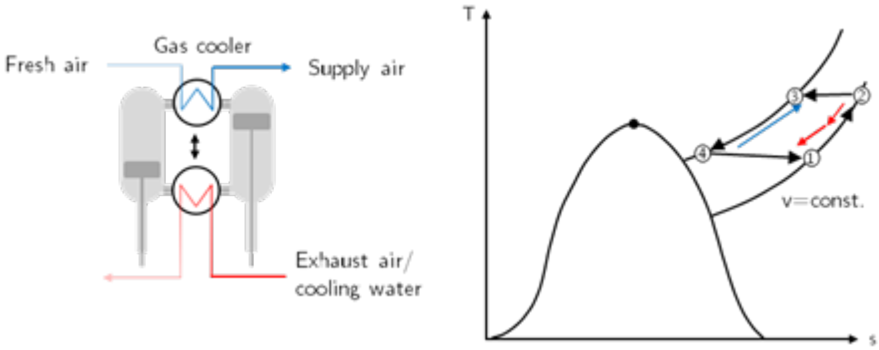



*Figure 3-20: Example of flow sheet and T-s diagram of a Stirling heat pump. 1-2: constant volume heat addition; 2-3 isothermal compression; 3-4 constant volume heat removal; 4-1 isothermal expansion*

*Table 3-8: Fact box with detailed description of heat pump concepts*

| **System type/name** | Stirling heat pump |
|---|---|
| **Short description** | • R704 (Helium), $N_2$<br>• Reversed Stirling cycle<br>• Double-acting piston compressors<br>• Only gas-phase operation<br>• Supply temperature up to 250 °C |

| | |
|---|---|
| **Capacity ranges** | 0.3 to 1 MW |
| **Expected performance** | <table><tr><td>$T_{source,in}$ [°C]</td><td>$T_{source,out}$ [°C]</td><td>$T_{sink,in}$ [°C]</td><td>$T_{sink,out}$ [°C]</td><td>$COP_{heating}$ [-]</td></tr><tr><td>85</td><td>65</td><td>206</td><td>212</td><td>2.0-2.15</td></tr><tr><td>16</td><td>12</td><td>206</td><td>212</td><td>1.6-1.7</td></tr><tr><td>135</td><td>113</td><td>154</td><td>160</td><td>3.3-3.7</td></tr><tr><td>80</td><td>50</td><td>154</td><td>160</td><td>2.2-2.45</td></tr><tr><td>16</td><td>12</td><td>154</td><td>160</td><td>1.75-1.9</td></tr></table> |
| **System complexity and estimated cost level** | 1200 €/kW |
| **Main advantages** | High supply temperatures and temperature lifts possible |
| **Main challenges** | |
| **Maturity** | • Industrial pilot installations in pharmaceutical and dairy industry with up to 50000 h industrial operating experience<br>• TRL: 6/7 |
| **Possible technology suppliers** | • HighLift from Olvondo<br>• HoegTemp from Enerin |

*Heat pump concept D: Reversed Brayton Cycle heat pump*

The reverse Brayton cycle works without a phase change in the gas phase of the working medium. As this is gaseous, only sensible heat exchange takes place. It is therefore well suited for heat sources and sinks with large temperature glides. Figure 3-21 shows the changes in state. The first change is an isentropic compression to a higher temperature and higher pressure. After this, an isobaric heat transfer to the heat sink takes place in the gas cooler before the gas expands isentropically. Finally, heat is isobarically absorbed from the heat source.

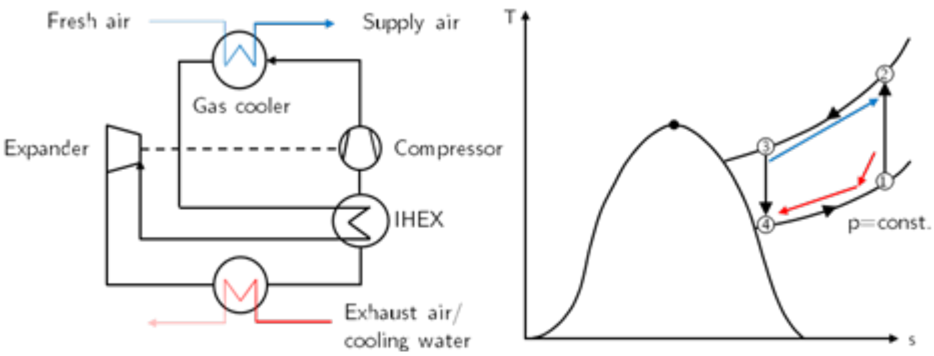



*Figure 3-21: Example of flow sheet and T-s diagram of the Reversed Brayton Cycle. 1-2: isentropic heat compression; 2-3: isobaric heat removal; 3-4: isentropic expansion; 4-1: isobaric heat addition*

*Table 3-9: Fact box with detailed description of heat pump concepts.*

| | |
|---|---|
| **System type/name** | Reversed Brayton cycle |
| **Short description** | • Natural refrigerants: R-744 ($CO_2$), R-729 (Air), R-740 (Argon)<br>• Mainly turbocompressor<br>• Only gas-phase operation<br>• Temperatures up to 400 °C and higher |

| | |
|---|---|
| | • The maximum compressor discharge temperature was found to be high enough to supply a process stream of up to 480 °C while high pressures of up to 140 bar were expected to be feasible.<br>• shell and tube heat exchanger<br>• Potential use in Carnot batteries (Pumped Thermal Electricity Storage |
| **Capacity ranges** | • large-scale applications with large-scale equipment from chemical processes with compressors up to 40 MW |
| **Expected performance** | • Carnot battery based on $CO_2$: heat source at 60 °C, COP of 1.3 for supply heat at 465 °C |
| **System complexity and estimated cost level** | • Components commercially available from chemical industry |
| **Main advantages** | • Can utilize high temperature glides efficiently |
| **Main challenges** | • Limited performance for low temperature glides |
| **Maturity** | • Simulation studies<br>• Lab-scale demonstration facility: German Aerospace Center: Brayton cycle test facility in Cottbus (CoBra) using dry air as working fluid with target temperatures up to 300 °C and a capacity of 250 kW<br>• TRL: 3/4 |
| **Possible technology suppliers** | |

# 4. Recommendations for the selection of integration concepts for given applications

The integration concepts can be categorized according to the heat pump applications: steam production, hot water production, applications with large temperature glides.

**Applications with large temperature glides:** Drying processes frequently involve large temperature glides on the heat sink side. Heat pump concepts can exploit efficiency advantages by matching the temperature-load profile of a heat sink closely as it can be done by sensible gas cooling in contrast to an isothermal heat transfer during condensation of a subcritical heat pump. In drying processes, the simultaneous occurrence of heat sinks in the form of drying air and heat sources in the form of hot, moist exhaust air is obligatory. Depending on the drying air and exhaust air temperature, high temperature lifts must be overcome. This can be achieved using cascaded heat pumps or technologies with high temperature lifts, such as the Stirling heat pump. To integrate them into a drying process at the process level, the following heat pump concepts can be used for heating along large temperature glides:

- Transcritical single-stage cycle with gas bypass, ejector or expander using R-744 ($CO_2$)
- Transcritical, cascaded cycles with gas coolers, gas bypass, ejector or expander using R-744, hydrocarbons or hydrofluoroolefins
- Stirling heat pump using R-704 (helium), R-728 (nitrogen)
- Reversed Brayton cycle using R-744, R-729 (air), R-740 (argon)

**Steam production:** Integration concepts for processes within the unit operations thermal separation, preservation, and treatment primarily rely on steam as an energy carrier medium due to its efficient heat transfer properties and existing and smaller-sized heat exchanger equipment. Steam is also used as a reactant when it is brought into direct contact with the product, such as pasteurization with steam injection. Another possible application is drying with superheated steam, for example, in the textile, food, or paper industry. Typical heat sources are cooling loads, waste heat streams, or vapours that can be recompressed. The following concepts can be applied depending on the required steam pressure and temperature:

- Direct steam-generating compression heat pumps using hydrocarbons or hydrofluoroolefins
- (Classic) heat pump for hot water production using a flash tank for steam generation
- Direct steam generating heat pump in combination with downstream steam compressor
- Steam compression in combination with an evaporator for steam generation

**Hot water production:** Heat supply with hot water is used in several applications and industries, such as process heating utility, e.g., in the pharmaceutical and food industries. Typical supply temperatures are in the range of 90 °C to 140 °C, with a corresponding pressure that ensures the water is in liquid form. In addition, applications based on other liquid energy carriers, such as thermal oil, are also described in this context. The heat source for the heat pump can be excess heat from the process, resulting in a reduced load of the cooling system, or another internal or external heat source. For hot water production, there are various potential heat pump concepts with promising thermodynamic and economic performances for a variety of applications. The obtainable performance, and thereby the competitiveness of each concept, depends on the specific boundary conditions, such as the temperature profile of the heat source and the heat sink. The following heat pump concepts can be applied:

- Single-stage, multi-stage, and cascade heat pump cycle using hydrocarbons or hydrofluoroolefins
- Transcritical single-stage cycle with gas bypass, ejector or expander using R-744
- Hybrid absorption compression heat pump using R-717/R-718 (ammonia/water)

Moreover, for heat pump integration, a storage device can be included both on the sink and on the source side of the heat pump. This is especially important if the demand does not coincide with the availability of the waste heat source.

The use of standardized templates allows for a structured collection and presentation of information. Despite explanations for defining the input, the consistent application of the terms and definitions for the heterogeneous processes by different authors was challenging, requiring a thorough review. The heat pump concepts aim to raise awareness of their application potential and are not intended to be comprehensive. Other heat pump concepts beyond those mentioned are possible. It should also be kept in mind that some of the heat pump concepts mentioned are still under development and are therefore only available on a laboratory scale. Further information on the development status and market maturity of HTHP technologies can be found in the final report of IEA HPT Annex 58 Task 1 [116].

Figure 4-1 provides an overview of process types and influencing parameters for characterising heat sources and heat sinks. It also provides qualitative recommendations on which heat pump concepts from the different heat pump application are suitable for fulfilling the different process requirements. Figure 4-1 summarises and categorises the main thermal processes in the report within the temperature range above 100 °C into the following basic operations: drying, hot water heating, thermal separation, thermal preservation and thermal treatment.

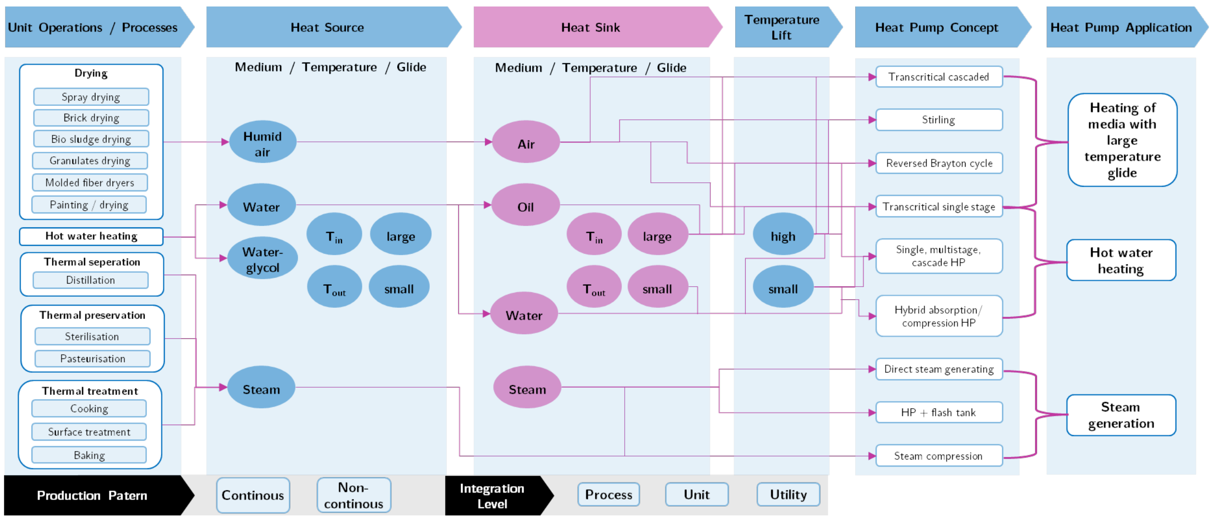



*Figure 4-1: Matching for blueprint integration concepts*

The warm, humid exhaust air is usually available as a heat source for the drying processes in order to heat the drying air accordingly by the heat pump. Depending on the target temperature, the temperature lift and the temperature glide, single stage (for smaller temperature lifts) or cascaded transcritical (for larger temperature lifts) as well as Stirling (for high target temperatures and large temperature lifts) or reversed Brayton cycle (for high temperature glides) heat pump concepts for heating of media with large temperature glides are available. A similar logic applies to the heating of hot water or thermal oil. The unit operations of thermal separation, thermal preservation and thermal treatment involve steam-consuming processes. Depending on the target temperature and whether the vapour can be directly recompressed or other heat sources need to be used, the following heat pump concepts are available: direct steam-generating heat pumps and optionally downstream steam compressor, heat pumps using a flash tank for steam generation or steam compression in combination with evaporator or by mechanical vapor compression.

In addition, production pattern such as continuous or non-continuous operation influences the need for thermal storage. The integration concepts are also differentiated according to their integration level.

# 5. Summary and conclusions

The report shows that HTHPs can be integrated into a wide range of industrial processes. However, the best practices for system layout and conditions vary depending on the specific case. To find the optimal integration concept for each process, it is crucial to understand the process requirements and it may be necessary to examine industrial sector profiles, applications, temperature conditions, energy, and Pinch Analysis. Pinch Analysis provides a graphical representation for targeting integration points accurately.

It was found that unit operations share similar process requirements. Therefore, heat pump concepts can be standardized to meet these requirements and can be assigned to the three basic applications:

- steam generation,
- hot water production, and
- heating along large temperature glides.

Based on these findings, recommendations were developed for the selection of sensible heat pump concepts for processes within the same unit operation. A comprehensive overview of application potentials was created.

**Fel! Hittar inte referenskälla.** provides a comprehensive overview of application potentials including:

- 12 Processes, falling under the categories of drying (6), thermal treatment (3), thermal separation (2), and thermal preservation (1)
- 27 Integration Concepts
- 15 Heat Pump Concepts

*Table 5-1: Overview of integration concepts*

| | Process | | | Source | | | | Sink | | | | Temperature ranges [°C] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Unit Operation | Production Pattern | Medium | $T_{in}$ [°C] | $T_{out}$ [°C] | $\Delta T_{Glide}$ [K] | Medium | $T_{in}$ [°C] | $T_{out}$ [°C] | $\Delta T_{Glide}$ [K] | 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 | Mean $\Delta T_{Lift}$ [K] | Integration Level | Heat Pump Concept | Heat Pump Application |
| 1. | Baking ovens | Baking | Continuous | Humid air | 110 | 90 | 20 | Air | 180 | 220 | 40 | | 100 | Unit | Transcritical cascaded | Heating along large temperature glides |
| | | | | | 90 | 65 | 25 | | 150 | 180 | 30 | | 88 | | | |
| 2. | Molded fiber dryers | Drying | Continuous | Humid air | 150 | 70 | 80 | Air | 150 | 250 | 100 | | 90 | Process | Reversed Brayton cycle | Heating along large temperature glides |
| | | | | | 150 | 100 | 50 | Steam | 150 | 165 | 15 | | 33 | | Single HP | Steam generation |
| 3. | Spray Drying | Drying | Continuous | Humid air | 50 | 20 | 30 | Air | 64 | 210 | 146 | | 102 | Process | Cascaded HP | Heating along large temperature glides |
| | | | | | 70 | 15 | 55 | | 15 | 210 | 195 | | 70 | | Transcritical cascaded | |
| | | | | | 50 | 23 | 27 | | 64 | 210 | 146 | | 101 | | Reversed Brayton cycle | |
| | | | | Water | 40 | 12 | 28 | | 15 | 210 | 195 | | 87 | | Cascaded HP | |
| | | | | | 40 | 12 | 28 | | 15 | 210 | 195 | | 87 | | Transcritical cascaded | |
| | | | | | 40 | 12 | 28 | | 64 | 210 | 146 | | 111 | | Reversed Brayton cycle | |
| 4. | Brick Drying | Drying | Continuous | Air (Water intermediate circuit) | 50 | - (*) | - (*) | Air (Water intermediate circuit) | - (*) | 180 | - (*) | | - (*) | Unit | Cascaded HP | Heating along large temperature glides |
| | | | Continuous | | 50 | - (*) | - (*) | | - (*) | 90 | - (*) | | - (*) | | Single HP | Heating along large temperature glides |
| 5. | Painting & Drying | Drying | Non-continuous | Humid air | 28 | 22 | 6 | Liquid | 130 | 150 | 20 | | 115 | Unit | Cascaded HP | Heating along large temperature glides |
| | | | | | | | 6 | | 70 | 90 | 20 | | 80 | | | |
| 6. | Biosludge drying | Drying | Continuous | Steam | 120 | 100 | 20 | Steam | 100 | 146 | 46 | | 13 | Process | Steam compression | Steam generation |
| 7. | Plastic granules | Drying | Continuous | Humid air | 60 | 30 | 30 | Air | 50 | 80 | 30 | | 20 | Process | Transcritical single stage | Heating along large temperature glides |
| 8. | Batch Sterilization | Thermal preservation | Batch | Water | 40 | 20 | 20 | Water | 100 | 150 | 50 | | 95 | Utility | Trancritical HP | Heating along large temperature glides |
| | | | | | 80 | 52 | 28 | Steam | 80 | 130 | 50 | | 39 | | Flash tank + MVR | Steam generation |
| 9. | Distillation | Thermal separation | Continuous | Water | 65 | 60 | 5 | Steam | 110 | 115 | 5 | | 50 | Utility | HP + flash tank | Steam generation |
| | | | | | 27 | 22 | 5 | Steam | 105 | 115 | 10 | | 86 | | Cascaded HP | |
| | | | | | 45 | 40 | 5 | Steam | 100 | 115 | 15 | | 65 | | SGHP/Flash tank + MVR | |
| 10. | Anodizing | Utility water heating | Non-continuous | Water | 60 | 50 | 10 | Water | 82 | 95 | 13 | | 34 | Unit | Single HP | Hot water production |
| | | Thermal treatment | | | 20 | 15 | 5 | Steam | 110 | 120 | 10 | | 98 | | Cascaded HP | Steam generation |
| | | Utility water heating | | | 40 | 35 | 5 | Water | 80 | 85 | 5 | | 45 | | Single HP | Hot water production |
| | | Thermal treatment | | | 20 | 15 | 5 | Steam | 110 | 120 | 10 | | 98 | | Cascaded HP | Steam generation |
| 11. | Oil and Gas Processing | Thermal separation | Continuous | Oil | 70 | 50 | 20 | Oil | 85 | 105 | 20 | | 35 | Process | Transcritical single stage | Heating along large temperature glides |
| | | | | Water-glycol | 45 | 35 | 10 | | 100 | 140 | 40 | | 80 | Supply | Cascaded HP | Hot water production |
| 12. | Extrusion cooking | Thermal treatment | Continuous | Humid air | 50 | 45 | 5 | Water | 100 | 160 | 60 | | 83 | Process | Transcritical single stage | Hot water production |

*(*: depending on the exact design and application)*

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