Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Department of the Environment, Transport, Energy and Communications DETEC
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

16 September 2024

Annex 58 HTHP-CH – Integration of HTHPs in Swiss Industrial Processes

Appendix 5

Integration Guidelines Report

Industrial heat pump integrated in the energy centre of a Swiss company (Photo: C. Arpagaus, OST, 4 June 2024)

Date: 16 September 2024

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:
OST Ostschweizer Fachhochschule
Institute for Energy Systems (IES)
Werdenbergstrasse 4, CH-9471 Buchs SG 1, www.ost.ch/ies

EPFL Valais
IPESE – SCI-STI-FM
Rue de l'Industrie 17, CH-1951 Sion, www.epfl.ch

HEIG-VD
Institute of Energies (IE)
Avenue des Sports 20, CH-1401 Yverdon-les-Bains, www.heig-vd.ch

CSD INGÉNIEURS SA
Route Jo-Siffert 4, CH-1762 Givisiez, www.csd.ch

Authors:
Cordin Arpagaus, OST IES, cordin.arpagaus@ost.ch
Daniel Alexander Flórez-Orrego, EPFL SCI STI FM, daniel.florezorrego@epfl.ch
Pierre Krummenacher, HEIG-VD IE, pierre.krummenacher@heig-vd.ch
Nicole Calame, CSD INGÉNIEURS SA, n.calame@csd.ch

SFOE project coordinators:
Stephan Renz, info@renzconsulting.ch
Elena-Lavinia Niederhäuser, elena-lavinia.niederhaeuser@bfe.admin.ch

SFOE contract number: SI/502336-01

This is an appendix to the summary report on the project "Annex 58 HTHP-CH – Integration of HTHPs in Swiss Industrial Processes". The report and other appendices can be downloaded at https://www.aramis.admin.ch/Texte/?ProjectID=49514.

Summary/Overview

High-Temperature Heat Pumps (HTHPs) are advanced thermal systems that supply heat at temperatures exceeding 100 °C, suitable for various industrial applications. These HTHP systems operate on the same basic principles as conventional HPs but utilize modified components and suitable refrigerants to achieve higher temperatures. The importance of HTHPs lies in their ability to reduce energy consumption and greenhouse gas emissions (GHG) and enhance the sustainability of various industrial sectors.

These guidelines are a dissemination document to raise awareness of the present possibilities with HTHP technology. The document presents technical, financial, and socio-economic aspects and offers a global view. The target audience includes managers, technicians, planners, and engineers.

The guidelines present current HTHP technologies and demonstration cases and offer insight from basic principles to defining efficient integration concepts. It provides preliminary checklists with thinking steps from early concept to final HTHP integration, and it will lead to further information and literature references.

Overall, the document is organized into 2 levels with several degrees of detail.

PART A provides an executive summary with general information.

- First, a brief HTHP technology overview and demonstration case studies are presented.
- Next, the basics of a HP are described with the potential for HTHPs in a Swiss context.
- Then, the major benefits/reasons for installing an HTHP for decarbonization (e.g., energy efficiency, CO_2 savings, OPEX savings) are explained.
- After that, the selection criteria for HTHP technology (such as refrigerant, capacity, heat sources, and sinks) are discussed.
- Finally, a brief introduction to Pinch Analysis is given, including possible integration points, a preliminary assessment checklist of technical options, feasibility, and profitability and CO_2 emission reduction estimates.

PART B offers a more detailed technical report for technicians, planners, and engineers.

- First, it addresses practical information on applying Pinch Analysis, describing the need to analyze simultaneously heat recovery and heat pump integration (before implementation).
- Then, the main steps in data collection, defining heat transfer requirements, and temperature and mass flow measurements are described.
- Next, key technical aspects are explained, including the influence of heat pump operation and performance, infrastructure requirements, safety aspects, maintenance, technology lock-in, and further references for planning.
- Then, the importance of financial aspects with business models, costs and funding schemes and possibilities of subsidies in Switzerland are described.
- After that, the socio-economic aspects are discussed, along with the main drivers of HTHP adoption and favorable market conditions and risks.
- Finally, a web-based tool for HTHP integration is presented with an introduction, data input, optimization methods, and reporting procedure. The application of the so-called ROSMOSE tool is exemplified in two industrial case studies.

Finally, an **outlook** covers the evolution of the HTHP market and provides a future development perspective for HTHPs towards 2030.

Summary/Overview **3**
Abbreviations **7**
PART A – Executive Summary **8**
1 Swiss Context and Potential for HTHPs **8**
1.1 National Heat Pump Market 8
1.2 Addressing Swiss Industrial Heating Needs 9
1.3 Characteristics of Industrial Landscape 9
2 Basics: What is a Heat Pump? **10**
3 Overview of HTHP Technologies **13**
3.1 Available HTHP Technologies 13
3.1.1 Electrically-driven HTHPs 13
3.1.2 Thermally-driven HTHPs 13
3.2 State of the global HTHP market 14
3.3 Selection of HTHP Technology 16
3.3.1 Large Temperature Glide 16
3.3.2 Hot Water Production 17
3.3.3 Steam generation 17
4 Demonstration Case Studies **19**
4.1 Overview of Integration Concepts 19
4.2 Overview of Demonstration Cases 19
5 Brief Overview of Pinch Analysis **23**
5.1 Pinch Analysis in a Nutshell 23
5.2 Composite Curves 23
5.3 Grand Composite Curve 25
5.4 Key Principles of PA 26
5.5 GCC and Integration of a Heat Pump: Dos and Don'ts 26
5.6 Extension of the Methodology to inter-process Heat Integration 27
6 Possible Integration Points for Heat Pumps **29**
7 Preliminary Assessment Checklist **31**
7.1 Optimized Process Heat 32
7.2 Sufficient Heat Source Capacity 32
7.3 Simultaneity between the Heat Source and Heat sink 32
7.4 Temperature Level of Heat Source 32
7.5 Temperature Difference between Heat Source and Heat Sink 32
7.6 Duration of Operation 33

8 Checklist of Technical Options and Feasibility 33
9 Preliminary Estimates of Profitability and CO_2 Emission Reduction 34
PART B – Technical Report 36
1 Pinch Analysis – Practical Information 36
1.1 General information – Main steps 36
1.2 Big picture of the site (organization, energies, utilities, processes) 37
1.3 Data collection and analysis 38
1.3.1 Preliminary steps before definition of heat transfer requirements 39
1.3.2 Temperature and mass flow measurements: 41
1.4 Applying Pinch Analysis 42
1.5 Feasibility study 45
2 Technical Aspects 46
2.1 Heat Pump Operation and Performance 46
2.1.1 Heat Source and Sink 46
2.1.2 Heat Pump Efficiency 47
2.1.3 Operating Range 48
2.1.4 HTHP Specifications 48
2.2 Infrastructure Requirements 49
2.2.1 Location for the Installations 49
2.2.2 Power Supply 49
2.2.3 Distribution Network and Thermal Storage 49
2.2.4 Automation System 49
2.3 Safety Aspects 49
2.3.1 Refrigerant Fluid 49
2.3.2 Redundancy Strategy 50
2.4 Maintenance 50
2.5 Technology Lock-in 51
2.6 Further References for Planification 51
3 Financial Aspects 52
3.1.1 Importance of Financial Aspects 52
3.1.2 Business models 52
3.1.3 Costs 52
3.1.4 Funding/subsidies in Switzerland for industrial HPs 53
4 Socio-Economic Aspects 55
4.1 Drivers of HTHP Adoption 55
4.2 Favorable market conditions and risks discussion 56

5 Web-based Tool for HTHP Integration ... 58
5.1 Introduction ... 58
5.2 Data Input, Optimization Methods, and Reporting Procedure ... 60
5.2.1 LAYER tab ... 61
5.2.2 UNITS tab ... 61
5.2.3 MSTREAMS tab ... 62
5.2.4 HSTREAMS tab ... 62
5.3 Application of ROSMOSE tool to two industrial case studies ... 64
5.3.1 Introduction to Two Case Studies ... 64
5.3.2 Tixotherm Case Study ... 66
5.3.3 Cleaning-in-place (CIP) case study ... 69
6 Outlook ... 73
6.1 Evolution of the HTHP Market ... 73
6.2 Future Development Perspective for HTHPs towards 2030 ... 74
7 Literature references ... 76
Appendix ... 80
Appendix 1: Overview of HTHP products ... 80
Appendix 2: Impact of integration level on KPIs ... 82
Appendix 3: Accessing the EPFL virtual machine and installing ROSMOSE ... 83
Appendix 4: Structure of directories and files of the ROSMOSE tool ... 88
Appendix 5: Access to OSMOSE framework (backend) ... 94
Appendix 6: Template for data input using Excel software ... 96
Appendix 7: Template for data input to the HTHP superstructure ... 98

Abbreviations

CAPEX	Capital Expenditures
CCs	Composites Curves
CCHP	Closed Compression Heat Pump
COP	Coefficient of Performance
HC	Hydrocarbon
HCFO	Hydrochlorofluoroolefin
HEX	Heat Exchanger
HEN	Heat Exchanger Network
HFC	Hydroflourocarbon
HFO	Hydrofluoroolefin
HP	Heat Pump
HTHP	High-Temperature Heat Pump
IHX	Internal Heat Exchanger
GCC	Grand Composite Curve
KPI	Key Performance Indicator
MVR	Mechanical Vapor Recompression
OPEX	Operating Expenditures
ORC	Organic Rankine Cycle
PA	Pinch Analysis
RCCs	Residual Composite Curves
ROI	Return On Investment
SGHP	Steam-Generating Heat Pump
TRL	Technology Readiness Level
VCHP	Vapor Compression Heat Pump

PART A – Executive Summary

1 Swiss Context and Potential for HTHPs

1.1 National Heat Pump Market

Switzerland has been at the forefront of developing and commercializing HPs. The first European HPs were introduced in Switzerland, such as the one installed in 1877 at the salt production fields in Bex (Zogg 2008). In recent years, HP sales have reached record highs, with almost 43'500 units sold in 2023. HPs are particularly well established in the small-capacity range for the residential sector and dominate the market in new buildings. However, larger capacity HPs are less common, with about 0.5% of units sold over 100 kW in 2023, as oil and gas boilers still dominate the industrial process heat generation sector (FWS 2023).

The Energy Perspectives 2050+ (EP 2050+) demonstrate the importance of HPs in Switzerland to achieve the climate policy goals by 2050 (SFOE 2023). To achieve the target of 1.5 million HPs in total (see Figure 1; today, there are 0.3 million HPs), around 46'000 HPs must be installed annually by 2050. According to the ZERO basis scenario (net-zero emissions), the proportion of HPs in existing residential buildings must increase from 16% (2017) to 68% by 2050.

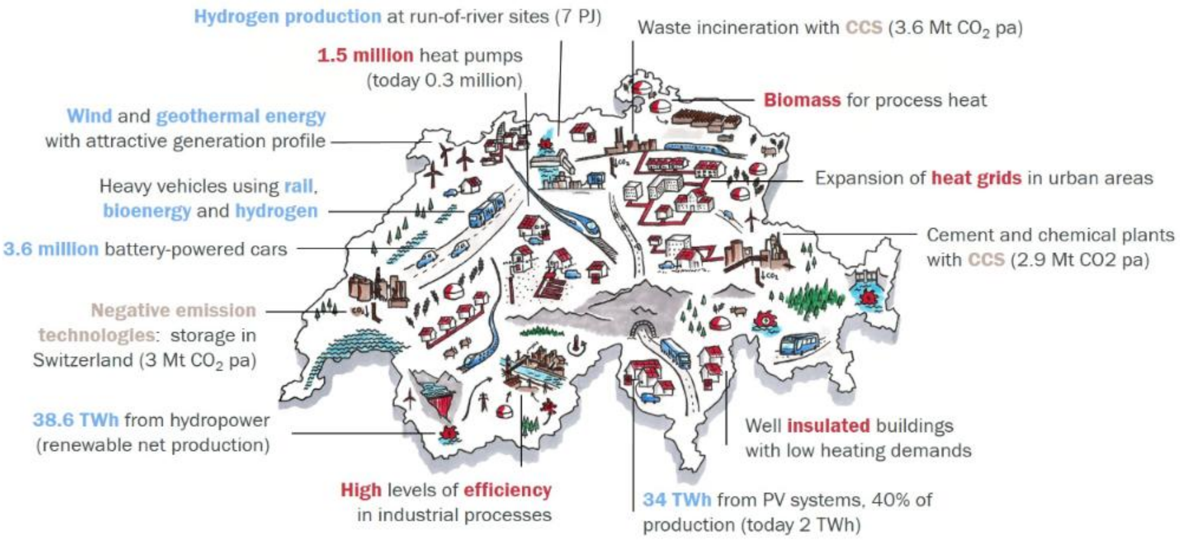


Figure 1: Objectives for a climate-neutral Switzerland by 2050 (Graphics: Dina Tschumi, Prognos AG).

To decarbonize the industry, significantly more HPs must also be installed. Therefore, HPs in the higher capacity range will also become particularly important.

Integrating high-temperature heat pumps (HTHP) into industrial processes not only aids in energy savings and CO_2 reduction but also aligns with Switzerland's Energy Strategy 2050 (BFE 2021), which aims to expand renewable energy and increase energy efficiency. HTHP technology is a key component in the federal government's strategy to achieve net-zero carbon emissions by 2050. As the market for HTHPs grows, it presents substantial opportunities for technological advancements and economic benefits within the Swiss industrial sector.

In Switzerland, manufacturers like Friotherm AG, MAN Energy Solutions AG, Walter Wettstein AG, Scheco AG, and CTA AG offer HTHP technology with supply temperatures above 100 °C (Arpagaus et al. 2024a).

1.2 Addressing Swiss Industrial Heating Needs

In 2022, the national industrial sector consumed about 40,9 TWh of energy (42.4 TWh in 2021), of which about 54% corresponds to process heat (> 80 °C), aside from space heating and hot water (BFE 2022).

The Heat Roadmap Europe (EU-28 2017) states that heat and steam needs below 150 °C account for about 30% of this consumption. Assuming a 40% technology shift to HPs and HTHPs, the energy savings potential can be estimated at around 2,755 GWh per year (as of 2022), which is approximately 6.7% of the total process heat demand (Arpagaus et al. 2022d). Besides recovering waste heat, HPs can deliver a twofold heating and cooling service while removing heat from the source side, thus further increasing the benefit.

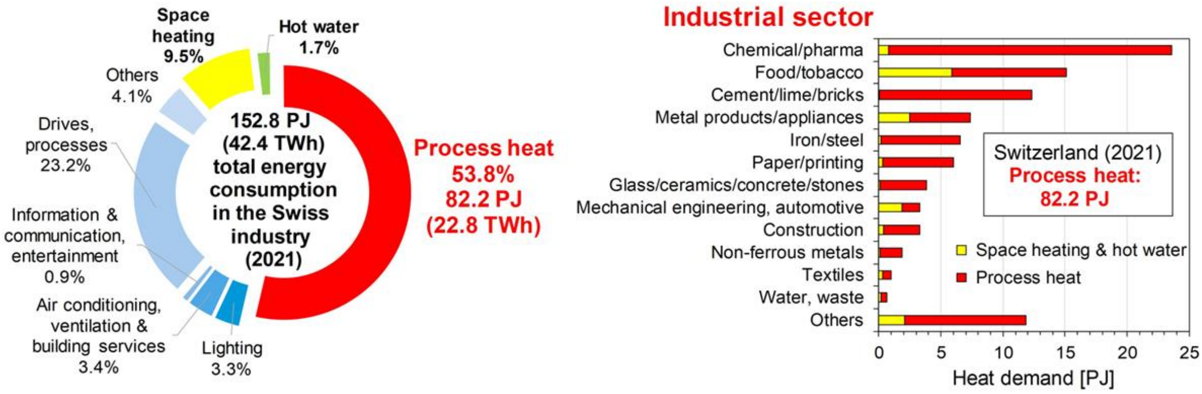


Figure 2: Process heat demand (> 80 °C) in the Swiss industry (2021) representing 54% of all energy needs and showing the potential for HP and HTHP integration in the industrial sector (Arpagaus et al. 2023c), Data adapted from SFOE (2021).

HTHPs that supply heat above 100 °C are crucial for replacing fossil fuels in production processes such as drying, evaporation, sterilization, distillation, pasteurization, cooking, washing, or dyeing. To this end, waste heat between 30 °C and 70 °C can be used as source heat to supply high-grade process heat demands ranging from 80 °C to 150 °C. Small to middle heating capacity HPs (30 to 100 kW) for integration at the process level also have a role to play.

Target markets for decarbonization of process heat in Switzerland with high potential for using HTHPs are the chemical/pharmaceutical, minerals, food/beverage, metal, and paper industries, as shown in Figure 2. The most promising sectors in terms of complementarity between available waste heat at 40 to 60 °C and process heat demand at 100 °C to 150 °C are expected to be the chemicals and pulp/paper industries(where almost all the demand at these temperatures can be covered by the use of industrial HPs), and the food industry (25% coverage rate) (Calame et al. 2017). In addition, the iron and steel industry also shows potential for waste heat recovery through industrial HPs.

Based on a study from EPFL (Wallerand et al. 2020), the most promising industrial sectors for HP integration are the food and beverage sector (overall carbon mitigation potential between 25 to 58% and payback times from 3 to 6 years), followed by the chemical sector (total of 22 to 74% emission reduction potential with a payback of 2.1 years).

1.3 Characteristics of Industrial Landscape

Switzerland's unique characteristics set it apart from other countries, particularly regarding the following aspects (IEA HPT 2022) (Section: Swiss National Market):

- **Proximity of industries to residential areas:** Compared to other countries, industries are often located closer to residential areas in Switzerland. This proximity calls for stringent regulations and innovative solutions to minimize environmental impacts and ensure the safety and comfort of nearby residents.

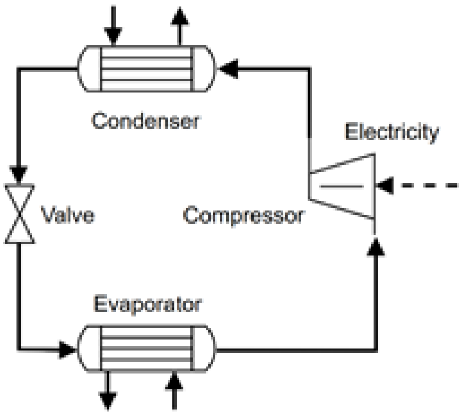
- **Specific industry mix:** The Swiss industrial landscape is distinct, with a significant presence of food and pharmaceutical/biotech sites. These industries have specific thermal energy needs that influence the adoption and integration of HP technologies.
- **Regulatory environment:** Switzerland's regulatory framework is complex, with different regulations at the municipality, canton, and national levels. This multi-layered regulatory environment impacts how HPs can be implemented across various regions.
- **Subsidy landscape:** Switzerland has a well-defined subsidy landscape that supports adopting renewable energy technologies, including HPs. These subsidies encourage industries and households to transition to more energy-efficient and environmentally friendly heating solutions.
- **CO_2 taxes:** The country imposes CO_2 taxes on all fossil thermal fuels (e.g., fuel oil, natural gas) to incentivize carbon emissions reductions. From 2022, the CO_2 levy is at CHF 120 per ton of CO_2. (FOEN 2022). This financial mechanism makes electrically driven industrial HPs an attractive alternative to fossil fuel-based heating systems, aligning economic incentives with environmental goals.

2 Basics: What is a Heat Pump?

Many industrial processes produce low-grade residual heat when converting high-quality energy (such as fossil fuels and electricity) into other value-added products. The industrial sector has traditionally regarded this thermal waste (or excess heat) as an undesirable side effect of the main production activity and devised means to collect and reject the excess heat to the environment.

This approach entails larger process inefficiencies and accentuated environmental impact. To tackle these issues, waste heat can be upgraded using specialized equipment called a heat pump (HP), whose working principle is the reverse of a refrigeration cycle, to supply the heating requirements partially or fully to an industrial process.

HPs use working fluids called refrigerants that can absorb low-temperature waste heat while *evaporating* in a heat exchanger (Figure 3, left). When the evaporated fluid is *compressed*, its temperature increases, facilitating the heat exchange with other process streams in a *condensing* heat exchanger. The heat upgrading effect from a lower to a higher temperature level is known as “heat pumping.” The evaporation, compression, and condensation cycle is closed by the refrigerant's adiabatic expansion and cooling. The capacity of refrigerants to achieve low temperatures is due to the Joule-Thomson effect, by which certain fluids exhibit rapid cooling accompanied by partial vaporization when *expanded* through an expansion valve, a capillary tube, or an expander.



T_cond in °C	20	30	40	50	60	70
180	1.4	1.5	1.6	1.7	1.9	2.1
170	1.5	1.6	1.7	1.8	2.0	2.2
160	1.5	1.7	1.8	2.0	2.2	2.4
150	1.6	1.8	1.9	2.1	2.4	2.6
140	1.7	1.9	2.1	2.3	2.6	3.0
130	1.8	2.0	2.2	2.5	2.9	3.4
120	2.0	2.2	2.5	2.8	3.3	3.9
110	2.1	2.4	2.7	3.2	3.8	4.8
100	2.3	2.7	3.1	3.7	4.7	6.2
90	2.6	3.0	3.6	4.5	6.1	9.1
	T_evap in °C					
					η_Lorenz =	50%

Figure 3: Typical components of a HP system (evaporator, compressor, condenser, expansion valve) (left) and COP values at different evaporation and condensation temperatures at 50% Lorenz efficiency (right).

In summary, a typical HP cycle consists of several components: an evaporator, a compressor, a condenser, and an expansion device. The main electricity demand is at the compressor, which depends on the compressor's isentropic efficiency and other design parameters.

To avoid misplacing heat pumping devices, it is important to consider the temperature levels at which waste heat is available throughout the industrial process and the corresponding pinch point (Flórez-Orrego et al., 2023). See Section 5 for more details about Pinch analysis and integrating a HP.

Since HPs are thermodynamic cycles, the ratio of the heat supply to the electrical power consumed, known as the Coefficient of Performance (COP) ($COP = \dot{Q}_{cond}/W_{el}$), is limited by the theoretical Carnot COP ($COP_{Carnot} = (T_{cond} + 273.15)/(T_{cond} - T_{evap})$). The latter is only a function of the temperature levels and does not depend on the working fluid or equipment. The ratio between the actual Carnot COP ($\dot{Q}_{cond}/(\dot{Q}_{cond} - \dot{Q}_{evap})$) and the theoretical Carnot COP is experimentally found to be around 45% to 55% (2^{nd} Law efficiency, h_{2nd}) (Arpagaus 2018; IEA HPT 2023). Although an ideal COP is virtually impossible to achieve, it can be approached by reducing the HP irreversibility.

Based on the knowledge of COP and the process heating demand ($\dot{Q}_{cond}$), the amount of heat absorbed in the evaporator ($\dot{Q}_{evap}$) and the electricity consumption (W_{el}) can be calculated as shown in Eqs.(1) to (5). Other common names for the heat absorbed in the evaporator ($\dot{Q}_{evap}$) and the heat released in the condenser ($\dot{Q}_{cond}$) are *source heat* ($\dot{Q}_{source}$) and *sink heat* ($\dot{Q}_{sink}$), respectively.

$$COP_{Carnot} = (T_{cond} + 273.15)/(T_{cond} - T_{evap}) \quad (1)$$

$$COP = h_{2nd} \cdot COP_{Carnot} \quad (2)$$

$$W_{actual} = \dot{Q}_{cond}/COP \quad (3)$$

$$\dot{Q}_{evap} = W_{el} \cdot (COP - 1) \quad (4)$$

$$\dot{Q}_{cond} = \dot{Q}_{evap} + W_{el} \quad (5)$$

According to Eqs. (1) to (5), several parameters influence the performance of a real HP system. The temperature lift ($\Delta T_{Lift} = T_{cond} - T_{evap}$) has a marked effect on the COP, as the larger the temperature lift, the lower the performance. In addition, as the temperature of the heat source drops, COP also decreases, which increases the electricity consumption. Other factors, such as the compressor polytropic efficiency, affect the HP electricity consumption. Lastly, for a given temperature lift, if the sink temperature increases, the COP of the HP also increases, which suggests the potential benefits of the higher HP operating temperatures. Figure 3 (right) shows typical COP values at 50% 2^{nd} Law efficiency.

In practice, selecting the temperature and pressure levels, the refrigerant, and the compressor and heat exchanger materials depends on a trade-off between the thermophysical and other structural constraints. The freezing and critical temperatures of the working fluid typically limit the evaporator and condenser temperatures, respectively. Moreover, the temperature and pressure are not independent for pure substances in subcritical, two-phase states. Therefore, the definition of the temperature also sets the operating pressure. To avoid air infiltration into the evaporator, the lowest cycle pressure is preferably set slightly above the ambient pressure.

On the other hand, the maximum cycle pressure is chosen to simultaneously guarantee the material integrity and the heat supply at the required process temperatures. In this regard, structural constraints (e.g., discharge pressure, sealing, isolation, flammability, etc.), vibration allowances (e.g., installation stability, noise, etc.), and space budget also impact the selection of the operating conditions and the materials used in the HP components.

Finally, due to an increasing public awareness of the environmental impact of certain refrigerants, some working fluids containing chlorine and fluorine have been banned or started to be phased out to become replaced by refrigerants with lower global warming potential (GWP) and ozone depletion potential (ODP), such as hydrocarbons, hydrofluoroolefins, ammonia, water or CO_2 (DAIKIN 2024).

Widespread assimilation of heat pumping technologies depends on several factors related to their economic profitability and attractiveness vis-à-vis other competing energy technologies (e.g., biomass boilers, electrical heaters, direct waste heat recovery, etc.), their decarbonization potential and risk perception.

Compared to conventional heating fuels (natural gas or fuel oil), favorable electricity prices make HPs more cost-effective. Thus, areas with high costs for heating fuels benefit more from switching to HPs. A higher load (or utilization) factor also improves HP's economic viability by amortizing the initial capital investment over longer periods of heat supply. HPs with higher COPs (i.e., lower electricity consumption to supply the sink heat) reduce operational costs, making them more economically attractive. Other factors, such as incentives, subsidies from governmental supporting strategies, and economies of scale, can lead to lower initial investment for HPs, thus improving their economic appeal. Finally, programs that offer financial incentives for installing energy-efficient systems, like HPs, can enhance economic feasibility.

HP technology can be decisive in the industry's efforts to decarbonize low-to-middle temperature heat supply. Replacing heating systems that rely on fossil fuels (e.g., oil, gas, coal) with HPs significantly reduces CO_2 emissions, especially if renewable electricity sources (e.g., wind, solar, hydro) are used. HPs generally have lower life cycle emissions than traditional heating systems, considering production, operation, and disposal stages (IEA 2022).

Thus, policies that set stringent limits on CO_2 emissions and implement a carbon tax for industrial heat supply can drive the adoption of industrial HPs. Advances in HP technology, such as developing more efficient compressors and refrigerants with low GWP, increase economic and environmental benefits.

Finally, informing consumers about the benefits of HPs can lead to broader market penetration and subsequent cost reductions. It is imperative to demonstrate the two-fold benefit of using HPs. On the one hand, they can help save costs by boosting waste heat recovery and upgrading while reducing fossil fuel consumption. On the other hand, HPs reduce the amount of waste heat released to the environment and, consequently, the overuse of cooling utility. In any case, it is crucial to correctly characterize the sources of waste heat within the industrial process (e.g., exhaust gas, cooling water or process stream) or from the environment (e.g., air, water, or geothermal heat source) so that the HP is adequately integrated, and the energy savings are truly achieved.

Accordingly, this report aims to identify and popularize favorable economic conditions and cost-effective decarbonization strategies linked to electrifying the industrial heat supply using HTHPs (Arpagaus et al., 2018).

3 Overview of HTHP Technologies

Various HTHP technologies can now supply heat at high temperatures, which presents an opportunity to find the right match for a given application. At this stage, it is important to remember that there is no one-size-fits-all HP in absolute terms: the best setup is the machine that fits and performs most adequately in a specific context.

3.1 Available HTHP Technologies

HTHP technological principles are grounded in thermodynamic cycles, primarily the Carnot and Lorenz cycles, which provide theoretical benchmarks for maximum achievable efficiency. Each HP type operates based on different principles, with varying COPs depending on the specific technology and application scenario. The ability of HTHPs to achieve high COP and integration with existing processes make them a critical technology for reducing industrial energy consumption and CO_2 emissions.

HTHPs can be categorized based on their driving mechanism and technological principles. Two main families of technologies, electrically and thermally driven HTHPs, are described hereafter. Section 3.3 gives insight into which type of machine is most suitable in each context.

3.1.1 Electrically-driven HTHPs

These machines use electrical energy to drive the thermodynamical cycle and can include various compressor types like piston, screw, scroll or turbo compressors. Each system has specific characteristics and applications. The different variants for the thermodynamic cycle layouts inside the HTHP are described hereunder. They are designed to achieve high performance. The most common system types include:

- **Single-stage cycle** (with or without internal heat exchanger): The simplest closed cycle concept.
- **Economizer cycle**: Increased efficiency with partial internal evaporation of the refrigerant.
- **Twin or multi cycles:** Connection in parallel or series of the sources or sinks allows higher temperature differences between source or sink temperatures.
- **Cascade cycle**: Two superposed cycles work at lower pressure ratios than a single-stage cycle and are more efficient at high-temperature lifts.
- **Condenser outlet split ejector cycle:** The expansion of the high-pressure refrigerant is used to compress and entrain low-pressure refrigerant using an ejector device to increase efficiency.
- **Transcritical cycle**: Heat released in the supercritical phase (above the critical point) by the refrigerant (usually CO_2) with a large temperature glide. Adapted for water heating from a cold source for best efficiencies.
- **Joule cycle** (or reverse Brayton cycle): The refrigerant always stays in the gaseous phase, working only with sensible heat exchanges. It is well suited for heat sources and sinks with large temperature differences.
- **Stirling cycle**: This gaseous phase cycle is mostly used in refrigeration applications at low temperatures. In the context of HTHP, it is especially adapted for high-temperature lifts.
- **Mechanical vapor recompression** (MVR): Vapor recovered from an industrial process is compressed to provide heat at higher pressure and temperature, which is then used by direct injection in a process or condensed in a heat exchanger in semi-open systems.
- **Steam compression systems:** Like MVR for recompression of low-pressure steam.

3.1.2 Thermally-driven HTHPs

These technologies use heat as the main driving energy source. Absorption (liquid-gas) and adsorption (solid-gas) HPs belong to this category, as they use sorption principles to harvest waste heat. Both absorption and adsorption systems are effective for medium to high-temperature applications, offering a sustainable alternative by utilizing low-grade heat sources.

Table 1 schematically shows how the two sorption (absorption or adsorption) processes can work, and Table 2 defines the COP with theoretical and practical values. Sorption HPs use heat at high and low-temperature levels to provide heat at a medium temperature. In contrast, heat transformers need medium-temperature heat as an input and produce heat at a higher and lower temperature. The adsorption HP has an intermittent cycle, unlike absorption HPs. Two adsorbent beds can be operated in a counter-phase to produce heat continuously. Advanced cycles can be found to improve the performance and compactness of these technologies.

Absorption machines are based on working pairs (absorbent-refrigerant) and are classified into three groups: water-based, ammonia-based, and organic-based. They run mostly with water as a refrigerant but could also use ammonia, methanol, and ethanol. Typical adsorbents are zeolites, silica gel, activated carbons, metal-organic frameworks, and composites.

Table 1: Principle of a sorption HP (left) and heat transformer (right) (L = low, M = medium, H = high) (IEA HPT 2023).

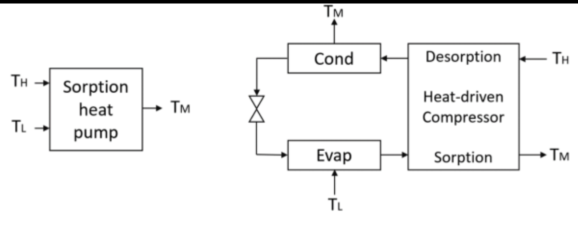
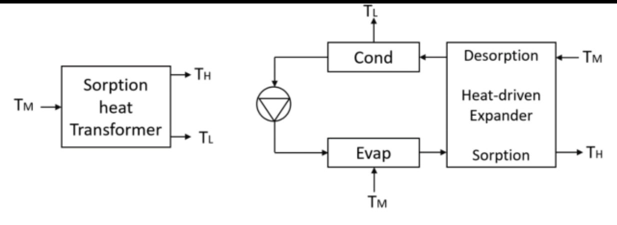
Sorption heat pump	Sorption heat transformer
	

Table 2: Definition of the COP for different technologies and typical COPs (TDHP: thermally driven HP, VCHP: vapor compression HP or "classical" HP). See Table 1 for the corresponding variables (IEA HPT 2023).

Technology	COP definition	Maximum COP	Typical COPs
TDHP – heat pump	$COP = \frac{\dot{Q}_{process}}{\dot{Q}_{high}}$	$COP = \left(1 - \frac{T_L}{T_H}\right) / \left(\frac{T_M}{T_M - T_L}\right)$	1.3 to 2.2
TDHP – heat transformer	$COP = \frac{\dot{Q}_{process}}{\dot{Q}_{waste}}$	$COP = \left(1 - \frac{T_L}{T_M}\right) / \left(\frac{T_H}{T_H - T_L}\right)$	0.2 to 0.5
VCHP	$COP = \frac{\dot{Q}_{process}}{\dot{W}_{el}}$	$COP = \frac{T_H}{T_H - T_L}$	2 to 5

3.2 State of the global HTHP market

The market for industrial HTHPs has been evolving rapidly in recent years as the industry is increasingly interested in implementing HP technologies. Figure 4 shows a graphical summary of electrically-driven HTHP products (37 technologies as of 2024) focusing on setups supplying heat at temperatures above 100 °C (Arpagaus et al. 2022e, 2024a). This overview highlights the diverse range, thus helping stakeholders understand the current state of the art and potential future developments in HTHP technologies.

The synthesis in Figure 4 is sorted by maximum supply temperature (100 °C to 280 °C) and heating capacity (logarithmical scale in MW_{th}). Included manufacturers are: Friotherm (Switzerland), MAN Energy Solutions (Switzerland), Spilling (Germany), Piller (Germany), Olvondo (Norway), Enerin (Norway), SPH Sustainable Process Heat (Germany), Heaten AS (Norway), Johnson Controls (Denmark), Fuji Electric (Japan), Mayekawa (Japan), ECOP Technologies (Austria) and others.

According to manufacturers' information, the HTHPs market includes various technologies with different technology readiness levels, from TRL 4 (feasibility demonstration) to TRL 9 (market ready). These products vary widely in terms of capacity (20 kW to 100 MW), maximum supply temperature range (100 °C to 280 °C) and specific investment costs (200 to 1’500 EUR/kW) (IEA HPT 2023).

The efficiency, price, and geographic availability of service networks influence the development and adoption of these HTHP technologies. For example, technologies for heat supply at 120 °C to 160 °C and capacities of 200 kW to 10 MW are primarily based on modified commercial and industrial refrigeration technologies. Novel technologies, such as compressors based on truck engines or turbochargers, are also being developed and tested as prototypes. HTHPs, including steam compressors and Stirling cycles, are being developed and demonstrated for higher temperature ranges above 160 °C.

The commercial rollout of these technologies is expected between 2025 and 2028, driven by the growing demand from industrial end-users (IEA HPT 2023). Appendix 1 provides a non-exhaustive list of HTHP products as of 2024.

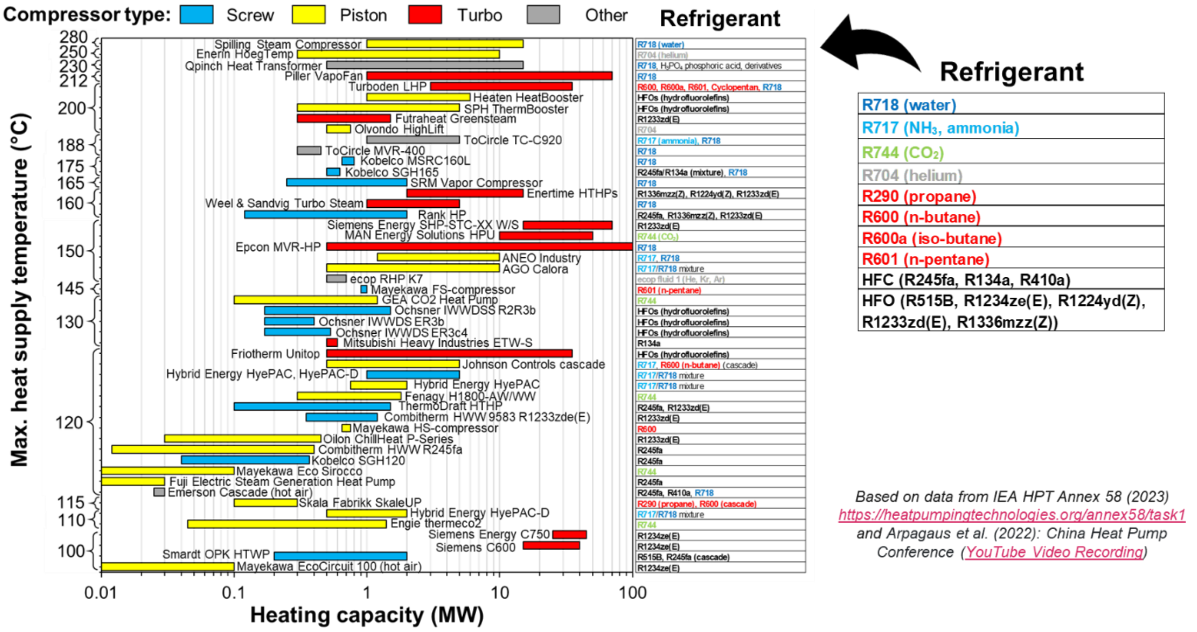


Figure 4: Market overview of industrial and large-scale HTHPs sorted by maximum supply temperature (100 °C to 280 °C) and heating capacity (logarithmical scale in MW) (non-exclusive list). The compressor technology is color-coded (blue: screw, yellow: piston, red: turbo, grey: other types). The refrigerant is indicated in the table. Note: The data are approximate values and may vary depending on the application) (Arpagaus et al. 2024a).

In addition, more HP technologies can supply heat below 100 °C, which is not shown in the graph (based on ammonia, CO_2, or R1234ze). Some of these can be obtained from Swiss manufacturers.

Indicative information about COP as a function of the lift temperature (difference between heat source and sink temperature) is shown in Figure 5 (left, right). These efficiencies are declared for:

- HTHP products with different technologies, including prototypes declared by the manufacturers
- Demonstration cases collected in the framework of IEA Annex 58 (IEA HPT 2023).

As expected, higher efficiencies are achieved with MVR systems due to the avoided exergy losses in the heat exchangers and reduced temperature lifts. Generally, a higher COP is reached by larger-scale machines rather than by small-capacity residential application HP, given the lesser losses in larger industrial-size compressors. Besides, the impact of the temperature lift on the efficiency is evidenced in the tendencies from Figure 5. Understanding that the COP of an HP is not a fixed value but can be affected by the heat source and sink conditions is essential. This comes into account when assessing the economic and environmental benefits of HTHPs, as more efficient systems are more economically attractive for industrial applications where energy costs are a significant concern.

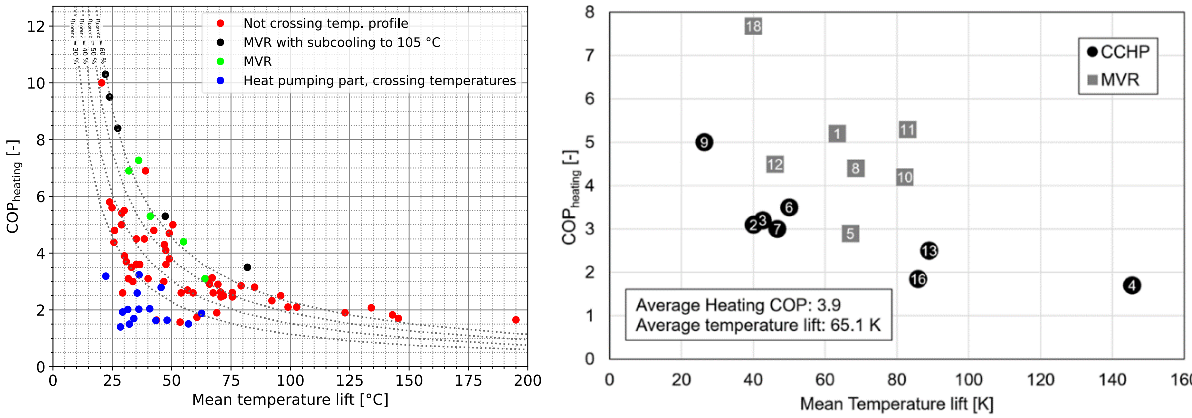


Figure 5: Indicative COP values declared by HTHP manufacturers for 37 technologies (left) and from 16 demonstration case studies (right) (IEA HPT 2023).

3.3 Selection of HTHP Technology

Each HTHP technology has advantages and drawbacks. To select the suitable HP, an overview of the processes with heating requirements at temperatures above 100°C and other influencing parameters are required to make qualitative recommendations regarding which HP type is better for a specific application. System layout and conditions are project-dependent, but unit operations share similar process requirements. The main processes targeted are drying, hot water heating, thermal separation, thermal preservation, and thermal treatment.

Three main application types will guide the choice (IEA HPT 2024a):

- large temperature glide,
- hot water, and
- steam production.

These aspects are presented in detail in the following sections.

3.3.1 Large Temperature Glide

The temperature glide is defined by the difference between a stream inlet and outlet temperatures (Figure 6). A temperature glide of more than ~20 K can be considered high.

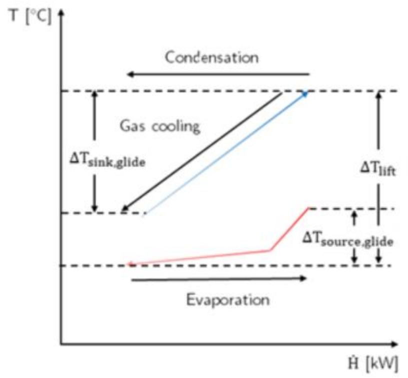


Figure 6: Temperature-enthalpy diagram of the heat sink (in blue) with a large temperature glide (IEA HPT 2024a).

Drying processes often involve significant temperature variations on the heat sink side. Some HP concepts take advantage of this characteristic by closely matching the temperature-load profile of a heat sink. This can be achieved through sensible gas cooling, which reduces exergy losses and increases efficiency.

Warm and moist exhaust air is usually available as a heat source for drying processes to heat the drying air using HP. Depending on the target temperature, the temperature lift and the temperature glide, single stage (for smaller temperature lifts, using CO_2) or cascaded transcritical (for larger temperature lifts, using CO_2, HC or HFO) as well as Stirling (for high target temperatures and large temperature lifts, using helium or nitrogen) or reversed Brayton cycle (for high temperature glides, using CO_2, air or argon) HPs are recommended. These can be integrated into a drying process at the process level.

3.3.2 Hot Water Production

Hot water is commonly used in many applications and industries as a process heating utility, e.g., pharmaceutical and food industries. Typical supply temperatures range from 90 °C to 140 °C, with a suitable water pressure. In addition, applications based on other liquid energy carriers, such as thermal oils, are also customary. The heat source for the HP can be excess heat from the process, resulting in a reduced load of the cooling system or another internal or external heat source (e.g., district heating, environment, etc.). There are various potential HP concepts for hot water production with promising thermodynamic and economic performances for multiple 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 HP concepts can be applied:

(A) Single-stage, multi-stage, and cascade HP cycle (using HC or HFO)

(B) Transcritical single-stage cycle (using CO_2)

(C) Hybrid absorption compression HP (using ammonia/water)

Possible variations on the internal thermodynamic cycle of the closed cycle HP (A) allow it to suit the specific boundary conditions best.

3.3.3 Steam generation

Integration concepts for distillation, sterilization, pasteurization, cooking, baking or surface 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 a reactant when directly contacting the product, such as in 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 vapors that can be recompressed.

If low-pressure steam is available, direct MVR is recommended. Meanwhile, thermal steam recompression is preferred if a much larger heat sink is needed than the source heat available as low-pressure steam. The concepts illustrated in Table 3 can alternatively be applied depending on the required steam pressure and temperature:

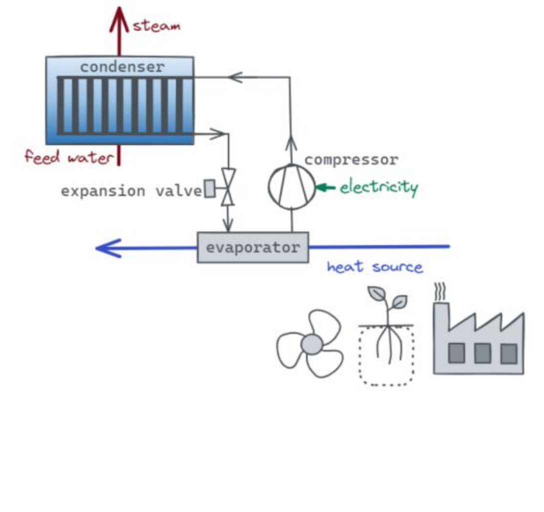
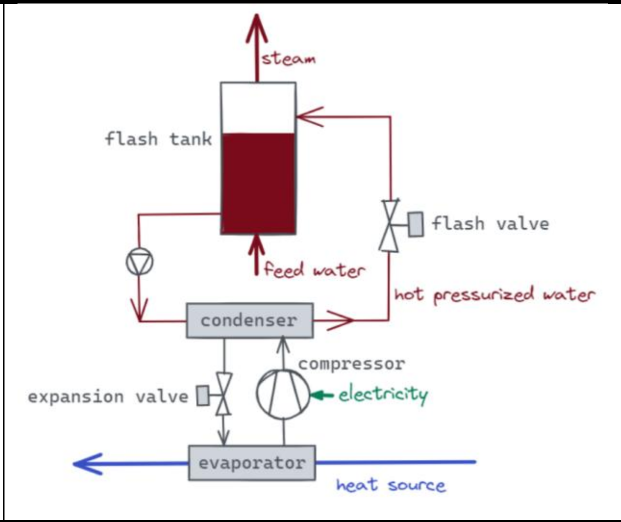
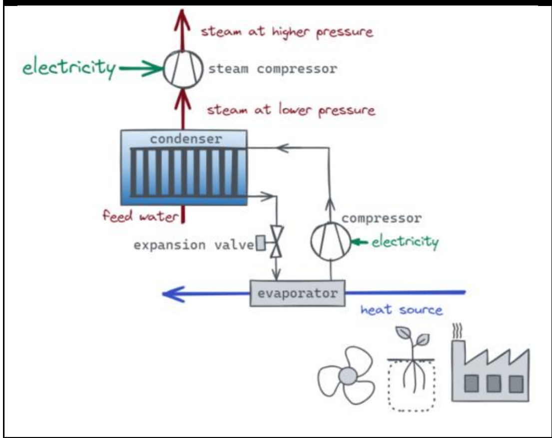
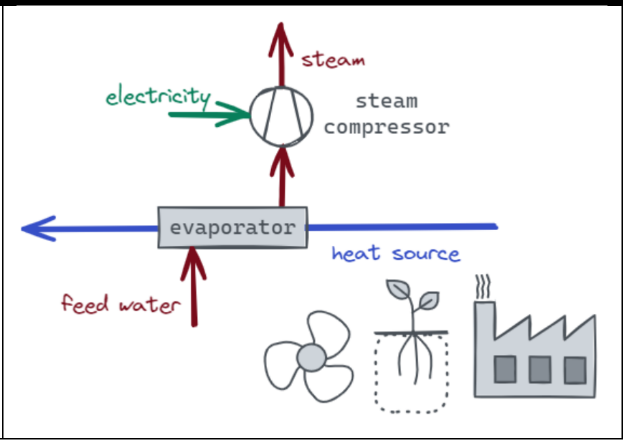
(A) Direct steam-generating compression HPs using HC or HFO

(B) (Classic) HP for hot water production using a flash tank for steam generation

(C) Direct steam generating HP in combination with downstream steam compressor

(D) Steam compression in combination with an evaporator for steam generation (vacuum conditions needed for waste heat temperatures below 100 °C)

Table 3: Illustration of steam generation concepts (A), (B), (C), and (D) (IEA HPT 2024a).

(A) Direct (once-through) steam generation	(B) HP with flash tank
	
(C) Direct (once-through) steam generation with post-compression	**(D) Compression with steam-generating evaporator**
	

Further information on HTHP technologies and integration concepts can be found in the IEA Annex 58 Task 1 and Task 2 reports (IEA HPT 2023, 2024a) and the final webinar (IEA HPT 2024b).

4 Demonstration Case Studies

4.1 Overview of Integration Concepts

HTHPs can be integrated into various industrial processes; however, the best practices for system layout and conditions vary depending on each case. To find the optimal integration concept for each process, it is crucial to understand the process requirements. It may be necessary to examine industrial sector profiles, applications, temperature conditions, energy demands, and outcomes of the PA. PA provides a graphical representation for accurately targeting integration points.

Some unit operations share similar process requirements. Therefore, HP 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 can be made for selecting suitable HP concepts for processes within the characteristics. A comprehensive overview of application potential was created in Task 2 of the IEA HPT Annex 58 project (IEA HPT 2024a). Table 2 provides a summary of application potentials for the 12 processes studied in the categories:

- drying (6),
- thermal treatment (3),
- thermal separation (2), and
- thermal preservation (1).

4.2 Overview of Demonstration Cases

Table 4 and Figure 7 summarize 18 demonstration cases and their characteristics using HTHPs collected in collaboration with HTHP manufacturers within the framework of the IEA HPT Annex 58 (IEA HPT 2023, 2024b). Most applications are in the food, chemical, sewage, and electrical industries. In addition, there are case studies from the refinery, mineral, paper, and pharmaceutical industries.

In 11 of the 18 demonstration case studies, the HTHPs generate steam. Seven cases have drying applications, three of which are steam-based and four of which are drying-air applications. Moreover, one HTHP generates hot process water. The maximum supply temperature for conventional closed compression HPs (CCHP) is 138 °C. In contrast, mechanical vapor recompression (MVR) reached 211 °C (saturation temperatures), and a sink temperature of 183 °C is reported for a Stirling HP.

The Stirling HPs achieve the highest temperature lift, followed by MVR applications. For lower temperature ranges above 100 °C, CCHP is the predominant technology. For steam generation, MVR, or a combination of HTHP, flash tank/evaporator and MVR are used. Further application case studies on industrial HPs are available in IEA HPT Annex 35 (IEA 2014) and IEA HPT Annex 48 (Jakobs and Stadtländer 2020).

Table 4: Overview of integration concepts for 12 processes based on 27 integration concepts and 15 HP concepts (*depending on the exact design and application) (IEA HPT 2024a).

	Process	Unit Operation	Production Pattern	Source Medium	Source T_{in} [°C]	Source T_{out} [°C]	Source ΔT_{Glide} [K]	Sink Medium	Sink T_{in} [°C]	Sink T_{out} [°C]	Sink ΔT_{Glide} [K]	Mean ΔT_{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)*

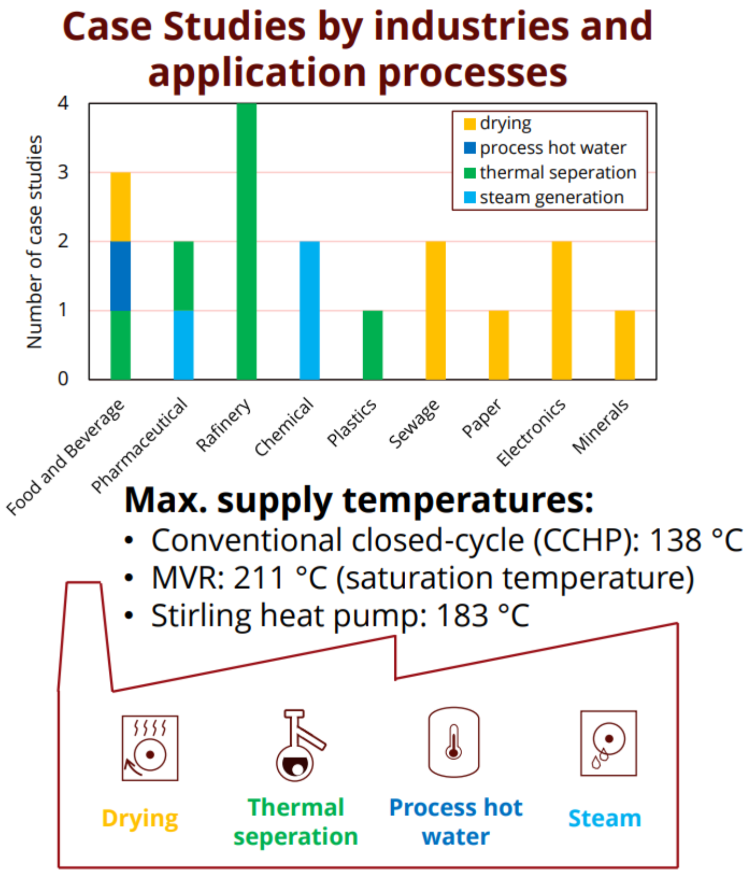


Figure 7: Overview of collected demonstration cases structured by industries and application processes (IEA HPT 2023, 2024b).

Key learnings and criteria for successful integration of HTHPs include a preliminary detailed analysis of process requirements (e.g., heat demand, temporal behavior, temperatures) and waste heat sources (e.g., amount, properties of exhaust gases and drying air and their effects on heat exchange).

Due to high pressures and temperature, challenges must be solved regarding material compatibility (e.g., lubricant, refrigerant, sealing materials), mechanical design (vibrations), infrastructure (e.g., pressure maintenance, measurement), and process control (e.g., start-up procedure, data transfer). One success criterion for economic implementation is the reduced cooling and steam demand. Furthermore, internal heat recovery cycles enable waste heat valorization from several processes at a site.

No.	Supplier	Industry	Process	Heat source			Heat sink			HP Type	Refrigerant	Compressor	Capacity	COP_H	Op. hours	Ref.
				Unit Operation	T_{out} [°C]	T_{in} [°C]	Unit Operation	T_{out} [°C]	T_{in} [°C]				[kW]		[h/a]	
1	n. a.	beverage	alcoholic distillation	product cooling	75	78.3	distillation	140	n. a.	MVR	n. a.	n. a.	350	5.2	n. a.	[1]
2	**Mayekawa**	electronic	coil drying	electro-painting cooling	25	30	drying	120	20	CCHP	R744	piston	89	3.1	n. a.	[1]
3	**AMT/AIT**	food	starch drying	waste heat	72	76	drying	138	96	CCHP	R-1336mzz(Z)	screw	374	3.2	4,000	[2]
4	**Olvondo**	pharma-ceutical	recooling	recooling heat	34	36	steam generation	183	178	Stirling HP	R704	piston	2,250	1.7	6,100	[2]
5	**Kobelco**	sewage	sludge drying	exhaust drying air	93	93	steam generation	160	160	MVR	R718	twin-screw, roots blower	675	2.9	n. a.	[2]
6	**Kobelco**	refinery	bioethanol distillation	process cooling	60	65	distillation	115	110	CCHP + Flash Tank	R245fa	twin-screw	1,850	3.5	n. a.	[2]
7	**MHI**	electronic	coil drying	waste heat	50	55	drying	130	70	CCHP	R134a	centrifugal	627	3.0	n. a.	[2]
8	**Piller**	plastics	thermal seperation	exhaust vapour	60	60	steam generation	131	126	MVR	R718	turbo (8 blowers)	10,000	4.4	8,000	[2]
9	**AMT/AIT**	minerals	brick drying	exhaust drying air	80	84	drying	121	96	CCHP	R-1336mzz(Z)	piston (8 compr.)	296	5	4,000	[2]
10	**Spilling**	pulp and paper	pulp drying	exhaust vapour	105	133	steam generation	201	n. a.	MVR	R718	piston (4 LT-, 2 HT-cylinders)	11,200	4.2	7,500	[2]
11	**Spilling**	chemical	chemical	exhaust vapour	105	152	steam generation	211	n. a.	MVR	R718	piston (4 LT-, 2 HT-cylinders)	12,000	5.3	7,500	[2]
12	**Rotrex, Epcon**	sewage	sludge drying	surplus steam	100	n. a.	steam generation	146	n. a.	MVR	R718	turbo (2 stages)	500	4.5	n. a.	[2]
13	**SkaleUP**	dairy	process hot water	(re)cooling	12, 0	20, 5	process hot water	115	95	CCHP	LT-C: R290, HT-C: R600	piston	300	2.5, 2.3	6,500	[2]
14	**QPinch**	chemical	steam production	exhaust vapour	120 - 145		steam generation	140 - 185		heat trans-former	H_2PO_4	heat-driven	2,900	0.45	2,500	[2]
15	**Huayuan Taimeng**	refinery	ethyl-benzene	waste heat	95	120	steam generation	152	n. a.	heat trans-former	LiBr-H_2O	heat-driven	7,553	0.48	n. a.	[2]
16	**Shanghai Nuotong**	beverage	alcoholic distillation	air	n. a.	18.9	steam generation	120	90	CCHP + Flash Tank + MVR	LT-C:R410a, HT-C:R245fa	screw	180	1.85	n. a.	[2]
17	**Huayuan Taimeng**	refinery	alkyl-benzene	waste heat	86	127	steam generation	150	n. a.	heat trans-former	LiBr-H_2O	heat-driven	5,100	0.48	n. a.	[2]
18	**Shandong Zhangqiu Blower**	refinery	ethanol distillation	exhaust vapour	76	n. a.	steam generation	116	n. a.	MVR	R718	centrifugal	n. a.	7.68	7,000	[2]

Figure 8: Overview of collected demonstration cases and their characteristics (Published in (IEA HPT 2023, 2024b), Further sources: [1] IEA HPT Annex 48 (Jakobs and Stadtländer 2020), [2] IEA HPT Annex 58 (IEA HPT 2023).

5 Brief Overview of Pinch Analysis

5.1 Pinch Analysis in a Nutshell

Pinch Analysis (PA) is a powerful and proven methodology for analyzing and optimizing the energy integration of any size and complexity of thermal processes.

Its holistic consideration and systematic analysis approach of heating and cooling requirements (so-called cold streams, respectively hot streams) allows the targeting and design of economically optimized heat recovery systems. At the same time, PA provides for identifying technology shifting opportunities and pre-designing promising energy conversion technologies, among which HPs, to minimize the energy demands, CO_2 emissions, costs, or a combination thereof.

By considering temperature levels and energy flows, PA provides a thorough understanding of the energetics of the operated processes. Based on the 2nd principle of thermodynamics, which assigns different values to different heat flows, PA transcends the energy balance represented by a Sankey diagram, thus highlighting the reasons (i.e., processes, operating conditions, etc.) that limit the heat recovery and helping to devise innovative solutions to overcome these limitations.

The fundamental tools and methods of PA are first set up for a single continuous process, implicitly assuming that its streams are all located “close enough” to each other so that direct heat transfer using heat exchangers between hot and cold stream pairs is physically possible, yet subject to temperature feasibility. Hence, for ease of understanding, the fundamental tools are presented considering the *Example Process* defined by the heat sources and heat sinks listed in Table 5.

Table 5: List of heating and cooling demands used for an Example Process of Pinch Analysis.

Example Process						
Stream (heat transfer requirement)	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	$\Delta\dot{H}$ [kW]
WasteWaterCooling	Hot (heat source)	45.0	25.0	5.50	4.20	462
ProcessWaterHeating	Cold (heat sink)	30.0	55.0	2.00	4.20	210
AirCompressorCooling	Hot (heat source)	80.0	40.0	1.50	4.20	252
TemperatureHolding	Cold (heat sink)	65.0	70.0	20.00	4.20	420

Setting up this list (i.e., defining the actual process energy requirements) is an essential step of PA, and their inventory obeys several key principles (see Section 5.4). For single continuous processes, PA has developed and extensively uses two fundamental graphical representations: the **Composite Curves (CCs)** and the **Grand Composite Curve (GCC)**.

Linnhoff's work (1993, 1998) provides a condensed presentation of PA tools and methods. The handbooks of Brunner and Krummenacher (2017a) (in German) and Brunner and Krummenacher (2017b) (in French) provide a detailed and pedagogical presentation of the tools and methods used in PA.

5.2 Composite Curves

The **Composite Curves** (hot CC and cold CC) sum up the heating and cooling requirements of the process as a function of temperature. Hence, they provide a global view of heat availability (heat sources) and heat consumers (heat sinks) (see Figure 9, left). Some remarks about the CC plots are:

1. The (horizontal) overlap of the CCs represents the heat that can be potentially transferred from hot CC to cold CC (hence the amount of heat recovery), reducing both the process's hot and cold utility demands. The extent of this overlap is a design aspect of the process heat integration (i.e., a degree of freedom), which influences both the heat recovery (and hence the corresponding utility costs) and the capital costs for the needed heat exchangers.

2. For any extent of overlap, the Pinch point is the location where the temperature difference between the hot CC and the cold CC (measured vertically) is the smallest (→ΔT_{min}). For any overlap (and corresponding ΔT_{min}), the amount of overlap defines a heat recovery target value, i.e. the maximum possible heat recovery that can be achieved in practice by a heat exchanger network (i.e. a set of heat exchangers) complying with the constraint of $\Delta T > \Delta T_{min}$ for all heat transfers.

3. Smaller ΔT_{min} results in larger heat recovery targets, larger heat exchanger area (i.e., higher capital costs) and reduced utility costs. ITheCCs also allow the calculation of target values for the minimum required heat transfer area, and formulas derived from the network theory will enable the calculation of target values for the minimum number of heat exchanger units. With these additional data, it is possible to calculate capital costs targets and hence determine an economically optimum $\Delta T_{min,opt}$ minimizing the total annual costs. Note that this is achieved without prior heat exchanger network design; this approach is called Target before Design and is a key advantage of PA.

4. The Pinch point determines the Pinch temperature (temperature midway between hot CC and cold CC at the Pinch point) that divides the heat integration problem into two sub-systems:
   - above the Pinch temperature (i.e., to the right of the Pinch), a sub-system featuring globally a heat deficit,
   - below the Pinch temperature (i.e., to the left of the Pinch), a sub-system featuring globally a heat surplus.
5. This fact leads to the 3 golden rules of PA (rules of heat transfer to achieve heat recovery targets, see Section 5.4).

6. As a result of the targeting stage, the $\Delta T_{min,opt}$ and Pinch temperature allows to generate a heat exchanger network (HEN), and, together with the Pinch Design Method, to design Maximum Energy Recovery (MER) HEN. The Pinch Design Method applies the 3 golden rules and sound heuristics principles. Note that this workflow is focused on heat recovery only, without looking at the potential optimization of the utilities (i.e., assuming the utilities are unchanged or still undetermined).

Another graphical representation, the Grand Composite Curve (GCC), is needed to optimize utility integration (e.g., changing the pressure/temperature levels of processes or steam headers or resorting to more efficient energy conversion systems, such as heat pumps).

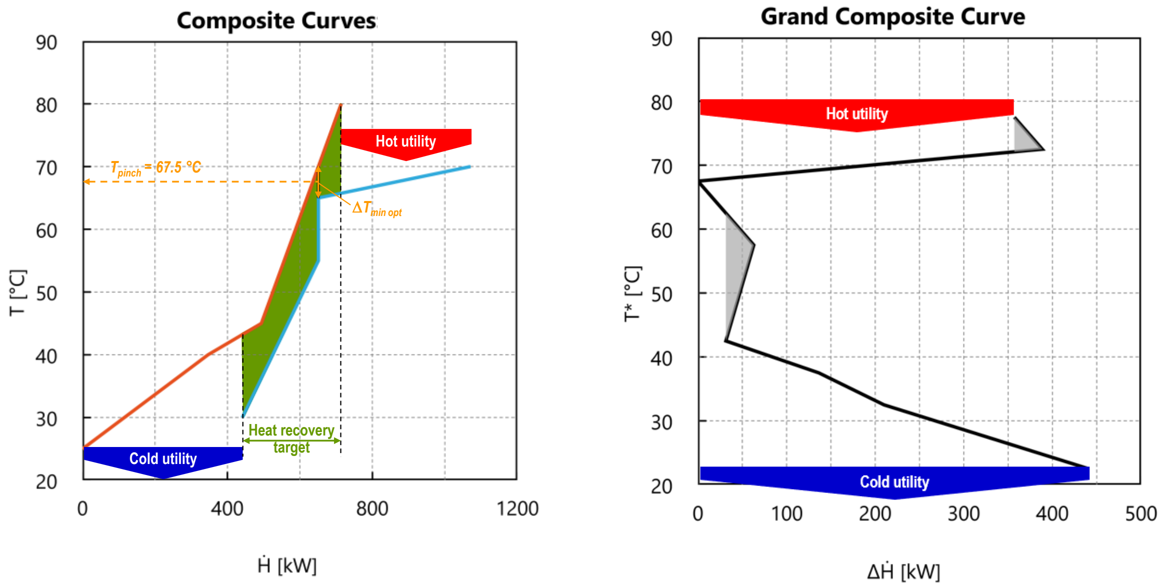


Figure 9: Composites Curves (CCs) (left) and Grand Composite Curve (GCC) (right) of the Example Process of Table 5, with $\Delta T_{min,opt} = 5\ K$ (refer to comments in the text).

5.3 Grand Composite Curve

The **Grand Composite Curve (GCC)** represents the net heat cascaded at a certain temperature level, calculated as the balance of heat supplied by the heat sources minus heat consumed by the heat sinks. It assumes that the heat transfer occurs observing the optimal minimum temperature difference $\Delta T_{min,opt}$. In other words, the GCC is derived from the CCs, for a given $\Delta T_{min,opt}$ (see Figure 9, right):

1. **At the Pinch temperature**, there is no net surplus or deficit of heat (confirming the separation into two sub-systems mentioned above).

2. **Above the Pinch temperature**, the GCC features a net heat deficit (corresponding to the hot utility required, as seen on the CCs). Still, more importantly, it represents how this heat deficit is distributed over temperature (minimum temperature required for hot utility).

3. **Below the Pinch temperature**, the GCC features a net heat surplus (corresponding to the cold utility requirement as seen on the CCs). It represents how this heat surplus is distributed over the temperature range (i.e., the maximum temperature required for cold utility).

4. Each utility system (steam boiler, cooling tower, etc.) or energy conversion technology (HP, MVR, heat transformer, internal combustion engine, gas turbine, ORC, etc.) performs differently depending on specific characteristics/conditions. The conditions that guarantee the highest efficiency can be readily identified from the GCC shape (profile), so promising utility systems can be identified and conceptually designed (e.g., capacity, temperature and pressure levels, etc.).

After the promising utility system alternatives have been conceptually designed leveraging the GCC profile, their corresponding streams are added to the list of process streams, and the CCs are plotted again, now named Balanced CC (BCC). HENs can then be optimized for both heat recovery and utility supply.

5.4 Key Principles of PA

PA relies on several key principles, among which:

1. **Keep hot streams hot and cold streams cold**: to maximize the heat recovery potential, define the heating requirements (cold stream) at their lowest temperature possible (i.e., as close as possible to the actual process requirement); likewise, for the cooling requirements.

2. **Do not extract features of the existing solution**: do not take existing operating conditions for granted, but challenge them to identify the real process requirements (e.g., prevent non-isothermal mixing, very large driving forces, etc.).

3. **Golden rules of heat transfer**:
    a. Do not cool hot streams above the pinch temperature using cold utility.
    b. Do not heat cold streams below the pinch temperature with hot utility.
    c. Avoid heat transfer across the pinch point from hot to cold streams.

Any violation of these rules decreases the heat recovery potential and entails an increase of OPEX or a reduced heat recovery for a given CAPEX.

5.5 GCC and Integration of a Heat Pump: Dos and Don'ts

The shape of the GCC of Figure 10 suggests that a vapor compression HP is adequate since:

- below the Pinch, there is a heat surplus, i.e., a heat source for the HP evaporator
- above the Pinch, there is a heat deficit, i.e., a heat sink for the HP condenser
- the temperature lift (about 75 – 25 = 50 K) can be tackled with a single-stage HP (COP ~ 3.5)

Figure 10 illustrates a reasonable placement of the HP on the GCC.

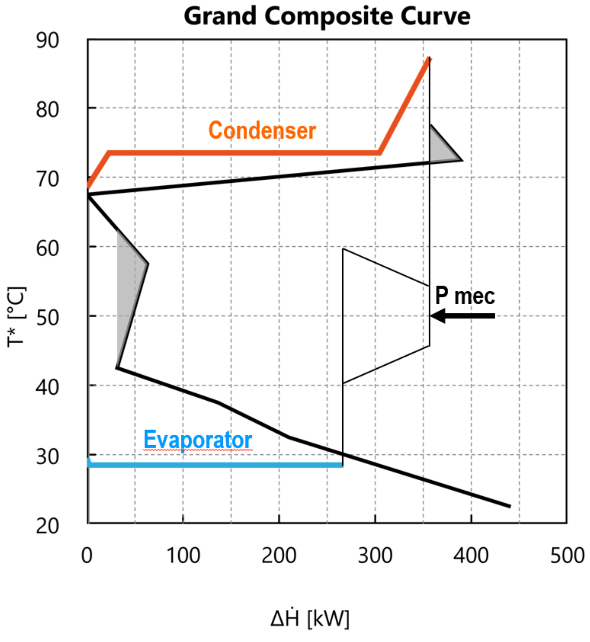


Figure 10: Optimal integration of a vapor compression HP by interpreting the GCC.

Assuming that the first two streams of Table 5 (WasteWaterCooling and ProcessWaterHeating) are close together and that the engineer knows neither the Pinch method nor, a fortiori, the Pinch temperature, combining direct heat recovery and heat pumping, as shown in Figure 11, would be an obvious local heat recovery action.

The HP would upgrade low-temperature heat from the wastewater to supply 126 kW at 60 °C for heating process water. Considering these two streams in isolation seems an efficient and profitable solution (COP ~ 6.5). However, when the scope of analysis is extended to include the two last streams of Table 5 (AirCompressorCooling and TemperatureHolding), which are still located reasonably close to the two first streams, the energy integration potential becomes different. In effect, the GCC of Figure 10 shows that the "global" Pinch temperature is at 67.5 °C, higher than the condenser temperature of 60 °C. The HP would then supply heat that is, in fact, not needed since the GCC highlights a surplus of heat at this temperature.

In conclusion, without a holistic consideration of heating and cooling requirements, what appears to be a straightforward, simple, and efficient local solution may be counterproductive. In this case, compared to the direct heat recovery potential shown in Figure 9 (without the integration of the HP as shown in Figure 10), the local HP would be an expensive and useless solution to heat the process water. It would increase the capital and operating costs since direct heat recovery using heat exchangers would only suffice.

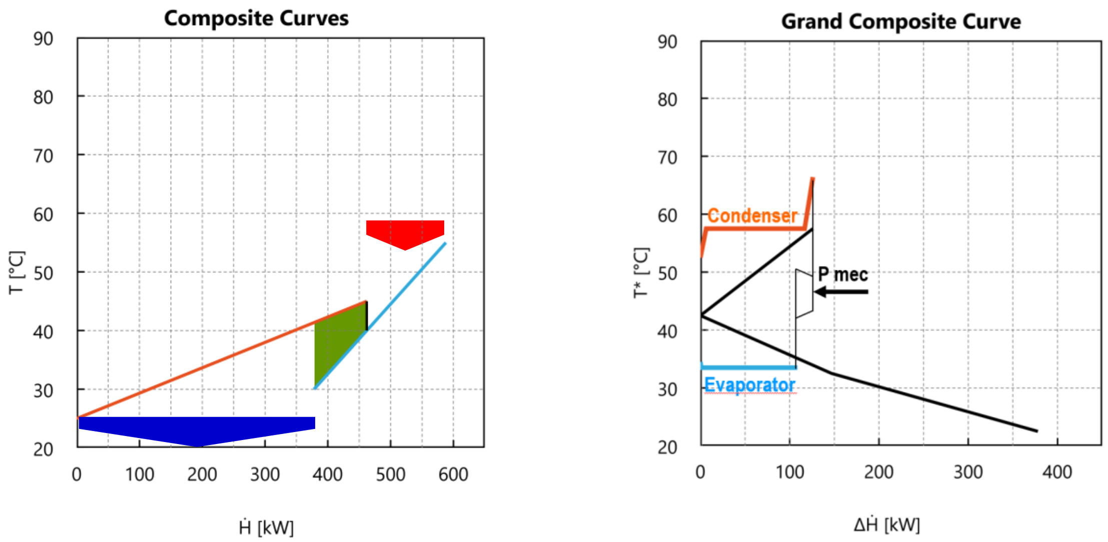


Figure 11: Composite Curves (CCs) ($\Delta T_{min} = 5\ K$) of the first two streams of Table 5 (left). Corresponding Grand Composite Curve (GCC) and integration of a HP as a local solution (right) (refer to comments in the text).

5.6 Extension of the Methodology to inter-process Heat Integration

The basic tools and methods outlined above hold for a single process or several independent processes whenever each process is considered separately (postulating no heat transfer between them). However, for most industrial sites,

- as the number of operated processes increases,
- as the distances between processes prevent direct heat transfer between process streams not belonging to the same process,
- and because not all processes are operated simultaneously (not to mention other practical constraints),

the number of possible options to analyze and compare also increases rapidly, and the principle stating that a HP must be integrated across the “Global Pinch” has to be applied with both care and engineering judgment. Often, practical constraints preclude a category of options and restrict the search space.

Data from the GCC of each process is used to construct Residual Composite Curves (RCCs), enabling inter-process heat integration. However, cost-effective heat transfer between processes over long distances is a significant challenge. It can only be achieved through heat recovery loops or intermediate utility networks, which can be difficult and expensive to implement due to space constraints and technical complexity.

These topics go beyond the scope of this guideline and are not properly addressed in existing literature. However, some general principles are presented in Part B, Section 1.

As a guiding principle, it is advisable to avoid local HP integration when the condenser heat can be economically supplied by heat recovery from another process without needing a HP.

Chapter 6 presents an overview of the possible levels of integration and a comparative analysis of their influence on KPIs. This chapter also sketches typical integration points and concepts.

6 Possible Integration Points for Heat Pumps

As mentioned in Section 2.6, there are generally many options for integrating HPs in an industrial site. Note that a HP must be understood in a generic sense: it can be a single unit or more HP units to improve reliability and best suit load variation.

The terminology used in the IEA SHC Task 49[1] for integrating solar heat is re-used here by analogy for integrating HPs. First, different levels of integration can be distinguished (Figure 10).

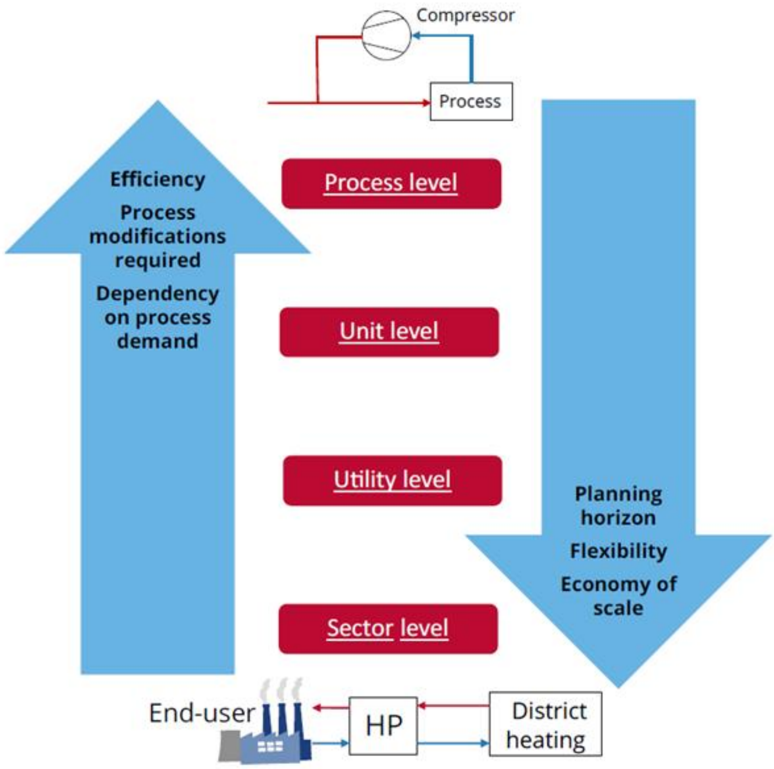


Figure 10: Different integration levels and their effects (IEA HPT 2024c).

- **Process stream level**: The heat of an exhaust stream (e.g., vapor from an evaporation process) is upgraded and fed back as heating steam. This is typically the case of mechanical vapor recompression.

  Unit (or process) level: In this case, the heat of one or several hot streams or waste heat sources of a process unit supplies the heat pump's evaporator. Then, the heat at the condenser supplies one or several cold streams of that processing unit. It can also happen that part or the totality of heat needed at the evaporator is extracted from another process (in case the heat sources available in the process itself are too limited, at a too low-temperature level, or the heat transfer to the evaporator is too expensive).

- **Utility level (site level)**: Waste heat collected, e.g., by the cooling water network, is upgraded by a HP into hot water or steam and distributed via the existing utility network. A hybrid solution

[1] https://task49.iea-shc.org/publications

(mixing unit level and utility level) could consist of an evaporator recovering heat directly from one or several hot streams (using a dedicated network) and a condenser supplying an existing utility network. Alternatively, heat can be extracted from the cooling water network, upgraded, and delivered “directly” to specific heat sinks.

- **Sector level (district, area level)**: In this case, the heat source(s) and the heat sink(s) do not belong to the same company/organization/industrial site (also named “over-the-fence integration”). It may consist of two companies: the industrial site and a district heating operator.

The above rough categorization lists typical cases. In practice, hybrid solutions allow for optimizing different KPIs of HP integration.

Once a level of integration is chosen, several integration points are considered. Here, the integration point means “where” or “with which source(s) and sink(s)” energy integration is achieved.

Finally, an integration level and an integration point are selected, and different integration concepts can be used. A concept means “how” or “with which integration schema.” An exhaustive list is beyond the scope of this document since different HP technologies (Chapter 3) and different applications (Chapter 4) allow for other case-specific concepts. For example, integration concepts for SGHP are presented in Section 3.3.3. MVR systems also feature specific integration concepts.

For closed-cycle vapor compression HPs, integration concepts can be distinguished typically by:

- Presence or absence of heat storage on the evaporator and/or condenser side
- Direct heat exchange with the source in the evaporator, either with the well in the condenser or indirect heat transfer via waste heat recovery loops.
- Separate de-superheating
- Mode of temperature control
- Position concerning backup (if any): in series, parallel, etc.
- etc.

Figure 10 presents the different levels of integration and their typical effects. However, the trend may vary depending on the specific characteristics of each industrial site. Table 12 in Appendix 2 compares the impact of the level of integration on KPI in more detail and suggests ways to improve it (e.g., hybrid solutions, etc.).

As a preliminary preparation step to setting up promising HP integration options, it is recommended that the spatial distribution of significant cooling and heating requirements (in terms of heat load, temperature level, total duration, and time profile) be represented[2] on the site map.

Highlighting the existing layout of relevant utility networks is also recommended.

This overview helps to devise and to compare potential solutions:

- grouping of sources and sinks versus piping issues (feasibility, costs),
- efficiency (temperature lift), and
- amortization of capital expenditures (operation duration).

[2] using readily remarkable graphical conventions: e.g. by circle diameter proportional to heat load, colour depending on temperature, angle of sector proportional to duration, …

7 Preliminary Assessment Checklist

Identifying a suitable integration point for a HTHP in an industrial environment can be complex, depending on the context of the sector and individual factory. The methodology presented in this section provides a list of questions that allow for a preliminary feasibility check for a given concept. This feasibility check can help industrial companies assess a HP integration's applicability. The objective is to prevent investing time and money without a clear, cost-effective potential.

The method assumes simple systems with low complexity in which only a few heat sources and sinks are present. A process with a known heat demand that an HTHP could potentially supply should have been identified to start the evaluation. The questionnaire allows one to verify the fundamental elements that must be considered when considering this investment.

Figure 12 shows the steps for assessing whether a HTHP is suitable. It requires information about the processes and the available heat sources and sinks. If all questions are answered with "Yes," using an HP is possible in principle and could be economically and technically feasible.

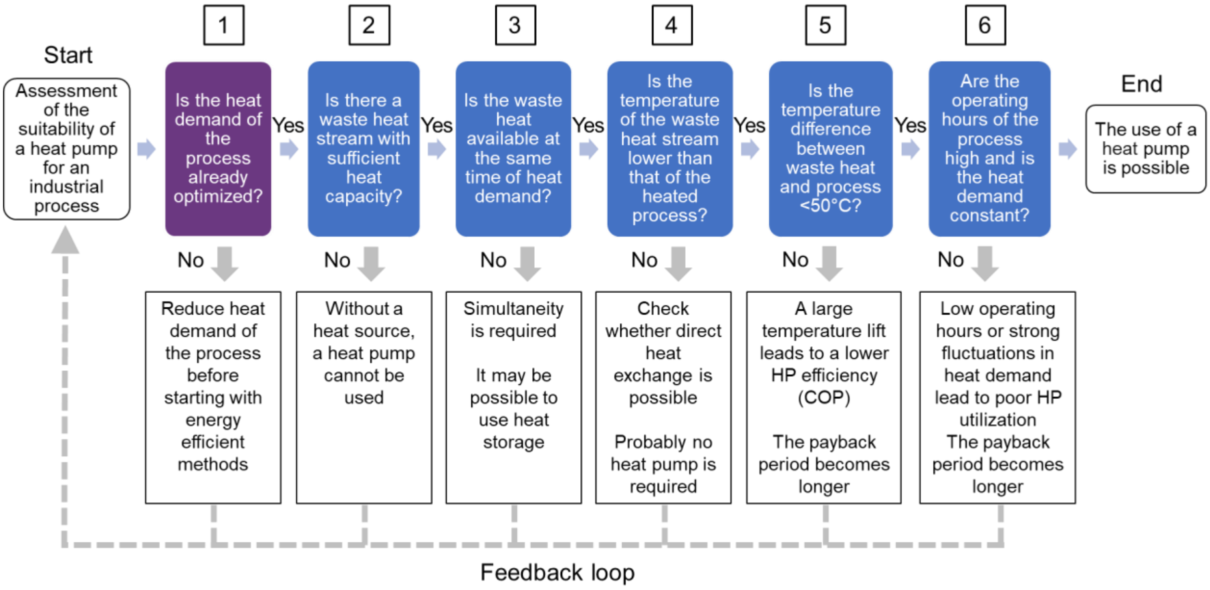


Figure 12: Checklist for industrial HTHP integration assessment, adapted from (Arpagaus 2018) based on the "Feasibility Check" by (De Kleijn Energy Consultants & Engineers 2018)).

A feedback loop for all negative answers leads to the starting point. For example, after step 2, potential waste heat availability, such as ambient heat or waste heat from neighboring processes, should be reevaluated if there are insufficient heat sources. After step 3, a combination of heat storage and HP is possible, with partial coverage.

Figure 12 also provides hints on how to handle negative answers. Therefore, the methodology can be iterative, with adjustments to the initial situation. Moreover, some factors leading to negative answers can be detrimental or even project killers. This applies to step (3) simultaneity of heat source and need, step (5) temperature difference and step (6) operating duration. In these cases, a financial assessment could confirm the go/no-go status, as the impact would mostly worsen the financial attractivity.

The steps from the checklist are detailed in the following sections.

7.1 Optimized Process Heat

This step aims to question whether the actual energy needs of the process are supplied correctly in the light of the PA. It is crucial when an HP integration is considered since its efficiency (COP) decreases with increasing production temperature. This can be led at different levels:

- Questioning the temperature level of the demand for heat, always reducing it whenever possible,
- Reducing the temperature (or steam pressure) of the utility supplying it, replacing steam with hot water wherever applicable,
- Recovering available heat through direct exchange to partially heat the stream,
- Reducing the heating capacity needed by upgrading process equipment with higher efficiency setups.

Conducting a PA at the industrial site is an effective way to reduce the heat and utility demand optimally, and it is especially recommended for its ability to define relevant solutions. According to VDI 4646 (VDI 2024), any process with more than two streams must match heat sources and sinks together correctly. Moreover, a PA allows for the determination of the Pinch temperature, which is the "boundary" between the zone with a net surplus of heat (below this temperature) and the zone with a net deficit of heat (above this temperature). Knowing the Pinch temperature, screening suitable heat sinks and heat sources is possible to ensure efficient integration of a HP (refer to Section 5.5).

7.2 Sufficient Heat Source Capacity

A HP fundamentally upgrades the temperature level of a heat source. Hence, it cannot function without the latter. A heat source with sufficient capacity is necessary, which can be estimated according to the equations in Chapter 2 (What is a heat pump?). Using a waste heat stream provides “free” heat close by and can reduce the need for cooling. However, alternative heat sources like geothermal energy could also be used. An absorption HP could be considered if there is enough available waste heat.

7.3 Simultaneity between the Heat Source and Heat sink

The heat source should be available when the HP needs to run. Heat storage can be considered in the case of mismatching load profiles, running times or batch processes to make thermal energy available when needed.

7.4 Temperature Level of Heat Source

If the heat source temperature is higher than the required heating temperature, then a direct heat exchange should be feasible, and there would be no need for a HP (an additional heat exchanger, a compressor and a throttling device. Conducting a PA provides the best matches (heat exchanger network) between the various streams in a complex system with several heating and cooling needs.

7.5 Temperature Difference between Heat Source and Heat Sink

Just like the heat demand should be supplied at the lowest possible temperature, the heat source should have the highest temperature for the best possible efficiency (COP). A higher COP also means lower OPEX and shorter payback time. For closed-cycle HPs, a temperature difference of about 50 K to 55 K (Kelvin) is the limit for a decent COP of 3 to 3.5 on average. However, for some HTHP technologies, like MVR, much higher temperature lifts can be achieved with good efficiencies (IEA HPT 2023). The COP value should be considered alongside the specific electricity cost for the project and compared to the current energy production costs. Moreover, if both the heat source and the heat sink streams are steam, a MVR system should be selected.

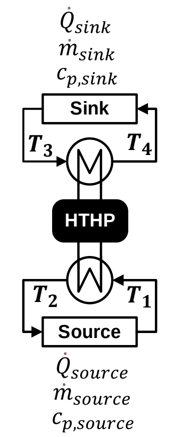
7.6 Duration of Operation

Ideal conditions would be a constant heat demand for long periods over the year. Low operating time, important part-load, discontinuous operation, or strong fluctuations lead to less saving potential. Thermal storage might be necessary on the sink and source side for a smooth HP operation. Further information can be found in Part B (Chapter 2, Technical Aspects).

8 Checklist of Technical Options and Feasibility

As the correct planning, design, and installation of a HP in an industrial context is complex, an expert planner or HP manufacturer should be consulted. A rough assessment of the potential application can be made based on the data collected. The information required for the integration of a HP is listed in Table 6, and the inputs needed for a preliminary assessment are listed in Table 7. Important aspects are the availability of waste (or excess) heat and the electricity supply capacity at the site.

Table 6: Information required (checklist) for the design of a HP integration (Arpagaus 2018).



Technical parameters	Unit	Heat source		Heat sink	
Medium (water, steam, air, oil, waste, etc.)					
Flow temperature	°C/bar(g)	T_1		T_3	
Return temperature	°C	T_2		T_4	
Heat source/sink capacity (cooling/heating demand)	kW	$\dot{Q}_{source}$		$\dot{Q}_{sink}$	
Mass flow	kg/s	$\dot{m}_{source}$		$\dot{m}_{sink}$	
Heat capacity	kJ/kg K	$c_{p,source}$		$c_{p,sink}$	
Operating hours (time availability)	h/year				
Economic parameters					
Electricity costs	CHF/kWh				
Costs of natural gas or oil	CHF/kWh				
Heat price at sink temperature (e.g., gas price for burner)	CHF/kWh				
Heat price at source temperature (mostly free waste heat)	CHF/kWh				

Table 7: Additional inputs needed for a preliminary assessment.

Application	Specification	Examples or unit
Type of industry		Diary / Pharma / Chemical
Type of application		Drying / Humidification / UHT
Current source for applied heat		Electric, gas, or oil burner
Heat pump location on site		Existing space / New build
Distance to heat source/sink		Meters
Electrical voltage level		400/600 V
Electrical power consumption		kW (see specifications of HPs)
Internet access (fixed IP)		Yes/No
Other information		

9 Preliminary Estimates of Profitability and CO_2 Emission Reduction

Industrial companies interested in HTHP integration may be driven by different goals, mainly decarbonization and economic profitability. However, economic profitability should not be the killing factor because an increase in total costs can be accepted if it leads to effective decarbonization.

A simple MS Excel-based economic model has been developed to assess a go-or-no-go decision on HTHP integration in an industrial site (Arpagaus et al. 2022a, c). It is intended to give an idea of the financial feasibility with limited input information. In addition, it is intended to answer whether an HTHP may be suitable and whether the stakeholder should proceed with further analysis. Figure 13 illustrates the concept for the economic calculation, and Table 8 lists the input and output parameters.

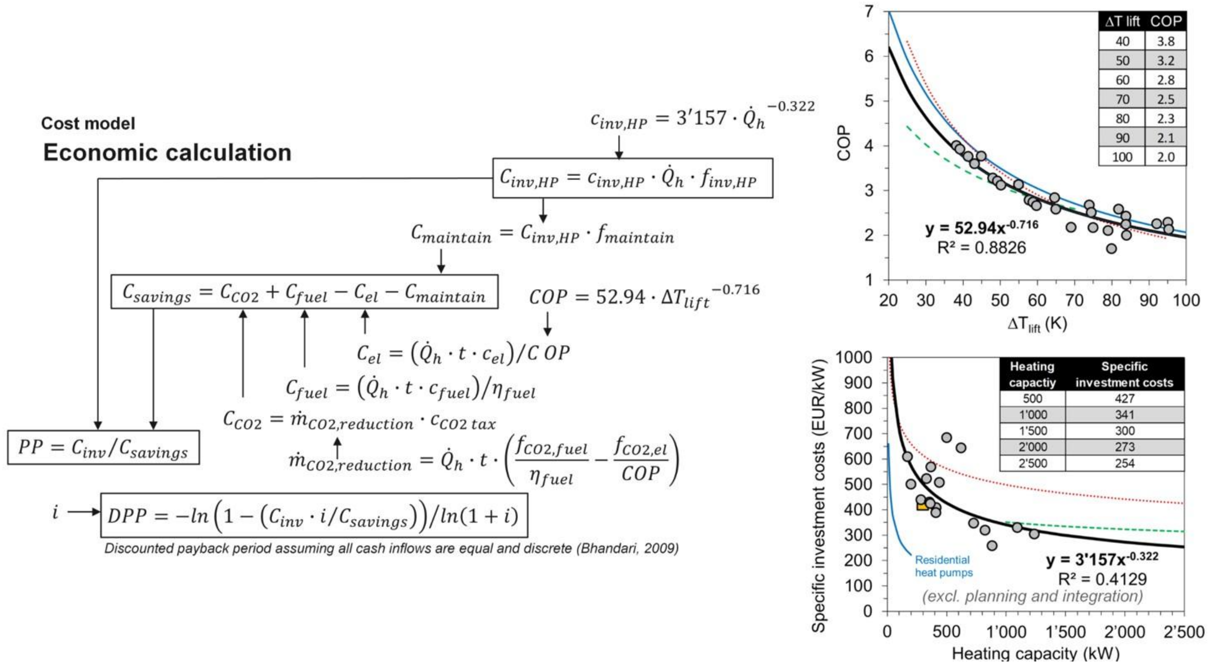


Figure 13: Cost model for the economic evaluation calculation (Arpagaus et al. 2022a, c).

Table 8: Input and output parameters of the cost model (Arpagaus et al. 2022c).

Inputs

$\dot{Q}_h$	Heating capacity	kW
ΔT_{lift}	Temperature lift	K
$c_{inv,HP}$	Specific investment costs of HP	EUR/kW
$f_{inv,HP}$	Cost factor for planning & HP integration	-
t	Annual operating time	h/a
$f_{maintain}$	Maintenance factor (on capital costs)	-
η_{fuel}	Efficiency of gas boiler	-
i	Interest rate (discount rate)	-
c_{fuel}	Fuel price (gas, oil)	EUR/kWh
c_{el}	Electricity price	EUR/kWh
$c_{CO2\,tax}$	CO_2 tax	EUR/tCO_2
$f_{CO2,el}$	CO_2 emissions factor electricity	kgCO_2/kWh
$f_{CO2,fuel}$	CO_2 emissions factor fuel	kgCO_2/kWh

Outputs

$C_{inv,HP}$	Investment costs of HP	EUR
$\dot{m}_{CO2,reduction}$	Annual CO_2 emissions reduction	tCO_2/a
$E_{savings}$	Annual energy savings	kWh/a
C_{fuel}	Annual fuel cost savings	EUR/a
C_{el}	Annual electricity costs	EUR/a
$C_{maintain}$	Annual HP maintenance costs	EUR/a
C_{CO2}	Annual CO_2 tax compensation	EUR/a
$C_{savings}$	Annual cost savings	EUR/a
PP	Payback period	a
DPP	Discounted payback period	a

The cost model assumes that the gas boilers' investment is depreciated and that they remain for production safety, redundancy, start-up operation, and peak load coverage.

The Excel tool has been tested on preliminary integration concepts for the case studies (Arpagaus et al. 2022b, c, 2023c, a). Despite the early stage of evaluated projects, further validations are still needed to provide the best possible results.

Parameters such as utility cost, electricity price, gas price, mode of operation, operation hours, heating capacity, temperature levels, equipment cost data, retrofit situation, etc., are inputs to the pre-assessment tool. Outputs are COP, a rough estimate of investments and operating costs that give an idea of the payback period. The go/no-go decision may vary based on an individual's financial expectations. Input parameters to the evaluation tool are:

- electricity price (c_{el}), gas price (c_{fuel}),
- operating hours (t),
- heating capacity ($\dot{Q}_h$),
- temperature lift between the heat source and sink (ΔT_{lift}),
- specific investment costs ($c_{inv,HP}$),
- maintenance cost factor ($f_{maintain}$), interest rate (i),
- the emissions factors of electricity and fuel (f_{CO2}), and CO_2 tax refund (subsidies).

The output results are the COP, CO_2 emissions reduction ($\dot{m}_{CO2,reduction}$), annual cost savings ($C_{savings}$), and the payback periods (PP, DPP). The calculation tool helps to quickly evaluate the economic feasibility as a "go/no-go" decision.

1) First, the efficiency of the HTHP is estimated using the temperature lift (ΔT_{lift}) and a COP fit-curve ($COP = 52.94 \cdot \Delta T_{lift}{}^{-0.716}$) derived from quotes from various HP suppliers (Arpagaus et al. 2022b, c).
2) Next, the investment costs ($C_{inv,HP}$) of the industrial HTHPs are evaluated based on the specific investment costs ($c_{inv,HP} = 3'157 \cdot \dot{Q}_h{}^{-0.322}$) according to price information from HP suppliers, the heating capacity ($\dot{Q}_h$), and a cost multiplication factor ($f_{inv,HP}$) accounting for planning and integration (typically between 1.5 to 4.0 depending on the complexity of integration, e.g., including heat storage, site's electrical installation, piping, hydraulics, etc.) (Arpagaus et al. 2022b, c). *Note: The specific costs depend also on the supply temperature, heating capacity (one large unit or several modules in parallel) and medium (steam, water, air). A rough cost estimate for a steam-generating HP is between 840 to 1'000 EUR/kW (HFO refrigerant) and 1'300 EUR/kW for n-butane (Arpagaus et al. 2024b).*
3) Then, the annual cost savings are calculated considering the following: electricity cost (C_{el}) to operate the HTHP, maintenance costs ($C_{maintain}$) of the HTHP using a multiplication factor ($f_{maintain}$) on capital cost (typically between 1.5% to 6%, in the case studies, 4% is used) (Arpagaus et al. 2022b, c), saved fuel costs (C_{fuel}) (assuming 90% boiler efficiency η_{fuel}), and possible refunds of CO_2 reduction (C_{CO2}) (e.g., carbon taxes or subsidies).
4) After that, the PP of the HTHP investment is evaluated as a trade-off between the investment costs versus the expected annual cost savings resulting from the HP investment.
5) Finally, the discount rates (i) are considered to calculate the discounted payback periods (DPP) (Bhandari 2009), depending on the investor's risk tolerance (e.g., sector, company size, energy intensity, funding source, new technology, etc.) (European Commission 2021). According to the reviewed literature, typical discount rates for HP investments range from 5% to 15% (Arpagaus et al. 2022c, b). The DPP (discounted payback period) is the period after which the cumulative discounted cash inflows cover the initial investment (Bhandari 2009). Therefore, the DPP can be interpreted as a period beyond which a project generates economic profit. In contrast, the static PP gives a period beyond which a project generates accounting profit.

PART B – Technical Report

1 Pinch Analysis – Practical Information

Chapter 5 of Part A provides an Overview of Pinch analysis (PA) and its main tools and principles. Kemp (2007) comprehensively describes PA tools and methods applied to numerous processes and site examples. The handbooks (Brunner and Krummenacher 2017a) (in German) and (Brunner and Krummenacher 2017b) (in French) explain the basics of tools and methods, including the analysis and the direct and indirect heat integration of batch processes (with heat storage).

1.1 General information – Main steps

PA is a powerful and proven methodology for analyzing and optimizing the energy integration of any size and complexity of thermal processes. A PA study requires time and resources. Except in a few cases, it must include all processes involving significant heat transfer at an industrial site. Unless the technical constraints dictate it, it cannot be limited to a process considered in isolation.

Only in this way can the study reveal the global integration perspective and provide an understanding of the site-specific energy issues. Moreover, only a holistic approach can lay the foundation for any energy integration and optimization measures (e.g., direct heat recovery, indirect heat recovery via recovery loops, heat storage, energy conversion units, etc.). In this regard, PA benefits the Site and Energy Managers far beyond assessing the integration of heat pumps.

Figure 14 illustrates the main steps of a Pinch analysis.

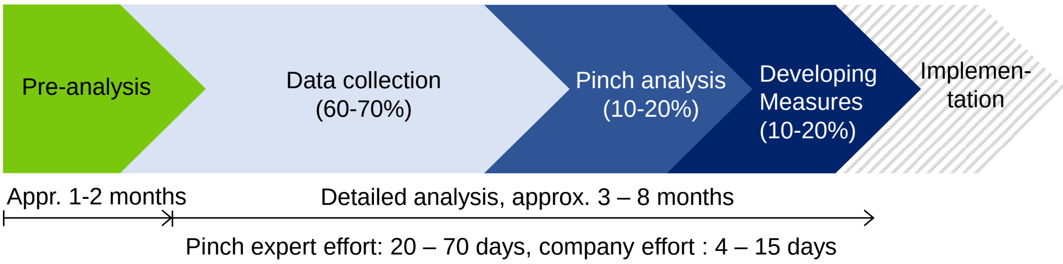


Figure 14: Main steps of a Pinch analysis and typical effort and duration.

In Switzerland, a preliminary PA pre-analysis has to be performed before possibly embarking on a detailed PA. This preliminary PA:

- identifies the major heating and cooling requirements,
- roughly quantifies these requirements,
- calculates and analyses the draft CCs and the corresponding GCC,
- estimates the energy-saving potential and issues preliminary recommendations regarding integrating heat pumps and other efficient energy conversion units.

In this way, the company's risks are limited: a detailed PA will only be ordered if the potential savings are bigger; hence, the study is not worth the effort.

Given PA's essential role in developing a decarbonization roadmap, the Swiss Federal Office of Energy (SFOE) promotes and subsidizes PA (pre-analysis and detailed PA). Figure 15 provides orders of magnitude of costs and the percentage of SFOE subsidies, which can be up to 60% of total expenses for pre-analysis and up to 40% for detailed analysis. Total costs include the company's services (e.g., data collection, working sessions, etc.), up to 20% of total costs.

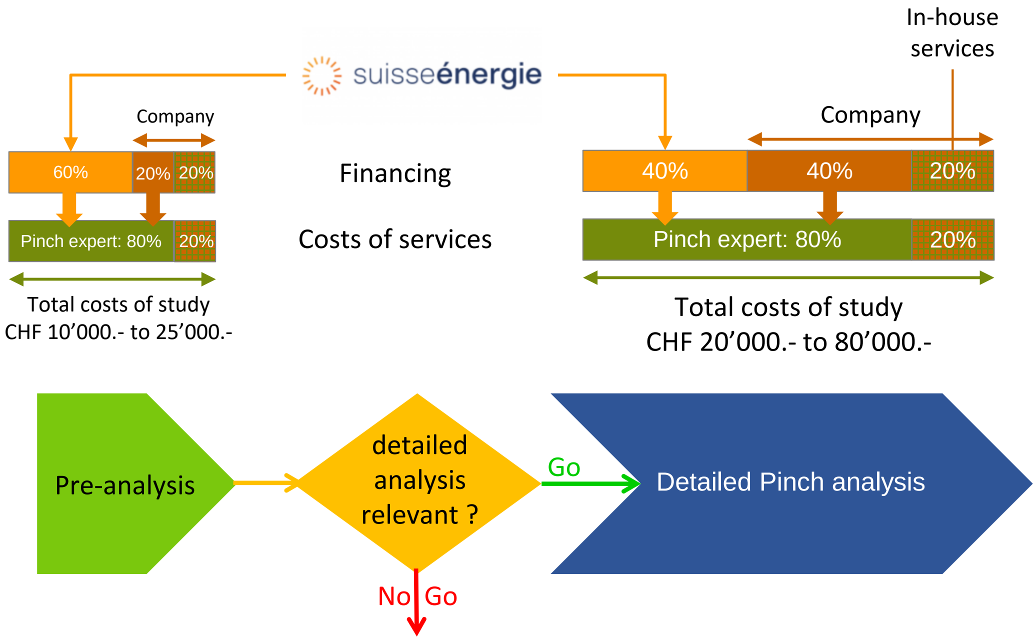


Figure 15: Typical costs and SFOE subsidies (conditions as of September 1, 2024) for the two-phase approach (specifications and subsidy conditions: see Pinch website[3]).

1.2 Big picture of the site (organization, energies, utilities, processes)

As is the case when performing an energy audit, getting familiar with the site arrangement is essential before analyzing the processes and extracting the heating and cooling requirements. Sketching the big picture is not a goal but a way to get a general understanding of the site, a broad view of distances and space constraints, and not to feel lost but to be able to locate the main elements relevant to the project. It involves:

1) **Looking for and documenting (e.g., on a general site map with scale) the following data:**
   a. The different zones (names of zones and levels, workshops, process facilities, etc.) and their functions / hosted processes.
   b. The existing utility systems (steam, hot water, cooling water, chilled water, etc.), hot water boiler, heat storage (if any), localized units (cold rooms, …), and distribution networks.
   c. It is also about collecting the economic frame conditions, energy and water prices, site-specific constraints, etc.

2) **Collecting data on main feedstock types and product types (names, quality/composition, %DM, etc.) and quantities**. Take note of significant by-products and wastes, if any.

3) **Collecting data regarding final energy consumptions, distributed utilities, on-site produced energies, energy metering schemes and data (and the corresponding metering perimeters).** Monthly, weekly, or daily data, if available. ¼ h resolution consumption profiles are useful. These data help analyze the seasonal variability and contributions (due to

[3] https://www.suisseenergie.ch/se-faire-conseiller/pinch/ and https://www.energieschweiz.ch/sich-beraten-lassen/pinch/

processes/production changes and/or to HVAC requirements), calculate top-down energy balance, and compare it to bottom-up balance based on process and production knowledge.

4) **Sketch a block diagram of the production organization and routes** (sequence of processes, type of processes (continuous, semi-continuous, batch)) **and collect data** such as schedule, facilities used, quantities, and annual operation durations (of production, but also idling, cleaning, etc., whenever relevant).

1.3 Data collection and analysis

The process heat transfer requirements (hot streams = cooling requirements, cold streams = heating requirements) are essential input data for Pinch Analysis.

To calculate CCs, a heat transfer requirement (stream) must be defined by the following core data:

- T_{in} [°C], T_{out} [°C], and $\Delta\dot{H}$ [kW].

To determine $\Delta\dot{H}$ [kW], other base data may be used, depending on the available data, on whether the requirement is sensible heat or phase change, and if the software used includes fluid models (notably water and humid air). For a ΔT_{min} optimization, an estimated value of the heat transfer film coefficient must be defined. Otherwise, one may use experience values for ΔT_{min}. To analyze/optimize the existing heat recovery and the utility supply, intermediate temperature(s) and information on HEXs and utilities used should be collected and recorded.

Table 9 specifies the base data needed in different cases to determine the core data.

Table 9: Different sets of parameters to specify streams, determine $\Delta\dot{H}$ and calculate CC (x_in / x_out : vapor quality, x_w : humidity ratio [kg_H_2O/ kg_DryAir]; α : heat transfer film coefficient).

Type of stream											
Sensible heat	T_in [°C]	T_out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]						α [W/(m^2K)]	$\Delta\dot{H}$ [kW]
Phase change	T_in [°C]	=T_in [°C]	$\dot{m}$ [kg/s]		Δh [kJ/kg]					α [W/(m^2K)]	$\Delta\dot{H}$ [kW]
Fluid model (e.g. Water)	T_in [°C]	T_out [°C]	$\dot{m}$ [kg/s]			P [bara]				α [W/(m^2K)]	$\Delta\dot{H}$ [kW]
Fluid model (e.g. Water)	x_in [-]	x_out [-]	$\dot{m}$ [kg/s]			P [bara]				α [W/(m^2K)]	$\Delta\dot{H}$ [kW]
Humid Air model	T_in [°C]	T_out [°C]	$\dot{m}$ [kg/s]			P [bara]	x_w [kg_{H2O}/kg]			α [W/(m^2K)]	$\Delta\dot{H}$ [kW]
Batch stream, sensible heat	T_in [°C]	T_out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]				t_start [h:m:s]	t_stop [h:m:s]	α [W/(m^2K)]	$\Delta\dot{H}$ [kW]

To specify the process “properties,” the following information/data are required:

- Continuous or batch.
- Parameters defining its scheduling of operation (on a daily, weekly, or yearly basis); these parameters allow for determining when the process is operated over the year and how many hours in total. For a batch process, additional data are the number of batches and the batch cycle duration.
- Type of modelling:
    - White box: ignoring existing heat recovery HEX (if any),
    - Grey box: only remaining heating or cooling (i.e., excluding the heat transfer achieved by existing heat recovery),
    - Black box: remaining heating or cooling at the level of utility supply.

1.3.1 Preliminary steps before definition of heat transfer requirements

Before heat transfer requirements can be defined, several preliminary steps are necessary:

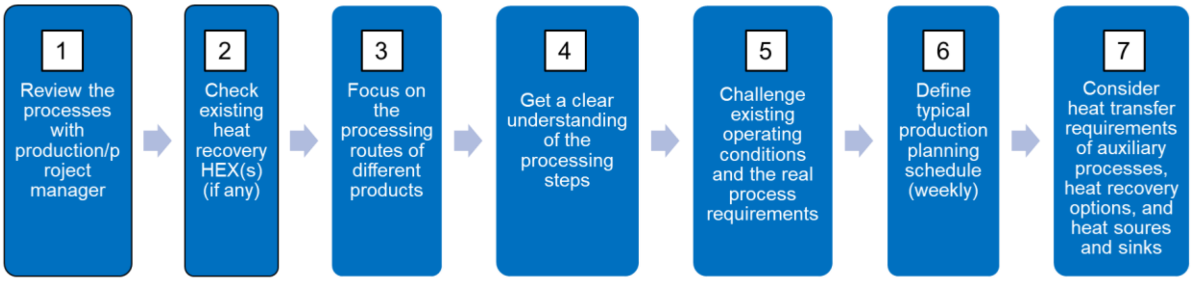


Figure 16: Preliminary steps before definition of heat transfer requirements.

1. **Review the processes with the production and/or project manager** to determine the planned / likely future evolution of the production (discontinued, increased volume, etc) and changes in processes and/or facilities. The goal is to identify the list of processes that will be operational in the coming years and their likely duration of operation.

2. **For the above processes, determine whether existing heat recovery HEX(s)** (if any) must be kept as is or can be modified (in other words, where is the boundary of possible changes for improving the heat integration). If the existing heat recovery (or part of it) cannot be changed, the corresponding cooling and heating are assumed to be satisfied and are not included in the list of heat transfer requirements to build the CCs (so-called grey box modeling). A black box model (no modification to the process, definition of heating and cooling requirements at the level of utility supply) may be necessary if the equipment supplier sets the scope of responsibility/guarantee for skids.

   Another criterion is whether the heat recovery HEX in place violates the 3rd golden rule (no heat transfer across the Pinch). If this is the case, the corresponding parts of hot and cold streams must be considered in the list of heat transfer requirements to allow redesigning the corresponding misplaced heat transfer.

3. Since many products have different processing routes/operating conditions, **focus on and sketch/record the processing route for 1, 2, or 3 products** that comprise the largest share (~80%) of the total production. Consider representative operating conditions.

4. Consult process engineers or plant operators for **explanations to get a clear vision/understanding of the processes/processing steps**. This insight into the processes helps define heat transfer requirements appropriately. Understanding the process allows reasonable heat and mass balance to be established to estimate unmeasured data or consolidate/reconcile data.

   For plants processing a large variety of products with different specifications in short campaigns (often the case in Switzerland), production facility heating at start-up, idling, and CIP / SIP can be responsible for significant energy consumption. Therefore, it is important to document the corresponding heat transfer requirements to better estimate the bottom-up heat balance and consider the requirements when designing an HP.

   Hints:

   - Ask whether any supplied schematic (block diagram, process flow diagram, P&ID, screenshot of supervision system, etc.) is up-to-date or whether significant changes have not been reported.
   - Cross-check important data given verbally by different persons (often inconsistent). Large discrepancies often exist. Get your estimates derived from your experience

values and global data such as energy consumption, duration of operation, production data, mass and energy balances, etc.

- Ask your respondents on the industrial site to validate the values collected before proceeding with the data analysis

5. As Chapter 5 of Part A states, do not take **existing operating conditions for granted but challenge them by identifying the real process requirement**s. Critically analyze the present operation conditions and question the business-as-usual approach (e.g., temperature, mass flow, the way heat is transferred, etc.):

    - Is this needed? (why/why not)
    - Which aim/constraint determines the operating temperatures?
    - Is there some scope for changing the operating conditions?
    - How close is the utility supply temperature to the required process temperature?

    Apply the principles of data extraction (e.g., *keep hot stream hot, keep cold stream cold*, *prevent non-isothermal mixing*, …).

    Also, document:

    - Existing heat exchangers, and
    - Which part of each heat transfer requirement is supplied by which utility (this helps with the bottom-up calculation of the energy balance and for devising HP integration options).

6. **Define typical schedule/weekly production planning (operation of the different processes over a typical week) with the support of the production manager/operators.** This is needed for both HP integration at the process level and HP integration at the utility level or for hybrid solutions to determine the classified heat load duration curve of sinks (to select HP heat capacity and split it into several units) and allow for realistic calculations of savings as a function of heat storage and of profitability. Also, start-up, idling, and CIP/SIP stages should be considered when scheduling them, as they have a significant impact.

7. After setting up the list of heat transfer requirements of actual production processes, do not forget to **include heat transfer requirements of:**

    - **Auxiliary (production support) processes,** such as CIP / SIP, volatile organic compounds (VOC) abatement facilities (regenerative thermal oxidizer, etc), water treatment, HVAC systems, and air compressors.
    - **Heat recovery opportunities** from waste heat discharge into air and water (soft streams).
    - **Heat sources and heat sinks of utility systems** (notably steam production and chillers).

    Note:

    Unlike the process stream requirements, the above streams depend on the amount (level) of production or utility consumption, which shall decrease as heat integration is improved. Be careful not to double-count streams, e.g.

    - 1) heat process cooling requirements (at the evaporator side of chillers) or condenser heat (or in the cooling water).
    - 2) wastewater flows (at the level of each process or the site level after mixing with other streams).

1.3.2 Temperature and mass flow measurements:

Remain cautious and critical if process engineers or operators manifest that the processes are well-instrumented, and all necessary data will be available/known. The quantities measured and recorded are those needed to control the process and to guarantee/verify product quality, but not necessarily those relating to energy and stream quantification.

All the quantities needed to define hot and cold streams are seldom available. For example, the temperature reached by the stream after preheating by heat recovery is usually not measured, as this value is not essential. Only the final (target) temperature is measured to control the utility heater. This also applies to waste heat streams in water or air, which are only measured if standards or legal requirements demand it.

Hence, be prepared to take measurements to quantify hot and cold streams, whatever the level of instrumentations of facilities/plants:

- **Temperature measurements** can be performed by placing temperature sensors (thermocouple type is recommended) on the external wall of corresponding pipes. It will be precise enough as long as:
    - the contact surface between the pipe and sensor is large enough,
    - a heat compound covers the contact surface to minimize contact resistance and
    - the sensor and a sufficiently large pipe area around it are thermally insulated with appropriate insulation material.
- In case of small temperature differences (T_{out}-T_{in} < 3 to 5 K), preliminary calibration of the whole measurement system (measuring instrument/datalogger, extension cable -if any-, thermocouple, at ambient temperatures like the ones encountered on site) is necessary to get reliable results.
- Measuring a temperature after a mixing point of two flows at significantly different temperatures (or in the case of temperature stratification in the pipe) may be tricky. Thus, ensure the flows have been well mixed at the measurement point (e.g., after a pump).
- Note that interpreting temperature measurements in dynamic/transient conditions (where thermal inertia and flow propagation / dead time play a role) is tricky and may be misleading if not correctly considered.
- A non-intrusive ultrasonic flowmeter is a must for liquid flow measurement in pipes. However, be cautious while choosing the measurement point to fulfill the conditions stated by the manufacturer as well as possible (distance downwards of perturbation of flow pattern, full pipe, no bubble, etc.). Ensure with the plant operator ahead of the measurement campaign that the plant will operate at representative conditions (ask the operator to record specific events if this is not automatically recorded in a log file of the supervision).
    - Note that streams existing in the range of the pinch temperature (or more generally in "pinched" regions of the CCs with small (vertical) temperature driving forces) must be known with sufficient accuracy, while in regions of CCs featuring large temperature driving forces, approximate values of temperature and heat load may be sufficient.
    - Double-check your measurements with another approach (heat and mass balance, etc.) to consolidate data and ensure they are not biased by systematic error. Naturally, measurements are prone to errors but often show more realistic data than the estimates operators or plant engineers communicate.

1.4 Applying Pinch Analysis

Once the list of heat transfer requirements of the different processes has been set up, the PA itself can be applied according to the simplified workflow of Figure 17 (focused here on the integration of HPs).

The workflow aims to guide the search for promising heat integration solutions, assessing them and selecting the most appropriate one(s). Chapter 6 of Part A highlights the combinatorial nature of the problem of inter-process heat integration with heat transfer loops, with or without HP(s):

- How many loops?
- Which heat source(s) to connect to which loop(s)?
- Which heat sink(s) to connect to which loop(s)?
- How and where to integrate HP(s)?

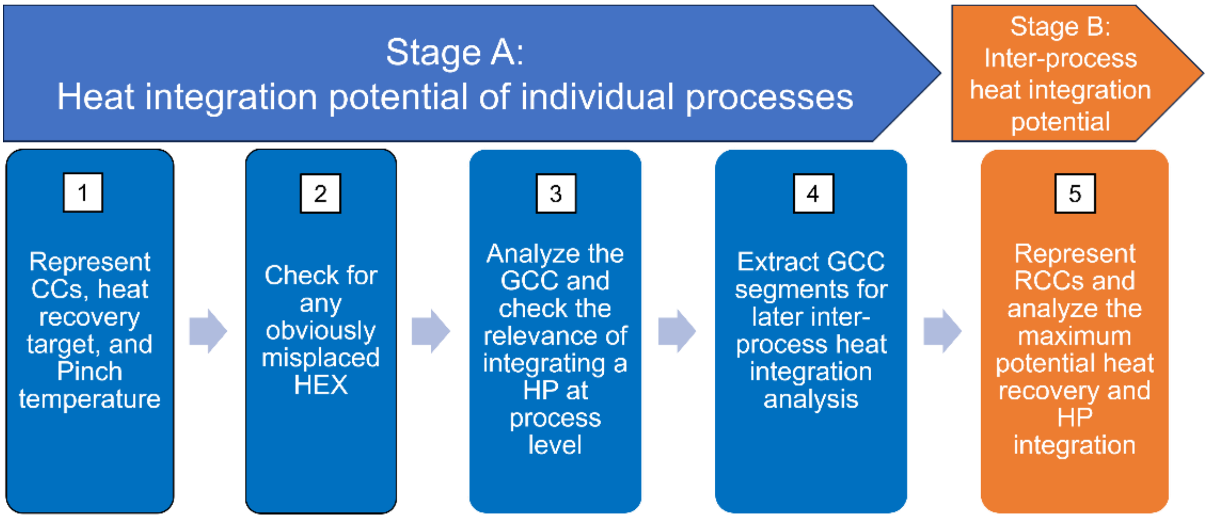


Figure 17: Simplified workflow for targeting and optimizing an industrial site's heat recovery and upgrading via HP(s), including several processes.

The workflow includes the following stages and steps:

Stage A: Heat integration potential (direct heat recovery, heat upgrading by HP) of individual processes.

In this stage, processes are analyzed independently of each other. Local direct heat recovery is prioritized since it is known to be more cost-effective than inter-process heat integration. This approach holds if heat transfer does not take place across the "global Pinch" (the notion of the "global Pinch" is explained below).

For each process, perform the following steps:

1. **Represent CCs (in kW), heat recovery target, and Pinch temperature:** Is there scope for improving the (internal) heat recovery within each process (considered in isolation)?
2. Knowing the Pinch temperature of the process, **check for any obviously misplaced HEX**, i.e., violating the golden rules (refer to Section 5.4 of Part A), concerning the Pinch temperature of the process. In addition, any heat recovery HEX with large temperature driving forces can be suspected to transfer heat across the "global Pinch" and should be temporarily blacklisted for further steps (whether the HEX violates or not depends on the cluster of processes (including the process under analysis) considered in Stage B for the inter-process integration).

3. **Analyze the GCC (in kW) and check the relevance of integrating a HP at the process level**, and if applicable, assess the profitability of possible HP(s) (the significance of the HP placement remains to be confirmed later once the “global Pinch temperature” will be known)

4. **Extract GCC segments** (in kWh/reference duration) (i.e., representing the remaining deficit, surplus of heat after internal heat recovery) **for later inter-process heat integration analysis** (extraction in kWh is needed since inter-process heat integration to be analyzed in Stage B will “mix” processes that very often are not operating synchronously).

   The reference duration must be chosen carefully to achieve realistic targets: it cannot be one year as it may mix in the Residual Composites Curves (RCCs) contributions that do not exist during the same season (unless efficient seasonal storage is available) on the contrary, it must be chosen so that “schedule misalignments/discrepancies” between processes can be coped with practical heat storage. Eventually, consider different operating cases.

   Different extractions of GCC segments can be considered depending on the situation:

   a. GCC without segments of pockets, without HP (if any);

   b. GCC with segments of the pocket(s) featuring “wide” (i.e., large temperature gap) and “deep” (i.e., large energy) pockets. This case is needed to prevent direct heat transfer across the “global Pinch” to take place in the process and allow for the “high temperature” excess heat part of the pocket to be transferred and used by another process. The “low temperature” deficit part of the pocket is supplied by excess heat of other processes (refer to (Brunner and Krummenacher 2017b) (in French), page 67). Two loops are needed to avoid temperature degradation of heat within the pocket; hence, the profitability in these heat transfers to and from other processes is low;

   c. GCC as (a) or (b) above, but with HP integrated at the process level. This case makes sense if integrating HP at the process level is profitable but still leaves a surplus of heat and/or heat deficit that can be supplied by inter-process integration.

   Note:

   - Processes too far from any other process(es) or subject to “hard constraints” preventing any cost-effective heat transfer with other processes must be integrated locally and independently. For these processes, the GCC segments are to be taken into the RCCs only in case of HP(s) integrated at the utility level using existing utility networks (or whenever the focus is on decarbonization or future extension, whatever the capital costs incurred);
   - If heat recovery is not possible or desired within the process for any reason, the GCC segments are then the streams themselves, shifted by $+/-\Delta T_{min}/2$.

Stage B: Inter-process heat integration potential (indirect heat recovery via heat transfer loops, heat upgrading by HP)[4].

This stage aims to determine the additional saving potential possible with inter-process heat transfer and HP(s) integration at the utility level and/or at the level of “clusters of processes.” Moreover, it also aims to assess the profitability of various promising HP alternatives (according to the methodology outlined in this document).

5. **Represent RCCs and analyze the maximum potential heat recovery and HP integration**.

[4] It is assumed here that heat transfer between processes cannot be achieved by direct heat transfer and must use heat transfer loops. If two processes are located close enough and are synchronously operated so that direct heat transfer would be economical, then these processes must be grouped into a single process before starting Stage A.

a. Begin with RCCs made of all extracted GCC segments (further shifted by their respective $-\Delta T_{min}/2$ for heat surplus segments and $+/\Delta T_{min}/2$ for heat deficit segments) to get an upper bound target. Check the influence of the different cases (GCC segments without pockets or with segments of “deep” and “wide” pockets) on the target.

Note:

- Unlike CCs of a continuous process, RCCs are made of residuals (not actual streams) and the residuals do not necessarily co-exist in time (in which case heat storage is needed or the actual heat recovery is smaller than seen on the RCCs);
- Heat transfer between processes (inter-process heat integration) is only possible via utility networks or dedicated heat transfer loops. These heat transfer loops incur significant investment costs and operational complexity, so only a few networks are generally viable. The number of loops needed for a given heat recovery (overlap of RCCs) can be calculated with simplifying assumptions and considering the start temperature of “deficit segments” of GCC of each process (above the Pinch temperature of that process), as well as the start temperature of the “surplus segments” of the same GCC (below the Pinch temperature). It also depends on how the processes are connected on the loop (exclusively in parallel or from case to case in series). Excluding processes/streams that are particularly constraining the operating temperatures of the loop and have a limited contribution can reduce the number of loops needed without significant adverse effects on heat recovery
- Hence, it may be worth setting up and analyzing different clusters (subsets) of processes (appropriate indicators may help select promising clusters). On the contrary, integrating a HP at the utility level to supply all processes is a “simple solution” not involving many decisions, but featuring poor energy efficiency and poor profitability (maybe low CAPEX thanks to economy of scale and existing utility networks, but high OPEX). Refer to Chapter 6, Part A.
- Regarding the “global Pinch temperature” to consider for checking whether a HP integrated at the process level is correctly placed or not: the “global Pinch temperature” of reference for the HP is then the Pinch temperature of the cluster of processes (which includes the process with that HP) that are selected to be part of the inter-process integration via the heat transfer loops considered. This means that this cluster is implicitly integrated “in isolation” and cannot have cost-effective heat transfer with other processes or clusters of processes. The same applies to checking potential violations of HEX temporarily blocklisted at Step 2 of Stage A.

b. Iterate Step 5 by building and analyzing different combinations of clusters (e.g., starting around two processes featuring large sinks and sources at appropriate temperatures and stepwise enlarging this core cluster to include other promising processes. Indicators to help devising promising clusters are related to costs, potential heat recovery, and efficiency, e.g., short piping distances, large energies (and large duration) with good simultaneity or improving it, small temperature lift, increase of HP capacity to benefit from the economy of scale, etc.

1.5 Feasibility study

Once promising clusters and the corresponding operating conditions of heat transfer loops and HP have been pre-selected, an hourly simulation based on the hourly profiles of selected heat sources and sinks over one year must be set up to get realistic results (actual energy savings, required number of start/stop cycles of HP, etc.). The simulation (which ideally should include heat storage) must show the influence of the following parameters (degrees of freedom) on the results:

- operating temperatures of heat transfer loops;
- capacity of HP, eventually split into several units;
- capacity of heat storage(s)
- list of connected sinks and sources

6. Calculate, record, and compare KPIs (CO_2 savings, CAPEX, OPEX, etc.) of candidate solutions to make a final decision.

2 Technical Aspects

The definition of specifications for a HTHP and related elements like infrastructure or safety measures are addressed in this chapter. The objective here is to provide an overview of the key aspects needed to define a HTHP project clearly. The following information is important to the manufacturers to offer suitable technologies, well-designed machines, and correct performance estimations for the customer. A well-defined project also allows to compare solutions better.

The content of this section is mainly based on various published reports (Arpagaus et al. 2023b; Bless 2023; IEA HPT 2024a, d, c). Important thinking steps in the evaluation are:

- **Heating capacity:** The demands of hundreds of kW to a few MW are common for industrial applications.
- **Supply temperature:** Many sites use a medium- to high-pressure steam supply. It could be adjusted to a lower supply temperature depending on the requirements. The HTHP must be able to supply the defined needs.
- **Efficiency (COP):** an indicator of HP thermodynamic efficiency bounded by the Carnot limit. The lower the temperature lift between source and sink, the higher the COP.
- **Refrigerant type:** The HPs must operate using low GWP and zero ODP refrigerants, which are considered sustainable. The trend is towards natural refrigerants. However, flammability (hydrocarbons) and toxicity (ammonia) must be handled.
- **Technology Readiness Level (TRL):** HTHP products are developing strongly. The TRL measures the maturity of a technology from conceptualization to commercialization. A higher TRL indicates a more reliable and robust technology. Market-ready products have a TRL of 9.

2.1 Heat Pump Operation and Performance

2.1.1 Heat Source and Sink

Each process is unique, and the specifications of the foreseen heat sources and sinks are necessary to identify and adequately size a HTHP. Key information includes the source and sink temperature ranges, ensuring the expected temperature lift is admissible with the HTHP specifications. In case this is a critical factor, the ability of the HTHP to follow source temperature fluctuations and the stability of the production temperature are to be clarified for a reliable operation.

Seasonality can impact both hot and cold sides and must also be considered. Simultaneous heating and cooling can significantly enhance the benefits of integration. In addition, optimizing the process by lowering the sink temperature and increasing the source temperature will improve the HP efficiency. However, it may affect the process by prolonging the heat-up times or requiring larger distribution pipes.

The availability (timewise and quantitative) of waste heat or process cooling needs as a source, and the advantages of a continuous process are as significant. The load profiles should be well-known. Depending on the processes, it might be possible to adjust them timewise to increase the simultaneity of the source and the demand profiles.

Moreover, the spatial location and quality (cleanness) of heat sources and sinks can strongly impact heat losses and costs linked to the distance, material selection, or fouling of heat exchangers.

The following information is required for the source and sink streams:

- Inlet and outlet conditions: temperature, description of max/min fluctuations and pressure levels
- Design mass flow and description of occurring max/min fluctuations
- Media (e.g., composition, phase, heat capacity, level of contamination, expected fouling characteristics and material requirements, if any, for piping, heat exchanger etc.)

- Operation duration and load profiles
  Maximum allowed cooling or required cooling on the source side

2.1.2 Heat Pump Efficiency

Chapter 1 in Part A gives insight into how the COP is linked to the heat source and sink temperatures. A HTHP can also be based on various technologies (see Part A, Chapter 4), so the achievable efficiency range is broad.

The COP dependency on temperature levels provides an opportunity to increase efficiency. On the other hand, potential temperature drifts from design conditions could negatively impact the HTHP's performance.

The supplier should be asked to select operating points for which performance data is required for further evaluation, considering fluctuations on the sink and source sides. Figure 18 shows an example of efficiency maps to overview a HTHP behavior over heat sink and source temperature ranges. The system's limits for a given COP should be clearly stated. In addition, it should be clarified if the COP value considers the electricity consumption of auxiliary equipment, like pumps or frequency converters.

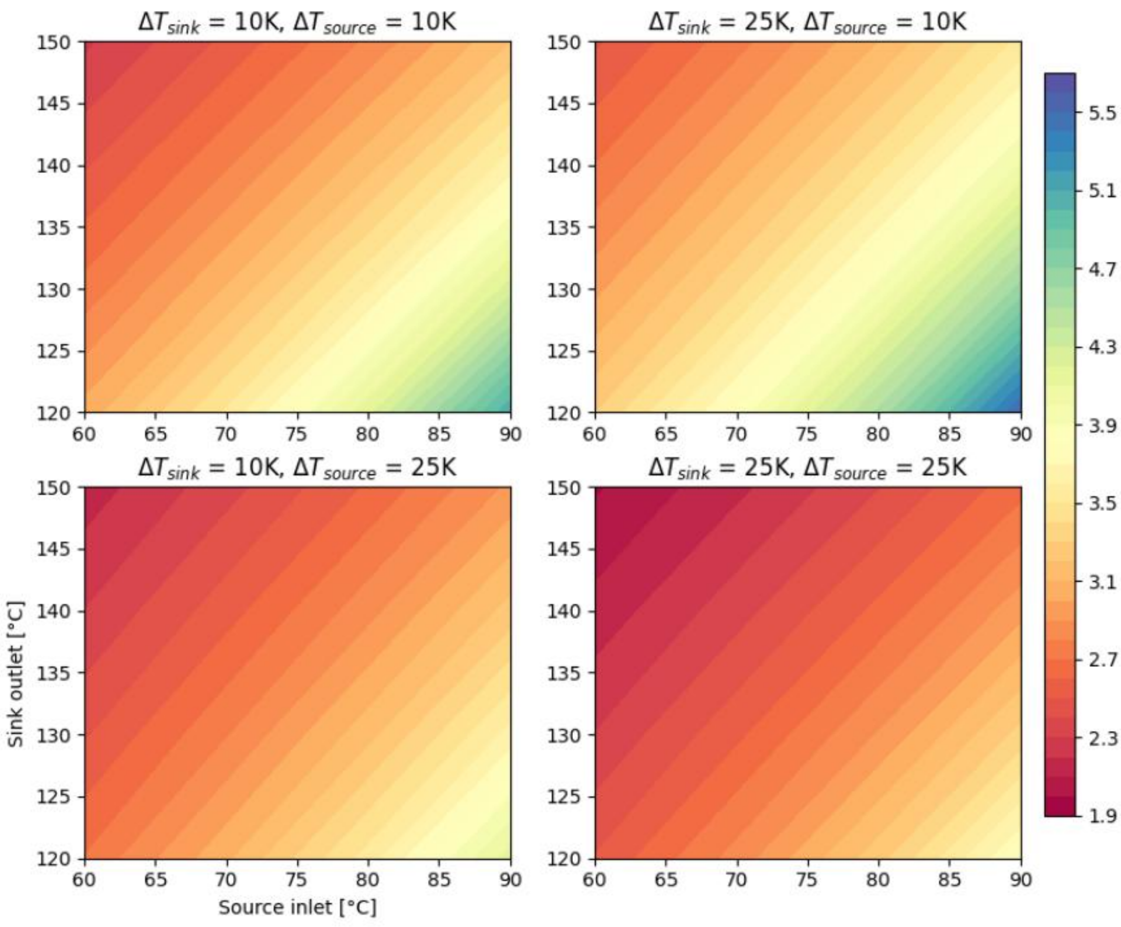


Figure 18: An example of 4 performance maps for the COP, each valid for their temperature range and glides on the heat sink and source (IEA HPT 2024c).

2.1.3 Operating Range

An operating map determines a HTHP's physical limits, mostly linked to the capacity, compression ratio and discharge pressure. Figure 19 shows operating ranges for a selection of HTHPs. The colored areas define the couples of source-sink temperatures between which the HTHP can work. The HTHP machines can only work within their given limits.

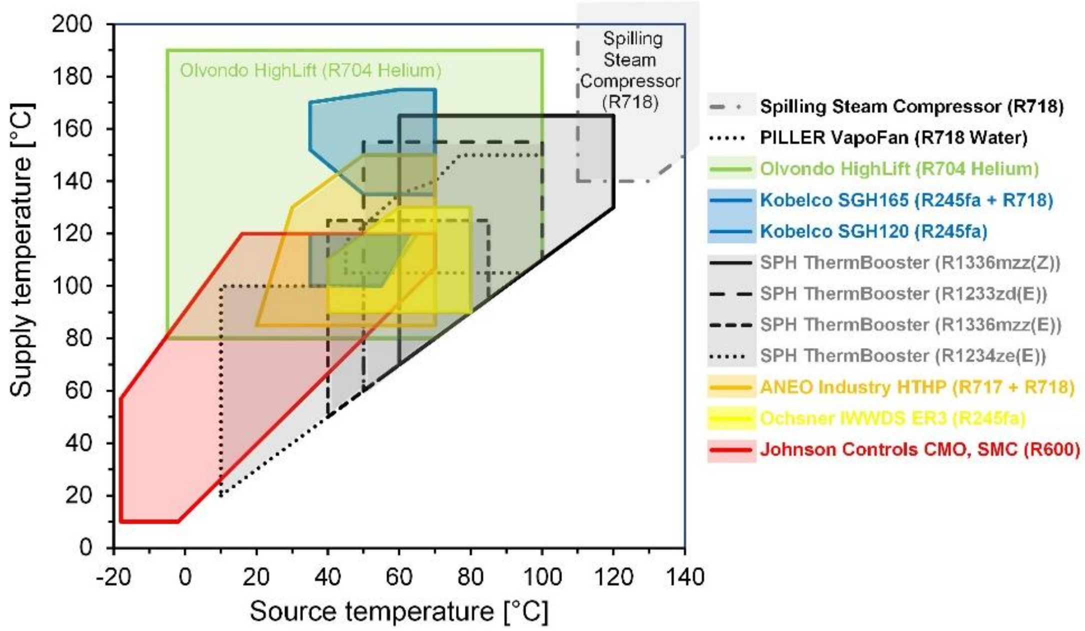


Figure 19: Operating ranges for a selection of HTHP products (Arpagaus et al. 2023a).

2.1.4 HTHP Specifications

HTHPs imply specific technical aspects. Hereafter is a list of information to be provided or confirmed by the manufacturer:

- Footprint and weight of the HTHP
- Minimum working duration after start-up, continuous operation capability and duration without maintenance
- Managing high variations in demand and source or sink temperatures (to maintain efficiency and stability)
- Minimum part-load functioning (% of design capacity)
- Start-up and shutdown times and capacity ramping rates
- Noise emissions and vibration (with available mitigation measures to comply with maximum allowed noise emissions)
- Precision of the output temperature
- Refrigerant type
- Material requirements
- Integration in automation system
- Electrical requirements (maximum voltage, current and frequency; standstill power; electrical noise and harmonic filter)
- Type of oil in the machine (for example, any requirement for food-grade oil to be specified)
- Environmental working conditions (humidity, ambient temperature)

Clear boundary conditions and roles between the customer and supplier, particularly concerning modifications to existing equipment and warranties, are essential.

2.2 Infrastructure Requirements

Implementing a HTHP system demands a thorough evaluation of existing infrastructures and the potential need for upgrades.

2.2.1 Location for the Installations

A suitable location for a HTHP offers sufficient space in terms of footprint and height for the machine, equipment, and thermal storage, if applicable. Providing enough space around the installations ensures easier maintenance. Container solutions for outdoor placement can be an option for limited space issues. The building's structural capacity and the weight and vibrations generated should also be assessed.

2.2.2 Power Supply

The electrical supply needed by the HTHP implies assessing the available power reserve to provide the HP with its maximum electrical requirement. Electrical cabling to the machine, adding extra transformers, or increasing subscribed power can represent a major cost factor. On the other hand, electrical HTHP can help increase the self-consumption of one's own PV installation.

2.2.3 Distribution Network and Thermal Storage

Integrating an HTHP at the process level has less impact on the distribution network since the machine supplies a limited number of streams that are ideally located nearby. Limiting the geographic distance also helps avoid extra distribution losses. Distribution networks may need to be built or modified to ensure the heat supply from the HTHP to the processes for decentralized integrations where the machine supplies heat at the utility level. This applies when a lower supply pressure or superheated water replaces an initial steam supply.

In some cases, decoupling the HTHP from the process with an intermediate water loop is needed to avoid contamination of the streams. This should be avoided from an efficiency point of view since it reduces the system's COP (i.e., additional temperature difference to overcome).

Regarding thermal storage, solutions for steam storage are available on the market, although much less common than water storage (for example, the "Dampfspeicher CoPES" from Jaske & Wolf Verfahrenstechnik GmbH) (Bless 2023). More information can be found at www.sweet-decarb.ch and https://heatpumpingtechnologies.org/annex58.

2.2.4 Automation System

Proper integration of the HP into an existing automation and control system is essential. Special care should be taken in hybrid systems where the HP must work harmoniously with another heat source.

2.3 Safety Aspects

2.3.1 Refrigerant Fluid

Ensuring the safety of HTHP installations involves comprehensive planning and adherence to regulations and internal standards and directives. Key technical requirements include proper enclosure, ventilation, detection, and alarm systems, especially considering the selected refrigerant gas. A thorough global risk analysis is necessary, including compliance with relevant standards such as:

- Chemical Risk Reduction Ordinance (ORRChem),
- Ordinance on Protection against Major Accidents (Major Accidents Ordinance, MAO),
- Ordinance on Air Pollution Control (OAPC),

- Directives on potentially explosive atmospheres (ATEX)
- Pressure Equipment Directive (PED) or
- Swiss National Accident Insurance Fund (SUVA).

Pre-validation of the project by local authorities should be conducted from the project's inception.

Figure 20 shows a breakdown of the working fluids used in current HTHP technologies (Zühlsdorf 2024). About 2/3 of the HTHP products work with natural refrigerants like CO_2 (R744), steam (R718), ammonia (R717), or hydrocarbons (R600, R600a, R601, R601a). Some HTHP technologies, like the MVR type, do not contain any refrigerant, as water steam plays this role in an open cycle. Depending on the refrigerant, toxicity and flammability lead to safety considerations.

SFOE (Swiss Federal Office of Energy) and FOEN (Federal Office for the Environment) recommend using natural refrigerants for efficiency and environmental reasons.

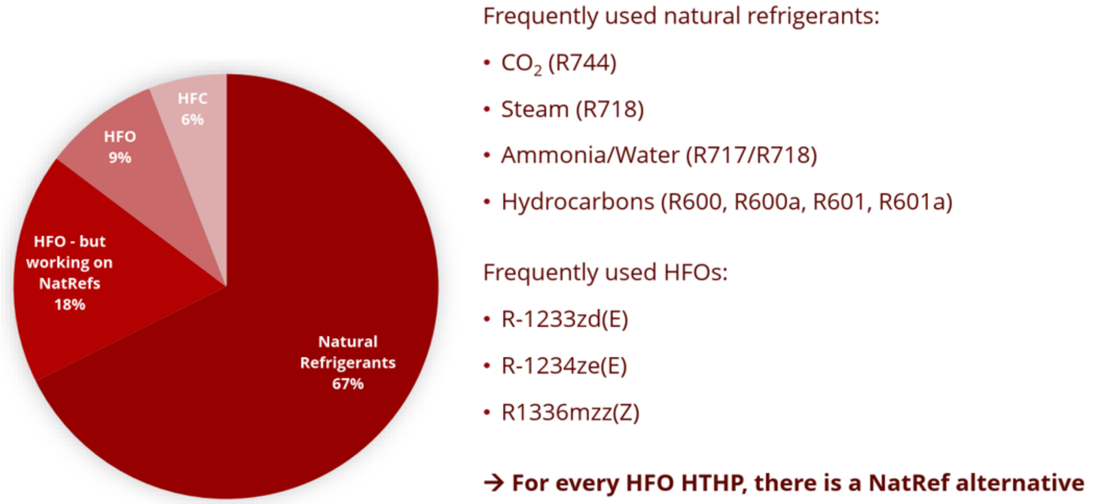


Figure 20: Breakdown of the refrigerants contained in HTHP. Information based on IEA HPT Annex 58 and other publicly available information (Zühlsdorf 2024).

2.3.2 Redundancy Strategy

A robust redundancy strategy is vital to ensure continuous operation and mitigate risks associated with heat production shutoff. Maintaining existing heat sources as backups, such as boilers, is common, though it necessitates careful planning regarding their heat-up duration and maintenance. The number of compressors per machine and the ability to replace one during operation should be verified with suppliers. A renewable backup solution should be evaluated. Assessing the risk and financial impact of heat production shutoffs is critical.

Redundancy during maintenance, renewable redundancy options, and a well-designed start-up and backup system are essential. Optimizing heat needs before installing a HTHP can reduce the requirement for backup. The process's criticality dictates the redundancy needed, and the speed of available backup heat is a key factor. The duration and costs of maintaining redundancy, including emergency generators for blackouts, must also be considered to ensure uninterrupted operation.

2.4 Maintenance

Effective maintenance strategies are crucial for the long-term success of HTHP systems. Training internal maintenance staff for routine checks and establishing long-term contracts with suppliers are highly recommended. Whether maintenance is performed internally or externally depends on staff capacities and the balance between reactivity and alignment with planned maintenance breaks. The periodicity and safety of maintenance tasks should be defined with the supplier. The supplier's proximity impacts the reaction time. The availability of spare parts is also to be considered. Adequate access for maintenance without ladders should be ensured during routine checks. Storing spare parts, particularly key components, at the supplier's facility can be beneficial. Reaction time, including remote control, should be specified in maintenance contracts, with financial penalties for delays.

2.5 Technology Lock-in

Past investment choices can lead to technology lock-in, making switching from fossil boilers to HP technology more difficult or costly. This applies to the following points (Zühlsdorf 2024):

- Process equipment designed for high pressures or not optimized for new energy supply
- Existing waste heat recovery from combustion processes or with large temperature difference
- Supply of waste heat outside the factory

2.6 Further References for Planification

Specifically for industrial HPs, the Association of German Engineers has elaborated the VDI 4646 Guideline for applications of large HPs (in German, January 2024) (VDI 2024). This document targets heat outputs >100 kW and provides information on the planning process for integrating large HPs.

Regarding HTHPs (>100 °C), the reports from IEA Annex 58 constitute a vast source of information and can be accessed at https://heatpumpingtechnologies.org/annex58. The following topics are addressed:

- Task 1: Technologies (IEA HPT 2023)
- Task 2: Integration concepts (IEA HPT 2024a)
- Task 3: Application and transition (IEA HPT 2024d)
- Task 4: Definition and testing of HP specifications (IEA HPT 2024c)

Moreover, Task 5 (Dissemination) gathers a list of presentations, webinars, and publications. Other technical guidelines and standards for HP system planning mostly target the building sector. Nevertheless, they contain valuable information on HP design and operation (for closed-cycle electrical HPs), such as:

- SIA Standard 384.348 (2007): Heating systems in buildings - Planning of heating systems with heat pumps along with SIA 380/1, 384/1, 384/2, and 384/3 (https://shop.sia.ch/europ%C3%A4ische%20normen/architekt/sia%20384.348/d/D/Product)
- SFOE (2018): Guideline on heat pumps: Planification, optimization, operation, maintenance (https://www.fws.ch/wp-content/uploads/2018/12/Buch_WP_Web_2018.pdf)
- RAVEL Cahier 3 (1993): Pompes à chaleur: Planification, construction et exploitation des installations de pompes à chaleur électriques (https://pubdb.bfe.admin.ch/fr/publication/download/2407)
- Standard DIN EN 378 describes the safety and environmental requirements for refrigeration systems and HPs. Other practical manuals for planners and installers are available on this subject.

3 Financial Aspects

3.1.1 Importance of Financial Aspects

The financial evaluation of heat production is a classic exercise for manufacturing companies. The HTHP workshop with participants from industry (Arpagaus et al. 2023b) showed that the most important economic indicators mentioned by all groups were:

- payback time,
- ROI (return of investment),
- operating costs,
- electricity and gas prices, and
- discounting.

Investment costs and funding opportunities were considered less important.

Further related financial aspects are:

- gas availability,
- the total cost of energy production,
- energy price fluctuations,
- energy contracts (electricity long-term contracts, gas more short-term day-by-day trading),
- energy price ratios (cost of energy vs overall OPEX),
- CO_2 tax expectations for the future,
- maintenance costs (gas/HP variations or fixed),
- operation hours/year,
  alternative heating technologies include biomass, cogeneration, solar thermal, electrical steam boilers, biogas, and electrical (air) heaters (Arpagaus et al.,.

3.1.2 Business models

A review of business models (Arpagaus et al. 2023d, 2024c) showed that a HTHP manufacturer typically sells their HTHPs directly to the customer, including a service and maintenance contract (Direct2Customer). This approach mainly involves project development and direct sales of the HTHP to end users. Revenue is supplemented by installation, commissioning, and future services such as maintenance and repair. However, future market success and penetration of HTHP technologies may presumably enable and require new business model approaches. Thus, each HTHP technology requires its business model evaluation based on the building blocks of the business model. Highly customer-integrated business models such as Heat-as-a-Service (HaaS) open new market opportunities for HTHP.

3.1.3 Costs

A correlation on the specific investment costs of a HTHP is given in Part A, Section 9 together with an economic model for preliminary estimates of profitability and CO_2 emission reduction (Arpagaus et al. 2022a, c). Typical cost multipliers to calculate the HTHP integration for a whole project can vary between 1 to 4 times the HTHP purchase costs. Maintenance costs are like those of a refrigeration system, typically a few % of the yearly investment. In general, the costs depend on:

- Heating capacity (e.g., economy of scale)
- Type of HP cycle (e.g., 1-stage, 2-stage, economizer, cascade)
- Refrigerant (e.g., tightness check, gas detection, ventilation)
- Temperature lift

3.1.4 Funding/subsidies in Switzerland for industrial HPs

There are several national funding programs at the federal level, like EnergieSchweiz and SFOE, to accelerate the integration of HPs in the industry. Table 10 gives an overview of a selection of funding programs for HPs for industrial process heat in Switzerland (IEA HPT 2023). The subsidies depend largely on a legal basis.

In general, funding programs are a dynamic field with details subject to change. Following Switzerland's failed CO_2 energy law in 2021, a provisional CO_2 law now secures the legal basis until 2024. What the legal provisions will look like after that is still being determined. But, judging by the public debates, subsidies will likely play a major role in achieving the goal of net zero by 2050. However, the subsidy share for HPs is still being determined. Further information on the programs, program managers, financing, and subsidy conditions is available via the info links.

Table 10: Funding programs for industrial HPs in Switzerland (IEA HPT 2023).

Funding program	Pinch Analyses	Heat Pumps for Process Heat	Klimaprämie (Climate bonus)	Pilot and Demonstration
Program Manager	EnergieSchweiz (SuissEnergie)	EnergieSchweiz	EnergieZukunft Schweiz	SFOE (Swiss Federal Office of Energy)
Financing	SFOE	SFOE	KliK Foundation	SFOE
Amount	• Pre-analyses: max. 60% of total costs • Pinch analyses: • Max. 40% of total costs	• Max. 40% of additional costs compared to conventional technology (e.g., oil or gas boiler)	• 0.18 CHF/kWh heat • About 360 CHF/kW heat at 2'000 h annual operation	• Up to 40% (60%) of non-amortizable supplementary costs
Criteria	• Using PinCH Software • Trained experts • Publication of findings (summary, final report)	• Industrial process heat • Payback >4 years • Funding request before construction starts • Companies with a CO_2 tax exemption are examined individually	• Replacement of oil/gas boiler with heat pump • Order not yet placed • CO_2 savings to be transferred to Energie Zukunft Schweiz	• Application potential • Innovative content • Pilot: TRL 4 to 7 • Demonstration: TRL 7 to 9 • Publication of findings (final report)
Infos	• Website[5], Flyer[6]	• Website[7], Flyer[8]	• Website[9], Flyer[10,11]	• Website[12]

In addition, the *myClimate* climate protection program promotes replacing fossil heating systems in the industrial sector with HTHPs (Myclimate 2024). Heat-related CO_2 emissions can be reduced by switching to renewable heating sources. Industrial companies in Switzerland that register for the funding program by the end of 2025 and want to implement a conversion project by 2030 can benefit from this funding.

---

[5] https://www.energieschweiz.ch/beratung/pinch/ (DE) and https://www.suisseenergie.ch/conseil/pinch/ (FR)
[6] https://pubdb.bfe.admin.ch/de/publication/download/8357 (DE) and https://pubdb.bfe.admin.ch/fr/publication/download/8357
[7] https://www.energieschweiz.ch/prozesse-anlagentechnik/industrielle-waermepumpe/ (DE) and https://www.suisseenergie.ch/processus-technique-dinstallations/pompes-industrie/ (FR)
[8] https://pubdb.bfe.admin.ch/de/publication/download/10753 (DE) and https://pubdb.bfe.admin.ch/fr/publication/download/10753 (FR)
[9] https://www.klimapraemie.ch (DE) and https://www.primeclimat.ch (FR)
[10] https://energiezukunftschweiz.ch/wAssets/docs/foerderprogramme/klimapraemie/klimapraemie-factsheet-grosse-anlagen_2022.pdf (DE) and https://energiezukunftschweiz.ch/wAssets/docs/foerderprogramme/klimapraemie/klimapraemie-factsheet-grosse-anlagen-fr.pdf
[11] https://energiezukunftschweiz.ch/wAssets/docs/foerderprogramme/klimapraemie/klimapraemie-detaillierte-foerderkriterien_wp_de.pdf (DE) and https://energiezukunftschweiz.ch/wAssets/docs/foerderprogramme/klimapraemie/klimapraemie-detaillierte-foerderkriterien_wp_fr.pdf
[12] https://www.bfe.admin.ch/bfe/en/home/research-and-cleantech/pilot-and-demonstration-programme.html

The eligibility criteria are:

- Industrial application > 50 kW_{th}
- Minimum share of 50% process heat and 50% renewable heat (fossil peak load permitted)
- Natural refrigerants such as carbon dioxide (R744, CO_2), hydrocarbons (propane R290, isobutane R600a) and ammonia (R717, NH_3) are recommended.

The subsidy amounts to 0.18 CHF/kWh, based on heat consumption over the last 3 years. Payment is made annually after successful monitoring at CHF 160/tCO_2 until the subsidy is reached. The CO_2 compensation is transferred to Klik. Double funding with the EnergieSchweiz/SFOE funding program "Heat pumps for process heat" is possible.

For example, a HP with 1.2 MW_{th} heating capacity and an annual consumption of 3'000 MWh would receive a maximum subsidy of 3'000*1000*0.18 = CHF 540'000. The effective annual payment with an estimated average emissions reduction of 500 tCO_2/a is = 500*160 = CHF 80,000/a. The expected funding period until the maximum funding contribution is reached, unless 31.12.2030 is reached, is 540,000 / 80,000 = 6.75 years.

4 Socio-Economic Aspects

4.1 Drivers of HTHP Adoption

When pondering whether to install a HTHP in an industrial setting, decision-making is usually steered by other socio-economic and environmental drivers. These include motivations such as:

- economic incentives for installing HPs or for achieving sustainability goals,
- expectations of future cost and energy savings or higher resilience to price shocks,
- concerns about potential drawbacks or risks and even
- incorrect notions about HP technology and its implications.

The relative importance of factors considered when installing a HTHP was surveyed among participants from industry, manufacturers, research, and government institutions at the Workshop on HTHPs held in Ittigen, Switzerland, in March 2023. This workshop, a collaborative effort of various industry stakeholders, provided valuable insights into the decision-making process for HTHP installation (Arpagaus et al., 2023b).

Figure 21 summarizes the poll results in which participants could vote for one or more factors as relevant drivers to trigger an investment in a HTHP.

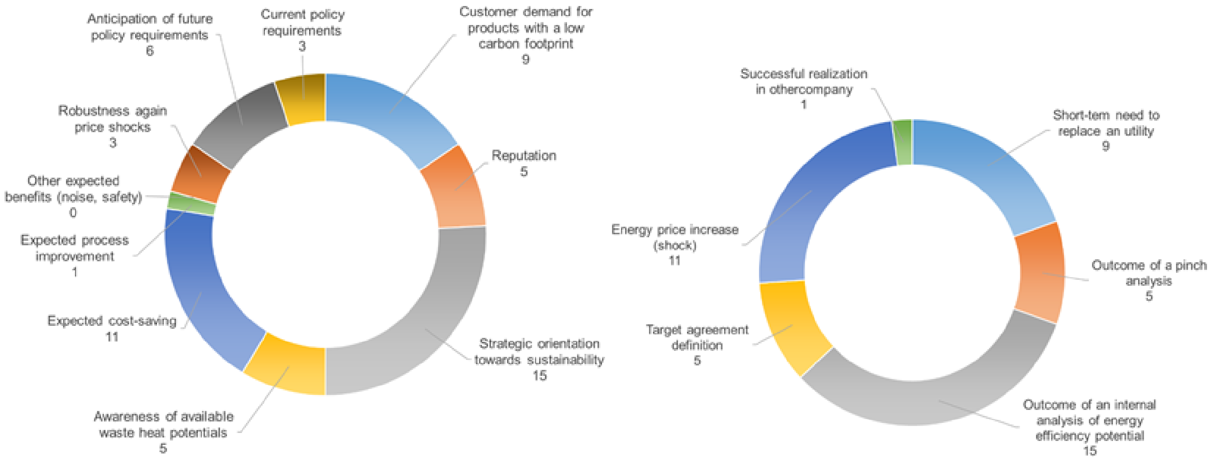


Figure 21: Drivers of HTHP adoption: Long-term (left) and short-term (right) factors (Arpagaus et al. 2023b).

One of the most significant drivers for installing a HTHP is the strategic orientation towards sustainability. As consumers become more environmentally aware, they prefer products from companies that aim to reduce their carbon emissions. This trend has led to a significant role for corporative factors, as companies seek to improve their brand image by demonstrating their commitment to sustainability and innovation.

Meanwhile, the expected cost savings linked to the available waste heat recovery potential are a second motivation for installing an HTHP in the industrial sectors. This perspective also anticipates more stringent environmental regulations, which may impact the operational viability of industrial assets reliant on fossil fuels susceptible to volatile market prices and geopolitical events.

While current policy requirements have less influence, the importance of anticipated future policies must be balanced. In the current context of subsidized fossil resources and high investment costs of HP units, current policies need to be revised to promote the electrification of industrial heat supply. However, some companies are more forward-looking and strategic in their planning, considering the robustness against future economic conditions, such as price shocks.

Finally, noise or workplace safety concerns appear as the least important factors in the decision-making process, suggesting that these are minor deterrents to adopting heat-pumping systems. In practice, the industry will adopt HPs driven by strategic, economic, and market-oriented motivations that strongly emphasize sustainability and cost-effectiveness. All these factors are expected to shape the so-called S-curve of adopting HTHP technology, as shown in Figure 22.

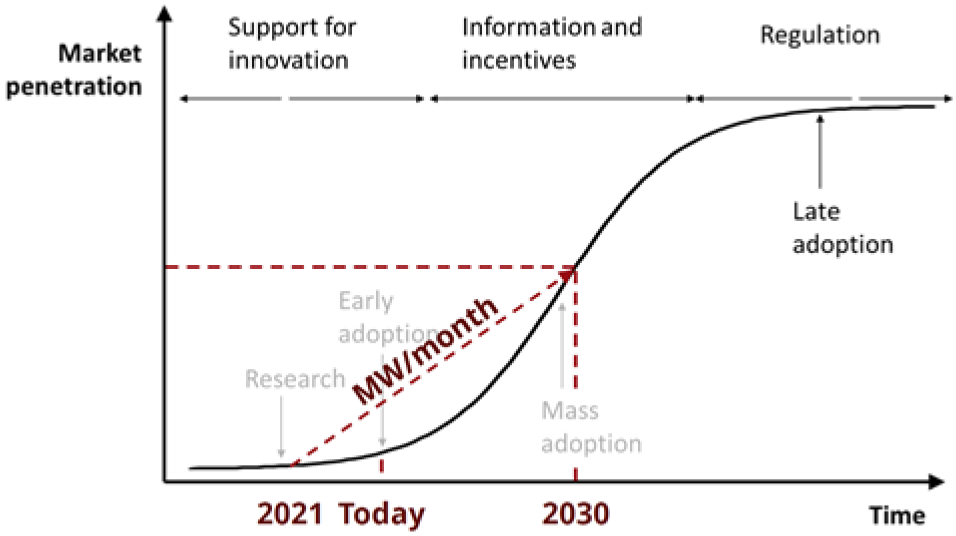


Figure 22: S-curve of the HTHP technology adoption (Zühlsdorf 2024).

The S-curve outlines the industry's technology and energy transitions. These undergo a slow initial growth, followed by rapid market uptake and then gradual leveling off as markets mature and saturate, with an eventual replacement of the incumbent technology (Mai et al. 2018).

4.2 Favorable market conditions and risks discussion

To overcome the early adopters' *analysis paralysis*, support for innovation and research, more information, and economic incentives are necessary for HTHP implementation. Technology awareness, commitment to sustainability and decarbonization, and the involvement of various stakeholders are critical actions in the early stages.

As soon as component and system developments are tested and demonstrated in selected pilot settings, other life cycle assessments and retrofitting analyses will assess the effectiveness of the decarbonization strategies. The leap to mass adoption, in turn, will require a paradigm shift in which the costs of fuels and emissions, the binding regulatory frameworks, and the subsidies and incentives will play a decisive role in the HTHP market development. Although one concern with subsidies for low-carbon technologies is that they tend to go predominantly to high-income adopters, HPs have proved to be important exceptions (Davis, 2024). Anyhow, a favorable environment is very important to guarantee the HTHP technology deployment in as many commercial projects as possible to accelerate the learning curve of both operators and suppliers.

Aside from the favorable market conditions, other factors linked to risk perception also impact the decision-making regarding implementing HTHPs. Risk perception depends on the perspective of both customers (industrial companies) and HP manufacturers. From the customers' point of view, risks can be classified into three categories, namely:

1) a perception of the low reliability of HTHP technology,
2) uncertain suitability of HTHPs to adjustable operating conditions, and
3) compliance risks arising from future policy changes.

From the manufacturers' point of view, the risks and challenges can be classified into two categories (Adner and Kapoor 2010), namely:

1) challenges arising from limited availability of suitable components, which impacts the manufacturer's ability to improve their products and
2) challenges arising from the limited availability of products/services necessary to install and operate HTHPs (e.g., installation and design specification) or quality issues or delays for these products/services.

The perceived low reliability of the HTHPs compared to conventional boilers stems from concerns about main product quality, the relatively higher equipment complexity, and the additional energy integration levels. Process-level integration requires a much clearer process understanding, although it can achieve better efficiency thanks to smaller temperature lifts and tailor-made specifications. On the other hand, some industries (e.g., the food industry) may apply more stringent regulations that prevent the employment of certain refrigerants in process-level HTHP integration. Other criteria to consider are the heating demand fluctuations and the required space since there is often limited or no space budget in the process area.

Meanwhile, utility-level integration is perceived as easier to implement and less risky. It may result in lower efficiency due to usually larger temperature lifts. The general perception is that integrating a HP system at the utility level could be more suitable for contracting, as the Energy Service Company (ESCO) does not need to intervene at the process level. From a confidentiality point of view, it may be preferable that the HP was owned and operated by the industrial company. Still, the higher upfront costs and the possibility of other investment opportunities may discourage an in-house installation of an HTHP system.

HTHPs are also perceived as more complex equipment due to a larger number of components, which is associated with a larger probability of component failure. In other words, as the failure of a single component may lead to a decrease in performance or to an imminent failure of the whole HTHP, this factor decreases the acceptance of the entire product. Other concerns argued by industrial firms can be related to the compliance of refrigerants with future environmental regulations, along with the acceptance or reluctance of utilizing potentially flammable, suffocating, or toxic refrigerants.

The performance of HPs in general (and HTHP, in particular) depends on several parameters that may not be easily designed, monitored, or controlled, such as the fluctuations of temperature levels and energy demands in real plant operation, not to mention the need for heat storage when renewable electricity is aimed to drive breakthrough technology. Suppose the feasibility studies, the design specifications, and the installation work of the HTHP are made based on a faulty assessment of these operating conditions. In that case, the technology provider risks becoming responsible for failure or low performance. In addition to being a liability issue, it represents a reputational risk for the technology provider.

Accordingly, to manage these risks, the manufacturing companies should be trained to perform both the engineering of the integration and the selection and design of the HTHP components based on proven HP technologies. For instance, mechanical vapor recompression (MVR) and other heat pumping systems are relatively mature and have been used in industry for decades in applications such as evaporation, distillation and drying (EECA 2019; Spilling 2024). It poses further pressure on manufacturers, as they will need to foresee changes in the operating conditions that could impair the equipment's performance or even render the HTHP unusable over a significant period of its lifetime.

By anticipating these potential shortcomings, elaborating and validating contractual specifications and developing better control strategies at the commissioning stages and later in the operation, HTHP suppliers can mitigate or prevent their own risk and the customer's risk. In the end, the deployment of the HTHP technology will get cheaper and more reliable the more it gets deployed, and it will get more deployed the more affordable and more reliable it gets, according to the historical observation of the S-curve.

5 Web-based Tool for HTHP Integration

5.1 Introduction

The mass and energy integration of the industrial processes is essential for promoting efficient use of natural resources and reduced environmental impact. By reusing waste heat, industries can minimize heat rejection into the environment and upgrade industrial residues, thereby increasing revenues and reducing overall energy input. In this regard, HTHP systems are important in capitalizing on waste heat.

However, considering the number of technological options, such as fired boilers, electrical heaters and waste heat recovery systems, a robust tool that can model, optimize, visualize and report the comparative performance of the alternative setups is needed to ensure that the best solutions are effectively implemented (Flórez-Orrego et al. 2022a).

Industries often need help with energy audits and integration analyses due to insufficient appropriate tools, leading to suboptimal decisions like oversized equipment or wrong integration approaches. This shortcoming is particularly common when integrating a HP, in which optimal energy integration depends on the correct localization across the process's pinch point temperature, as explained in PART A, Section 5 and PART B, Section 1 of this report.

Improving data management is another major concern, as industries generate vast amounts of data daily, making safe data handling and storage necessary in different data formats like .csv or .json files. Documentation also poses challenges since technical information and auditing reports are often dispersed across directories, while versioning of calculation memories and results documentation could be better managed.

The cost of a supporting tool is also a major concern among enterprises, which are often reluctant to invest in expensive vendor energy management software licenses with unmodifiable or inaccessible backend algorithms and featuring simplified interfaces restricted to pre-defined models. The proprietary nature of that software typically limits accessibility and user flexibility, hindering the communications among various software and libraries, either open source or commercial, for evaluating and optimizing the overall energy integration of the industrial processes.

To address these problems, EPFL has developed the ROSMOSE tool as a flexible, open-source tool for modeling, analyzing, and documenting the energy integration results of industrial energy systems (Figure 23). The web-based tool operates primarily as a frontend, reducing the need for programming skills and focusing on user-friendly reporting and graphical representation of results. It manages data input and passes optimization tasks to the OSMOSE backend; the operating principle is detailed in the next sections.

Compared to conventional reporting, where data is treated as characters and figures as plain images, the Quarto environment upon which ROSMOSE builds allows for the automatic generation of sensitivity analyses and graphical reports, including in the same document the data handling, the energy integration (pinch analyses), the plotting of integrated curves and the calculation of thermodynamic, economic, and environmental indicators. Many output formats are implemented, from portable document formats (PDF) to interactive hypertext markup language (HTML) files, which are well-suited for web-based reports that can be accessed through any web browser.

By automating these tasks, the open-source supporting tool provides access to the most updated technical information about the industrial process to the different actors involved, from suppliers to managers, as soon as the process data changes. This approach improves coordination and decision-making across industrial applications that operate within a wide range of process parameters and energy prices.

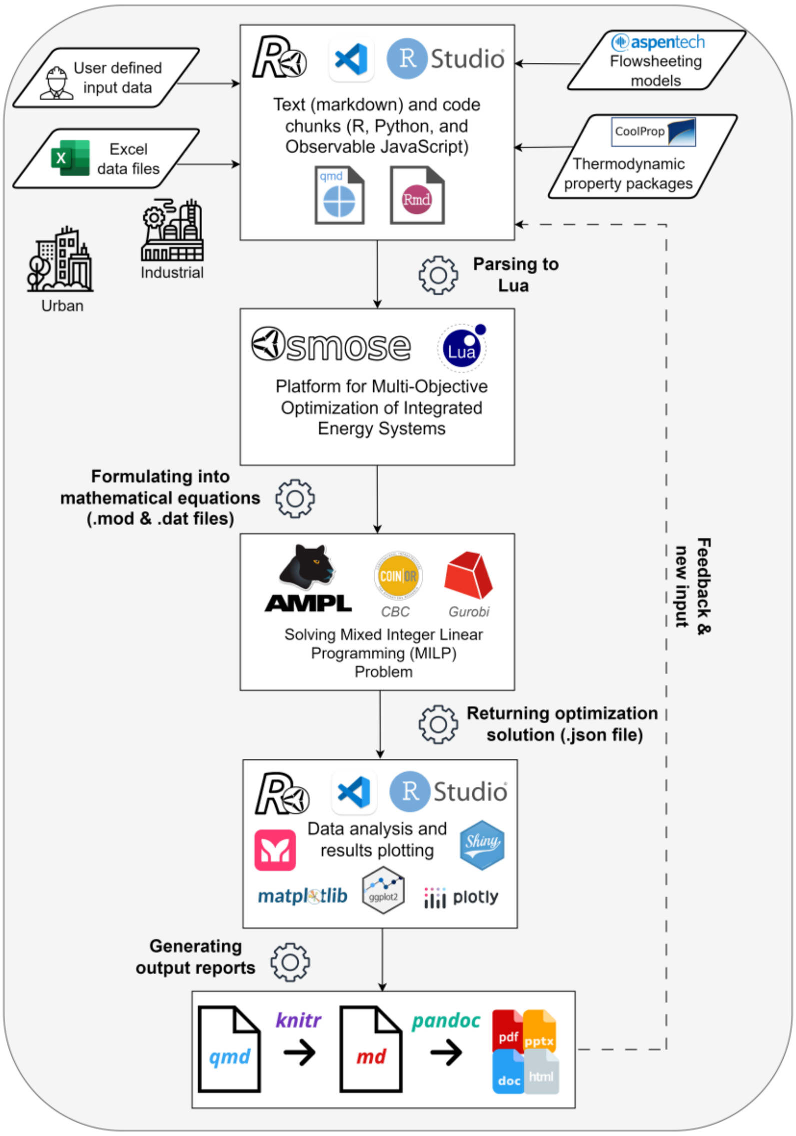


Figure 23: ROSMOSE web-based tool working principle (Flórez-Orrego et al. 2022b; Dardor et al. 2024).

In this way, pinch methodology experts can use ROSMOSE to screen the most adequate heat pumping temperature levels and choose the most suitable fluids to operate one or more HTHPs. The developed tool can assess whether sufficient waste heat is available to reduce the energy input or avoid incorrectly integrated utility systems, as demonstrated using two case studies. Trained users can update and interact with the digital twins of the industrial processes and the energy technologies (e.g., HP, boiler, etc.) to propose changes to the industrial process and its utility systems.

Software flexibility is granted to more experienced analysts and users of programming languages such as Python, JavaScript, or R. In contrast, compatibility with high-level data handling and modeling tools like Excel spreadsheets and Aspen flowsheeting suites is maintained. Both requests were raised during the HTHP workshop held in Bern. Using open-source libraries like Coolprop[13] becomes essential to

[13] www.coolprop.org

calculate the thermodynamic properties of substances involved in the energy conversion systems, such as the new working fluids in industrial HTHPs.

Finally, the SFOE discusses ROSMOSE installation, maintenance, and handling of confidential data, particularly when using web-based tools hosted on servers like those at EPFL. Different solutions are proposed, including reconfiguring EPFL servers to adopt a more scalable infrastructure and addressing robust and secure data handling while keeping costs manageable for users and maintainers.

Another solution proposes the containerization (e.g., using Docker) of the required libraries and optimization (OSMOSE) and visualization (Quarto) frameworks so that local execution can be accommodated for end-users who may not have access to external servers (e.g., firewalls) or want to avoid disclosing the confidential data. In any case, the development team at EPFL will ensure the maintenance by monitoring and managing the open-source community contributions, guaranteeing the tool's integrity and adaptability to changing industrial needs.

5.2 Data Input, Optimization Methods, and Reporting Procedure

The ROSMOSE tool relies on Pinch Analysis and uses a superstructure-based mixed integer linear programming (MILP) optimization problem. Applying these methods requires the input of mass flow rates, thermodynamic properties, and supply and target temperatures of all streams relevant to the heat integration approach. Other electricity flows and design parameters of the components constituting the energy integration superstructure are also necessary.

A superstructure of utility systems includes alternative heating (e.g., fired or electrical heaters, waste heat recovery systems such as HPs, etc.) and cooling systems (air or water cooling, refrigerator, etc.), as well as cogeneration systems (reciprocating or rotary engines), photovoltaic systems (PV panels), and other utility and decarbonization technologies. An extensive database and description of those models are given in (Florez Orrego et al. 2024).

In this report, the ROSMOSE tool focuses on determining the minimum energy requirement (MER) and maximizing the waste heat recovered in industrial processes using heat pumping technology, especially at high-temperature levels using specialized fluids.

To apply the PA, the ROSMOSE tool capitalizes on the OSMOSE engine, an optimization framework largely validated in various research, academic and industrial projects. The mathematical formulation is described in detail in Annex 6. The optimization framework works in the backend and processes the input data for calculating:

- Minimum energy requirements (MER) (heating and cooling),
- Pinch point temperature(s),
- Graphical representations of the hot and cold composite curves (CC),
- Graphical representations of the grand composite curve (GCC),
- Graphical representations of the Carnot composite curve (CCC),
- Levels of temperature for suitable condensers and evaporators, as well as fluids selection for HP systems,
- Compression power and coefficient of performance of HP systems,
- Detailed list of mass and energy flows of the analyzed process, including energy imports and exports, as well as fossil CO_2 emissions and avoidance, as well as
- Preliminary total costing (i.e., capital plus operational expenditures) given the fuel and other mass and energy prices of the overall process.

The HP superstructure considers a combination of evaporators, condensers, mixers, economizers, saturators, superheaters, subcoolers, and throttling valves, as well as the selection of optimal working fluids and operating conditions (e.g., temperatures, number of compression stages, discharge temperature, compressor type, etc.) to maximize the waste heat recovery (Figure 24). An extensive list of working fluids relevant to different applications and temperature levels has been pre-defined in the

HP superstructure, considering the industrial awareness of the global warming potential (GWP) and ozone depletion potential (ODP). Several refrigerants already phased out or will be phased out soon (e.g., R141b, R123, R12, R134a, R13) can still be simulated for comparative purposes.

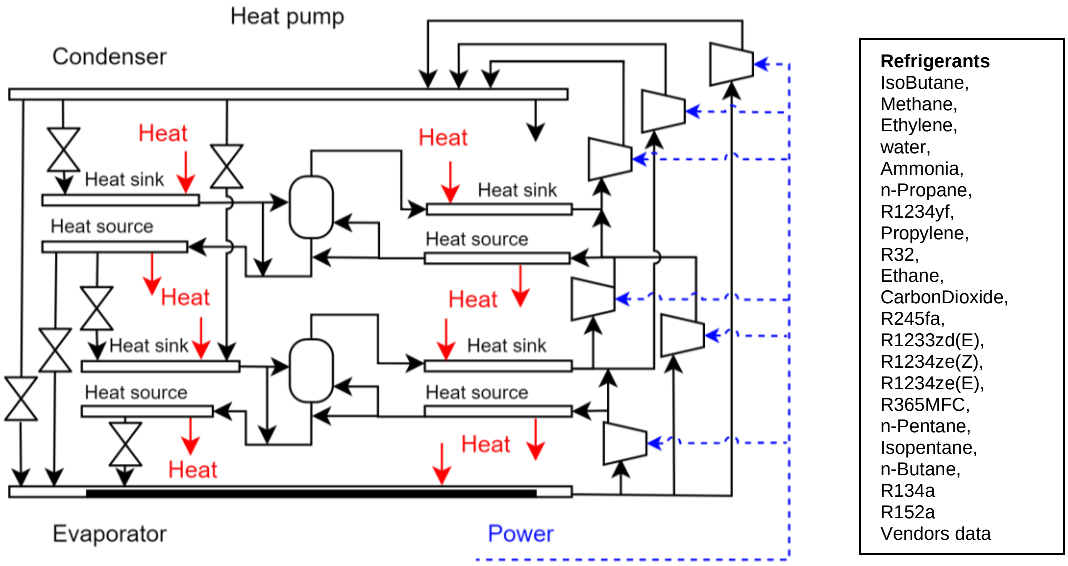


Figure 24: Superstructure of the HP utility systems considering several components and refrigerants (Wallerand et al. 2018).

Data input can be done via manual insertion of the hot and cold stream characteristics into the low-level interface of the Quarto environment, as well as imported from flowsheeting software like Aspen® or DWSIM. However, for the sake of simplicity, the ROSMOSE tool also uses a user-friendly template based on the well-known office application Microsoft Excel®. Data collected on-site in an acquisition OPC (Open Platform Communications) server, either in .json or .csv format, can be arranged into an Excel spreadsheet divided into the following tabs (See Annex 6 for further details):

5.2.1 LAYER tab

The layer concept in ROSMOSE can be interpreted as the pipe through which similar streams flow (electricity, natural gas, water, refrigerant, CO_2). It is characterized by a name, a set of more intuitive display names and a physical unit. The layer through which the waste heat is recovered and distributed throughout the industrial process is, by default, defined in ROSMOSE and does not need to be explicitly defined. Therefore, if electricity or mass streams are not envisaged, this tab could be left blank except for the headers. Layers are relevant for ensuring mass and energy balances and for costing the import of commodities, such as fuel, electricity, and feedstock, to the industrial processes.

5.2.2 UNITS tab

The building blocks of a ROSMOSE project are the energy technology (ET) models. Each ET can connect multiple units to other ETs and their associated units through the layers. For instance, a given ET (like the one defined by a complete Excel flowsheet) may represent a single water-cooling system with only one cooling tower unit up to a complex ET (a dairy plant) composed of several units (evaporation, pasteurization, cleaning in place, etc.). Moreover, each unit of a given ET can be classified as process or utility, the former implying that the energy demands of the industrial process are fixed during the optimization problem. In contrast, the size of the utility units needs to be optimized to meet the process energy requirements. This is the case with steam boilers, cooling systems, refrigeration units, CHPs, market grids and industrial HPs, whose performance has to be compared to other types of energy solutions (electrical or fired heaters) before it can be deemed as thermodynamically and economically attractive considering the systemic view of the process integration. The units can have multiple attributes that can be input in this tab, including specific operating (cost1 and cost2, in

EUR/kWh/y and EUR/kWh, respectively) and investment costs (cinv1 and cinv2, in EUR/kW/y and EUR/kW, respectively), and environmental impact factor (imp2 in kg_{CO2}/kWh), which help to define the objective functions. Moreover, in this tab, the bounds to the sizing factor (fmin/fmax) and activation factors (binary) used as some of the optimization variables can be defined. In this way, if direct process-to-process waste heat recovery suffices or a sensitivity analysis on the total costs concludes that implementing other solutions is better than a HP, the ROSMOSE tool can help elucidate which are the conditions for which HPs do and do not outperform their inherent counterparts, adding robustness and objectivity to the decision-making. As a final note, this tab cannot be left black, as any ET must have at least one utility or process unit.

5.2.3 MSTREAMS tab

The ***MSTREAMS*** tab allows for defining resource streams, namely material and electricity flows, that are involved in the optimization problem of energy integration. Those streams are linked to one of the previously defined layers and require an indication of their direction regarding the unit: *in* (for consumption in a HTHP unit) or *out* (for production in a CHP unit).

In the case of modeling HTHPs, this tab can be used to define the electricity input to the compressor. However, using the HP superstructure requires defining further design parameters, which will be discussed later. It is also worth mentioning that the operating costs that arise from electricity or natural gas consumption are calculated via the multiplication of these flows by the specific cost of the electricity or natural gas grid. This approach is also used for other energy resources (biogas, steam, biomass, etc.). If electricity or mass streams are not envisaged, this tab could be left blank except for the headers. If only electricity or mass streams are involved, as is the case of the market and grid units, the following tab (heat streams) can be left blank, except for the headers.

5.2.4 HSTREAMS tab

The ***HSTREAMS*** tab lists all the cold and hot heat streams. It requires information such as inlet (also known as source) and outlet (target) temperatures of those streams (°C), together with the inlet and outlet enthalpies (kJ/kg) or, alternatively, mass flow (kg/h) and heat capacities (kJ/kg K) or heating and cooling duties (kW) of the process streams.

Other heuristic parameters used in the pinch method, such as the minimum temperature approach contribution (K) and the heat transfer coefficient (kW/m^2 K), characterize each stream, process, and utility unit. This tab is the most relevant for preliminary heat integration analyses.

An advantage of using Excel as an input method is the possibility of performing calculations in other cells not intended to contain ROSMOSE fields and linking those results to the cells reserved for that purpose, automatically updating any changes performed in the streams' characteristics.

In the specific case of the HP superstructure, more details than those required to define the industrial process are necessary. To capture the versatility of HP systems and achieve an optimal selection of their operating parameters, other inputs must also be provided, including (see Annex 7 for a detailed template):

- List of fluid candidates
- Temperature levels associated either to condensers or evaporators (special cases of supercritical fluids can also be addressed) (in °C)
- Superheating temperature differences linked to those temperature levels (to avoid liquid phase in compressors) (in K)
- Subcooling temperature differences linked to the referred temperature levels (to extend the condenser heat recovery to the subcooling region) (in K)
- Minimum temperature difference contribution associated with each level (for reasonable heat exchange area)
- Layer of electricity (for compressor power supply)

- Maximum and minimum bound for the compressor capacity, as well as for evaporators and condensers
- Fixed (EUR/a) and variable investment cost (EUR/kW/a) of the compression, evaporation, and condensation units for costing, as previously explained in the UNITS tab definition
- Number of compressors that can be installed per fluid (1, 2, etc.) and per mode
- Isentropic efficiency of the compressor (e.g., 0.8)
- Minimum and maximum compressor size allowed (in kW)
- Minimum and maximum pressure of compressor (bar) and pressure ratio (-)
- Additional heat exchanger information, such as heuristic heat transfer coefficient (in kW/m^{2}K) and fitted costing parameters
- Minimum and maximum valve differential pressure (in bar(g)), as well as
- Other bounds for the load factors of flash drums, mixers, and superheaters (in any).

The step-by-step procedure follows the typical solution of an energy integration problem in the ROSMOSE tool, i.e.:

a) Process data is taken from real audits completed together with the commercial partners, and data is inputted into the ROSMOSE tool, which leverages the pre-defined template in Excel format. Those filled templates and the other archives generated during the problem definition, preparation, modeling, optimization and reporting tasks are available via the project's Gitlab repository, as discussed in Annex 4.
b) Utility models (cooling and heating technologies and market grids) are readily defined using the same approach, but utility units are specified instead of process units, as described in Annex 4.
c) The frontend file orchestrates the solution of the modeling and optimization problem in the OSMOSE engine. It simultaneously generates the energy integration results obtained during its execution in the Quarto environment. The .json output file is generated containing all the information needed to report the PA results (composite curves) and other performance indicators.
d) The generated .html report summarizes the problem definition, the assumptions, and inputs, and finally, the graphical representations of the PA results (tables, plots, etc.) in a structured and shareable form.
e) The location(s) of the process pinch point(s) and the graphical tools used to unveil the opportunities for integrating different energy technologies, such as HTHPs. The penalized heat exchangers (i.e., heating or cooling processes below or above the pinch point, respectively) are also spotlighted, and actions towards better integrating the energy systems can be proposed and adopted.
f) The integration of the HTHP to the industrial case studies is not completely automatic, as the information gained from a previous simulation effort can be used to improve the characteristics of the utility systems, more specifically, the HP system, which closely interacts not only with the process but also with the other utility systems (refrigeration system, environment, cooling tower, etc.).
g) For this reason, the design parameters of the HP superstructure are defined separately for both case studies and summarized in Annex 7.
h) It is very important to notice that, due to the flexibility of the ROSMOSE tool, simpler models of HTHPs can also be adopted, where only the condenser and evaporator temperature levels, together with a heuristic Lorenz efficiency, can be utilized to estimate the coefficient of performance of a HP system, before defining a full superstructure of the HP.
i) Vendors' data reported in open access, including source and target temperatures, temperature lift, COP and capacity, can also be used to create black box models and determine which commercial solutions fit the industrial process demands.

5.3 Application of ROSMOSE tool to two industrial case studies

5.3.1 Introduction to Two Case Studies

The application of the HP superstructure in the ROSMOSE tool is exemplified in two case studies, namely (Figure 25):

(1) a whey and ultrafiltration retentate drying unit (Tixotherm® process) and
(2) a cleaning-in-place (CIP) unit

The objective is to determine and quantify the potential for waste heat recovery and valorization using HTHPs to reduce or even eliminate the natural gas-fired boilers for heat supply, considered as the base case of the comparative analysis of fuel savings, emissions avoidance, incremental operating and capital expenditures, and overall process efficiency. Implementing the HTHP superstructure in ROSMOSE is exemplified by the relatively higher complexity and the better insights provided by this functionality.

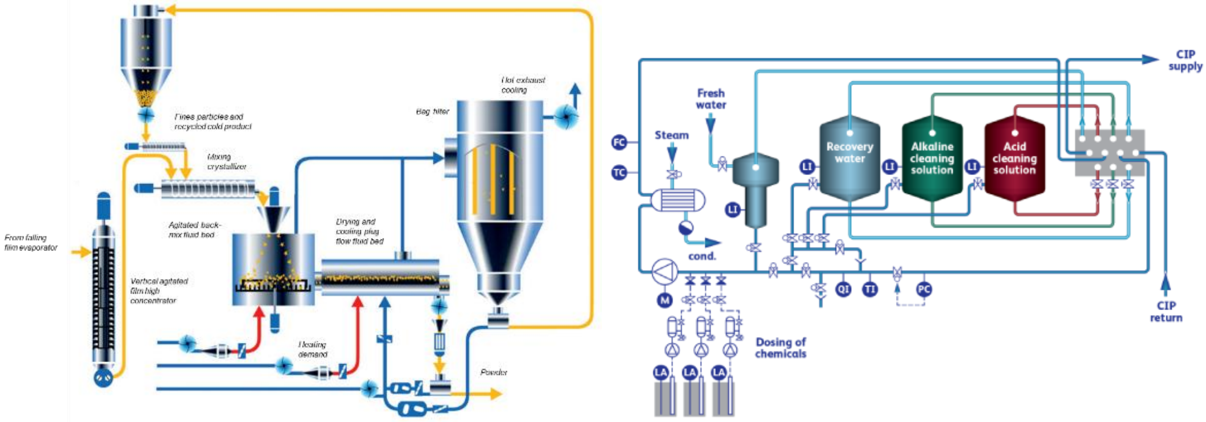


Figure 25: Process flow diagram of two typical case studies for HP systems application: Left: Whey and ultrafiltration retentate drying (Pisecky 2012), Right: Cleaning in-place (CIP) system (Solenis 2024).

The TIXOTHERM™ process is a technology used to valorize the whey and ultrafiltration retentate, featuring different advantages:

a) it does not require pre-crystallization tanks
b) the high-concentration step takes place at atmospheric pressure
c) the spray drying is not necessary
d) significant economic costs and energy savings (30%) can be made, rendering investment costs more attractive than the alternative processes (Písecký 2005).

CIP is fundamental for food and pharmaceutical industries to avoid risks to product quality. A CIP system pumps cleaning, rinsing, and sanitizing solutions to eliminate products from internal surfaces vulnerable to spoilage and bacteria growth. Its advantages include (Solenis 2024):

a) automated cleaning to reduce the chances of human error
b) reduced contamination risks with monitoring sensors
c) reduced employee chemical exposure to cleaning solutions
d) less production time lost to cleaning and
e) lower water and energy usage through repeatable cycle control.

These processes are good candidates for recovering waste heat from the process stream cooling using HP systems, as heat at relatively low temperatures is the largest energy consumption. As no major exo- or endothermic reactions occur in the process, all the heating utility provided must be removed, and it is typically rejected by the environment.

The relevant heat stream data have been gathered from the Tixotherm and CIP processes at the commercial partners' site, and the information has been input using the pre-defined Excel-based template, as shown in Annex 6.

In ROSMOSE, a fired heater, a water- or air-cooling unit, and a single-stage refrigeration system (if needed) are adopted as the simplest utility systems to deliver the heating requirement. They are loaded into the frontend file following the description in Annex 2, considering the total cost as an objective function (Annex 3) and allowing reporting of other environmental and thermodynamic scenarios as secondary targets. The advanced scenario adopts electrification for heat supply to the industrial processes using HTHPs.

For all case studies, the costs of electricity (0.2 EUR/kWh) and natural gas (0.07 EUR/kWh), as well as the CO_2 tax (100 EUR/tCO_2), are considered representative of the industrial case studies analyzed and are consistent with the historical data in Switzerland[14]. The yearly operating hours and the capital investment annualization factor are set as 4000 h/y and 0.08, respectively. The lower heating value of the natural gas is assumed to be 50 MJ/kg (methane CH_4), whereas the ratio of CO_2 emitted to CH_4 burned is assumed to be 2.75 kg_{CO2}/kg_{CH4}. The indirect CO_2 emission factors for the electricity and natural (allowing to do level playing fill comparisons including the scope 2 emissions of electrification solutions) are set as 62.63 g_{CO2}/kWh_{ee} and 0.0049 g_{CO2}/kJ_{ng}, respectively. The fired furnace investment costs are assumed as 200 EUR/kW_{th}, whereas an HP investment is set as 450 EUR/kW supply. Other equipment, such as water or air cooling systems, costs 50 EUR/kW_{ee} (Florez-Orrego et al. 2024).

While these input parameters can be used by default to determine the incremental capex, the energy savings, and the avoided environmental emissions when a HTHP is installed, they can be easily modified to conduct sensitivity analyses to the commodity prices and more stringent emission taxes. Specific HP installation costs can also be modified to simulate the effect of the mass deployment, economies of scale (learning curve) and subsidies. Some outputs of the energy integration analysis in ROSMOSE include but are not limited to the graphical representations derived from pinch analyses, natural gas and electricity consumption (kW_{avg} or kWh/y), and breakdown of electricity consumption by compression and pumping systems (kW). Total, operating and capital expenditures can also be reported, along with the indirect and direct emissions and the CO_2 avoided. Many other performance indicators and sustainability metrics can be derived from the mass and energy balances and other energy technology characteristics (e.g., sizing).

A preliminary examination of the composite and grand composite curves (Figure 26) suggests the availability of a large amount of waste heat (1000-1800 kW) below 45 °C and 25 °C for the Tixotherm and the CIP unit, respectively, which could be used to feed a HTHP that upgrade waste heat up to temperatures above 90-120 °C. The HP superstructure implemented in the ROSMOSE tool allows for proposing a set of temperature levels and refrigerants that are potentially favorable for HP setups. Afterward, ROSMOSE selects the best levels that reduce energy consumption and maximize waste heat recovery using a combination of multi-stage and cascaded HPs.

[14] https://www.energiedashboard.admin.ch/preise/strom

Figure 26: Composite (above) and gran composite curves (below) illustrate the estimation of the minimum energy requirement for Tixotherm (left) and CIP (right) processes.

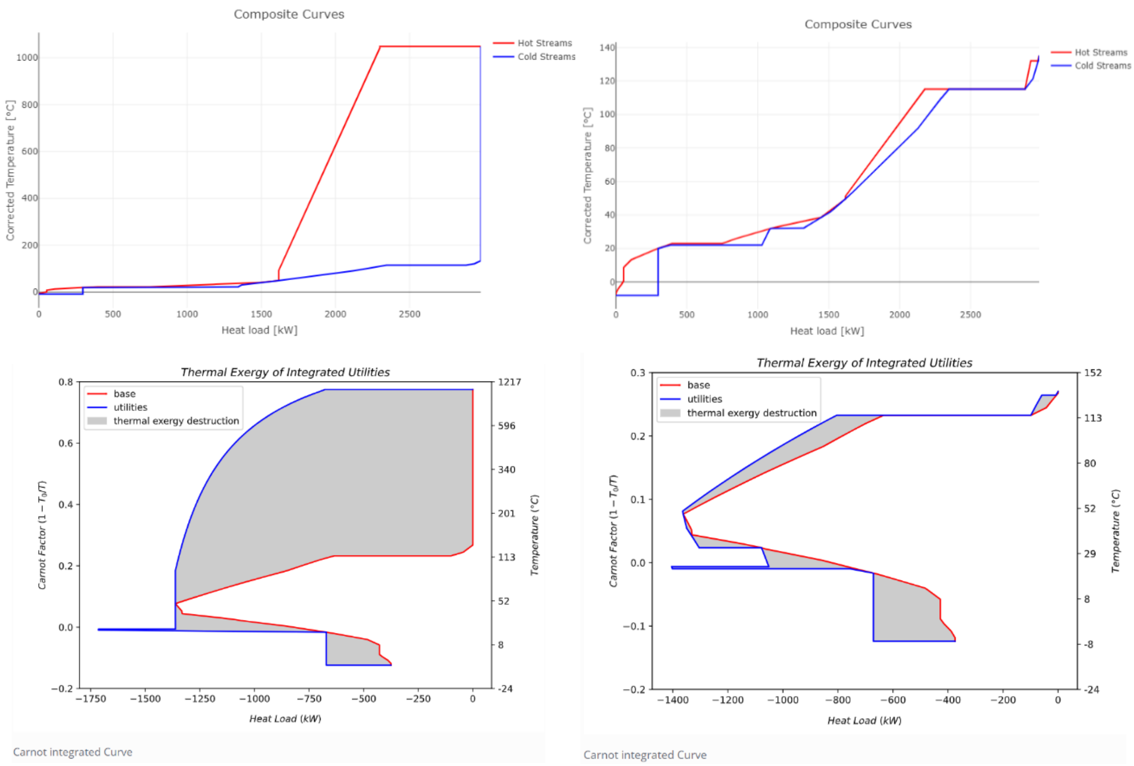
5.3.2 Tixotherm Case Study

Figure 27 presents the results of the energy integration analysis for the Tixotherm process when the heating and cooling demands are supplied either by conventional utilities (e.g., fired heater, water cooling and refrigeration units; left) or by a HP system with ancillary units (e.g., water cooling, auxiliary electrical heater; right). As seen, using a very hot utility (i.e., natural gas combustion) only to preheat process streams up to 140 °C entails an avoidable driving force that incurs higher inefficiencies. Moreover, the base case needs a large cooling duty to bring the products and by-products to the ambient temperature. Lack of waste heat recovery from the condenser of the refrigerator worsens the performance, as it increases electricity consumption and the heat rejection to the environment.

From an exergy point of view, a better solution is integrating two cascaded HP cycles. The first one works with n-butane and extracts heat from the process at the lowest temperature (-10 °C) to pump it up to 20 °C. From there, another fluid (R1234ze(Z)) absorbs heat from the condenser of the bottoming refrigeration cycle and from the industrial process itself (~20 – 30°C) to pump it up to 117.15 °C (see Figure 27, right).

Due to the process curve's shape, the liquid's subcooling, leaving the evaporator at the highest temperature level, can still supply a large share of the high-grade energy requirements of the Tixotherm process. According to the results of the ROSMOSE tool, the use of a small HP for supplying heat at the highest temperature level (140 °C) causes a large temperature lift that renders the HTHP installation less effective (COP < 1.5) than using an electrical heater to finalize the work. According to the reported results for the mass and electricity streams, the total cost of natural gas consumption (1,460 kW) when the conventional utilities are activated achieves 408,540 EUR/y. In contrast, the electricity consumed in the refrigeration systems (79 kW) contributes 62,800 EUR/y to the total operating cost. More interestingly, about 127,824 EUR/y (or 21% of the operating costs) are associated to the carbon tax, due to an estimated CO_2 emission of 1,278,240 kg/y.

On the other hand, when integrating a HTHP to the Tixotherm process, the electricity consumption (462 kW) entails an operating cost of 370,250 EUR/y and indirect emissions of only 115,960 kg/y. It means economic savings of up to 29.5% (considering total expenditure), thanks to energy savings of up to 70% and emissions reduction of more than 90.9% compared to the base case scenario. Naturally, a HP installation is more expensive, but all the benefits arising from its optimal integration offset the initial investment. Moreover, since the waste heat is recovered instead of rejected to the environment, the amount of cooling utility is also reduced, indicating the twofold advantage of a HP installation. Lastly, although the direct fossil emissions are avoided, the indirect emissions associated to the natural and the electricity supply chains become comparable (around 20-30 kg_{CO2}/h), which emphasizes the fact that future decarbonization scenarios based on electrification must encourage the energy transition of the power sector as well to reduce the carbon footprint of the industrial processes reliant on such electricity.



Heat pumping system details:

Total Evaporator Heat (kW): 296.7

Total Condensers Heat (kW): 353.27

Total Compressors Power (kW): 56.59

Calculating HP overall COP (kWth/kWee): 5.24

Activated Fluids: F19

Activated Compressors: Comp12

Heat pumping system details:

Total Evaporator Heat (kW): 1243.6

Total Condensers Heat (kW): 1619.63

Total Compressors Power (kW): 406.94

Calculating HP overall COP (kWth/kWee): 3.06

Activated Fluids: F19, F14

Activated Compressors: Comp12, Comp24, Comp23

Mass and electricity streams:

The following tables shows the mass and electricity streams, without and with details of the internal streams of the HP superstructure:

Without HP Internals | With HP internals

Connection	From	To	Value	Units
EnvCO2Em	furnace_Furnace	market_EnvCO2tax	288.9	kg/h
EnvCO2Em	market_ElecSell	market_EnvCO2tax	4.92	kg/h
EnvCO2Em	market_NatgasSell	market_EnvCO2tax	25.74	kg/h
NATGAS	market_NatgasSell	furnace_Furnace	1459.08	kW
Electricity	market_ElecSell	coolingtower_CoolTower	21.92	kW
Electricity	market_ElecSell	refrigerator_ss_F19_Comp12	56.59	kW
WATER	market_WaterSell	coolingtower_CoolTower	101.82	kg/h

Mass and electricity streams:

The following tables shows the mass and electricity streams, without and with details of the internal streams of the HP superstructure:

Without HP Internals | With HP internals

Connection	From	To	Value	Units
Electricity	market_ElecSell	refrigerator_ss_F19_Comp12	56.59	kW
Electricity	market_ElecSell	heatpump_ssTixo_F14_Comp24	88.25	kW
Electricity	market_ElecSell	heatpump_ssTixo_F14_Comp12	231.4	kW
Electricity	market_ElecSell	heatpump_ssTixo_F14_Comp23	30.7	kW
Electricity	market_ElecSell	coolingtower_CoolTower	1.79	kW
Electricity	market_ElecSell	HeaterEE_EE_heater	54.09	kW
EnvCO2Em	market_ElecSell	market_EnvCO2tax	28.99	kg/h
WATER	market_WaterSell	coolingtower_CoolTower	8.29	kg/h

Figure 27: Composite (top) and Integrated Carnot composite (bottom) curves of the Tixotherm process when the heating and cooling demands are supplied by conventional utilities (e.g., fired heater, water cooling and refrigeration units; left) or by a HP system with ancillary units (e.g., water cooling, electrical heater; right). Other HP indicators and mass and energy flows are also summarized. F14: R1234ze(Z), F19: n-butane.

Figure 28 shows a breakdown of the economic indicators estimated for the Tixotherm process when heating and cooling demands are supplied by conventional utilities (e.g., fired heater, water cooling and refrigeration; left) or a HP system and ancillary units (e.g., water cooling, electrical heater; right).

Economic indicators:

Optimized objective: obj_totalcost

Operational expenditure (CHF/y): 600189

Capital expenditure (CHF/y): 47999

Impact (kg_{CO2}/y): 1278211

Total Expenditure (CHF/y): **648187**

Total investment (non-annualized) (CHF): 471258

Economic indicators:

Optimized objective: obj_totalcost

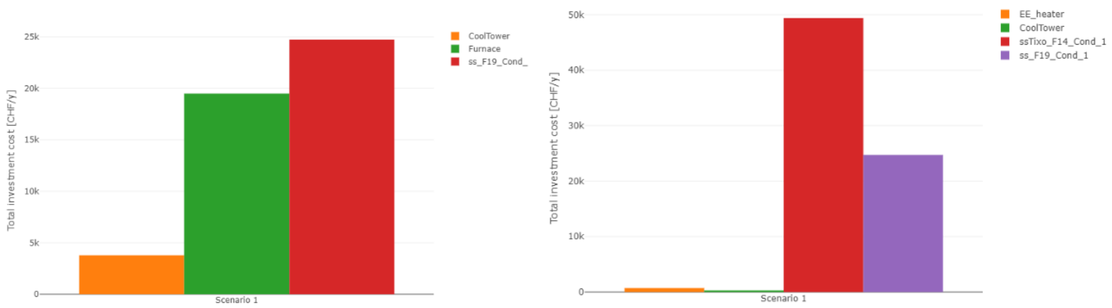
Operational expenditure (CHF/y): 381934

Capital expenditure (CHF/y): 75166

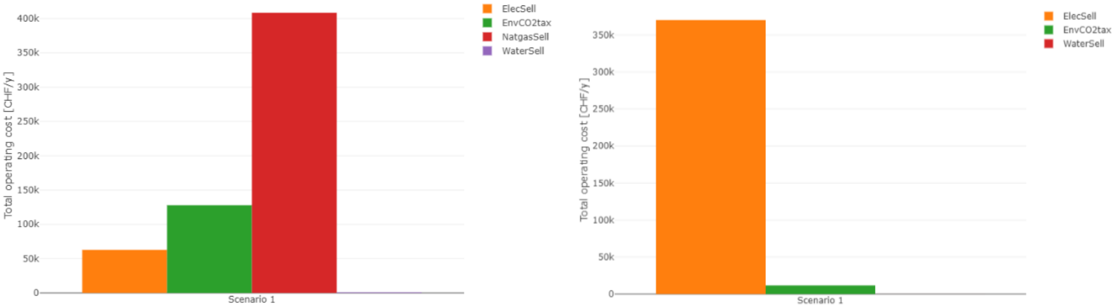
Impact (kg_{CO2}/y): 115946

Total Expenditure (CHF/y): **457099**

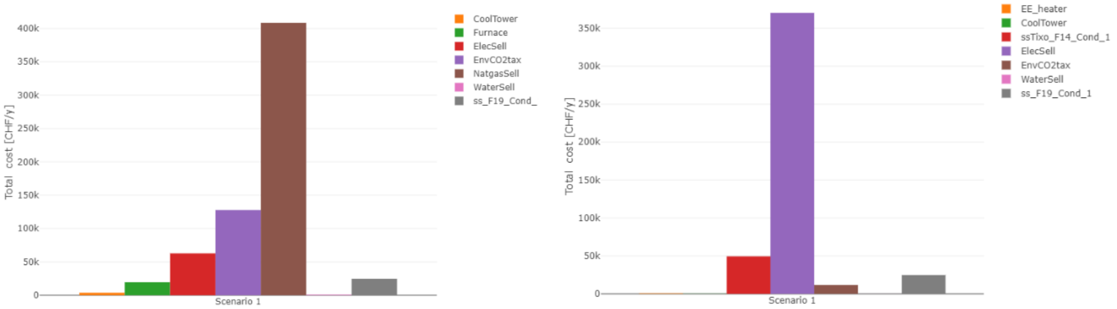
Total investment (non-annualized) (CHF): 737987



Breakdown of investment costs



Breakdown of operating costs



Breakdown of total costs

Figure 28: Techno-economic and environmental remarks of the Tixotherm process when heating and cooling demands are supplied by conventional utilities (e.g., fired heater, water cooling and refrigeration; left) or a HP system with ancillary units (e.g., water cooling, electrical heater; right).

5.3.3 Cleaning-in-place (CIP) case study

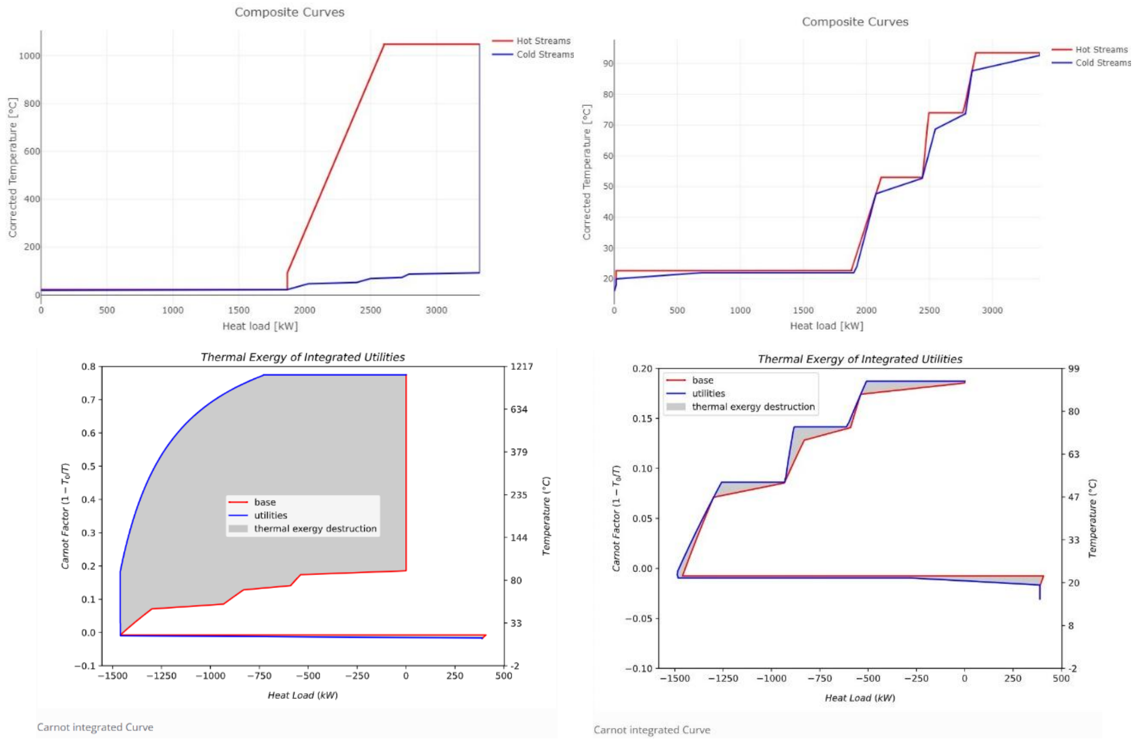
Figure 29 presents the results of the energy integration analysis for the CIP process when the heating and cooling demands are supplied by conventional utilities (e.g., fired heater, water cooling and refrigeration; left) or HP system with ancillary units (e.g., water cooling, electrical heater; right).

Like the Tixotherm case study, energy consumption can be reduced if the waste heat is upgraded using an HTHP setup. In this case, the HTHP unit features three compression stages, one evaporator (at 20 °C) and three condensers (at 95.5 °C, 76 °C and 55 °C, respectively) using R1234ze(Z) as refrigerant.

When comparing the composite (Figure 29, left) and Carnot integrated curves (Figure 29, right), it becomes evident that the waste heat available at the lowest temperature can be capitalized to supply heat to the process at the expense of higher initial investment.

However, analogous to the Tixotherm process, since the natural gas consumption can be fully phased out, the integration of a HTHP to the CIP process allows not only reducing the process irreversibilities but also almost halving the total expenditure from 634,513 to 370,250 EUR/y and reducing the indirect emissions by 95% (from 1,1359,936 kg/y to 72,680 kg/y).

Finally, energy savings of up to 81.9% compared to the base case scenario are expected when a HP unit is integrated. Again, the indirect CO_2 emissions linked to the electricity import should drop in a future scenario of decarbonization strategies based on electrification, considering that the supply chains of both energy commodities become comparable for the current electricity mix assumptions.



Heat pumping system details: (left)
Total Evaporator Heat (kW): 0
Total Condensers Heat (kW): 0
Total Compressors Power (kW): 0
Activated Fluids:
Activated Compressors:

Heat pumping system details: (right)
Total Evaporator Heat (kW): 1231.7
Total Condensers Heat (kW): 1327.83
Total Compressors Power (kW): 276.22
Calculating HP overall COP (kWth/kWee): 4.46
Activated Fluids: F1
Activated Compressors: Comp34, Comp24, Comp12

Mass and electricity streams:

The following tables shows the mass and electricity streams, without and with details of the internal streams of the HP superstructure:

Without HP Internals | With HP internals

Connection	From	To	Value	Units
EnvCO2Em	furnace_Furnace	market_EnvCO2tax	309.81	kg/h
EnvCO2Em	market_ElecSell	market_EnvCO2tax	2.43	kg/h
EnvCO2Em	market_NatgasSell	market_EnvCO2tax	27.6	kg/h
NATGAS	market_NatgasSell	furnace_Furnace	1564.7	kW
Electricity	market_ElecSell	coolingtower_CoolTower	38.83	kW
WATER	market_WaterSell	coolingtower_CoolTower	180.39	kg/h

Mass and electricity streams:

The following tables shows the mass and electricity streams, without and with details of the internal streams of the HP superstructure:

Without HP Internals | With HP internals

Connection	From	To	Value	Units
EnvCO2Em	market_ElecSell	market_EnvCO2tax	18.17	kg/h
Electricity	market_ElecSell	coolingtower_CoolTower	13.95	kW
Electricity	market_ElecSell	heatpump_ssCIP_F1_Comp34	34.25	kW
Electricity	market_ElecSell	heatpump_ssCIP_F1_Comp12	38.3	kW
Electricity	market_ElecSell	heatpump_ssCIP_F1_Comp24	203.67	kW
WATER	market_WaterSell	coolingtower_CoolTower	64.83	kg/h

Figure 29: Composite (top) and Integrated Carnot composite (bottom) curves of the CIP process when the heating and cooling demands are supplied by conventional utilities (e.g., fired heater, water cooling and refrigeration; left) or HP system and ancillary units (e.g., water cooling, electrical heater; right). Other HP indicators and mass/energy flows are also summarized. F1: R1234ze(Z).

Figure 30 shows a breakdown of the economic indicators estimated for the CIP process when heating and cooling demands are supplied by conventional utilities (e.g., fired heater, water cooling and refrigeration; left) or a HP system and ancillary units (e.g., water cooling, electrical heater; right).

Economic indicators:

Optimized objective: obj_totalcost

Operational expenditure (CHF/y): 606918

Capital expenditure (CHF/y): 27595

Impact (kg_{CO2}/y): 1359372

Total Expenditure (CHF/y): **634513**

Total investment (non-annualized) (CHF): 270930

Economic indicators:

Optimized objective: obj_totalcost

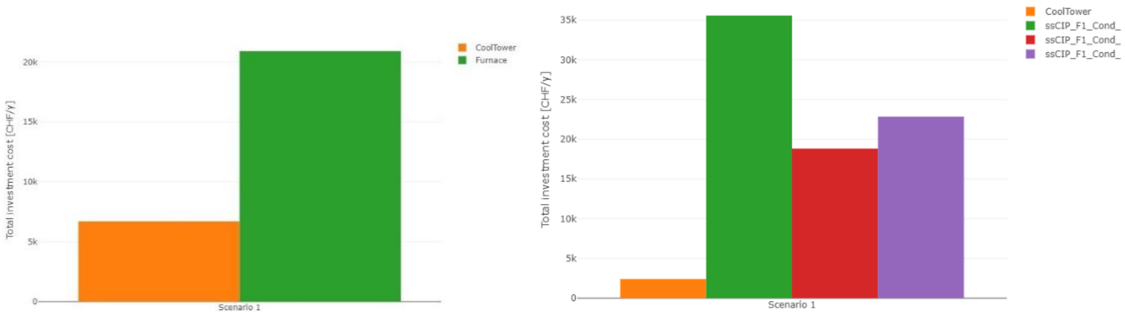
Operational expenditure (CHF/y): 240061

Capital expenditure (CHF/y): 79658

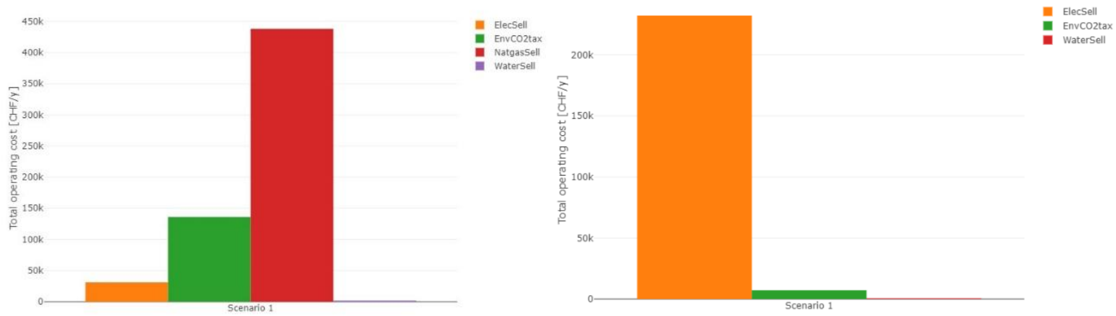
Impact (kg_{CO2}/y): 72696

Total Expenditure (CHF/y): **319719**

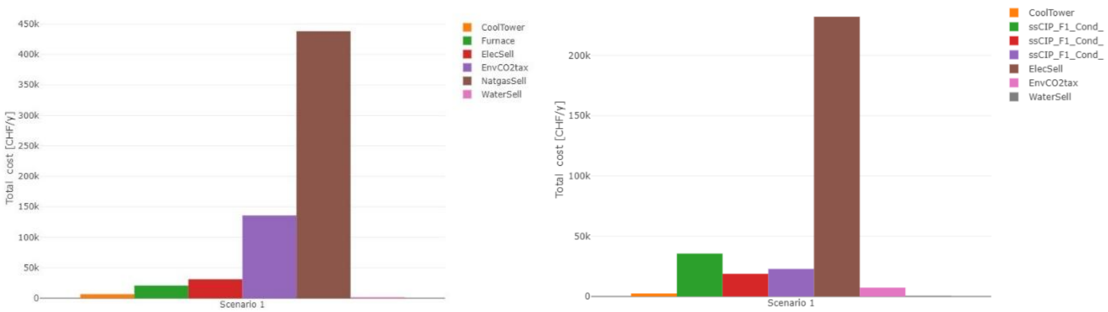
Total investment (non-annualized) (CHF): 782092



Breakdown of investment costs



Breakdown of operating costs



Breakdown of total costs

Figure 30: Techno-economic and environmental remarks of the CIP process when heating and cooling demands are supplied by conventional utilities (e.g., fired heater, water cooling and refrigeration; left) or a HP system with ancillary units (e.g., water cooling, electrical heater; right).

In conclusion, it becomes evident that process electrification and waste valorization are crucial for decarbonizing the heat supply to dairy plants, particularly in whey processing and cleaning-in-place units. Yet, the competition between different utility technologies, namely fired heaters, HPs, refrigerators, coolers, engines, and other utility systems for satisfying the process demands calls for a tool to systematically compare the performance of those alternative utility systems when they interact with each other (Flórez-Orrego et al. 2023a). Moreover, advanced computational and reporting tools have proved to be fundamental for modeling different energy integration scenarios, in which CO_2 taxations and waste heat valorization in food and beverage industries may favor HP deployment by offsetting initial investments (Flórez-Orrego et al. 2023b).
Logically, many challenges related to reliability, space budget and maintainability of the solutions, as well as risk perception within firms, should still be addressed. Nevertheless, preliminary analyses have shown significant potential for recovering waste heat while shifting towards economically favorable and environmentally friendly configurations involving HTHPs.

Appendix:

Appendix 3: Accessing the EPFL virtual machine and installing ROSMOSE

Appendix 4: Structure of directories and files of the ROSMOSE tool

Appendix 5: Access to OSMOSE framework (backend)

Appendix 6: Template for data input using Excel software

Appendix 7: Template for data input to the HTHP superstructure

6 Outlook

While various HTHP technology solutions are already commercially available and implemented, it's crucial to emphasize that significant efforts are still required to develop and demonstrate the diversity of solutions at scale. This is necessary to achieve the required implementation targets for the decarbonization of industries.

6.1 Evolution of the HTHP Market

Figure 31 shows the recent **evolution of the HTHP market**. There are increasingly more HTHP products. In 2018, there were about 25 HTHPs that delivered a temperature of 90 °C and above, and in 2024, about 50 HTHP products can provide more than 100 °C. The number of suppliers and products has almost doubled in six years. This also includes HTHPs that can generate and compress steam (MVR systems) and use water as a refrigerant. The developing HTHP market offers a wider range of products and is more competitive. Realized installations are leading the way.

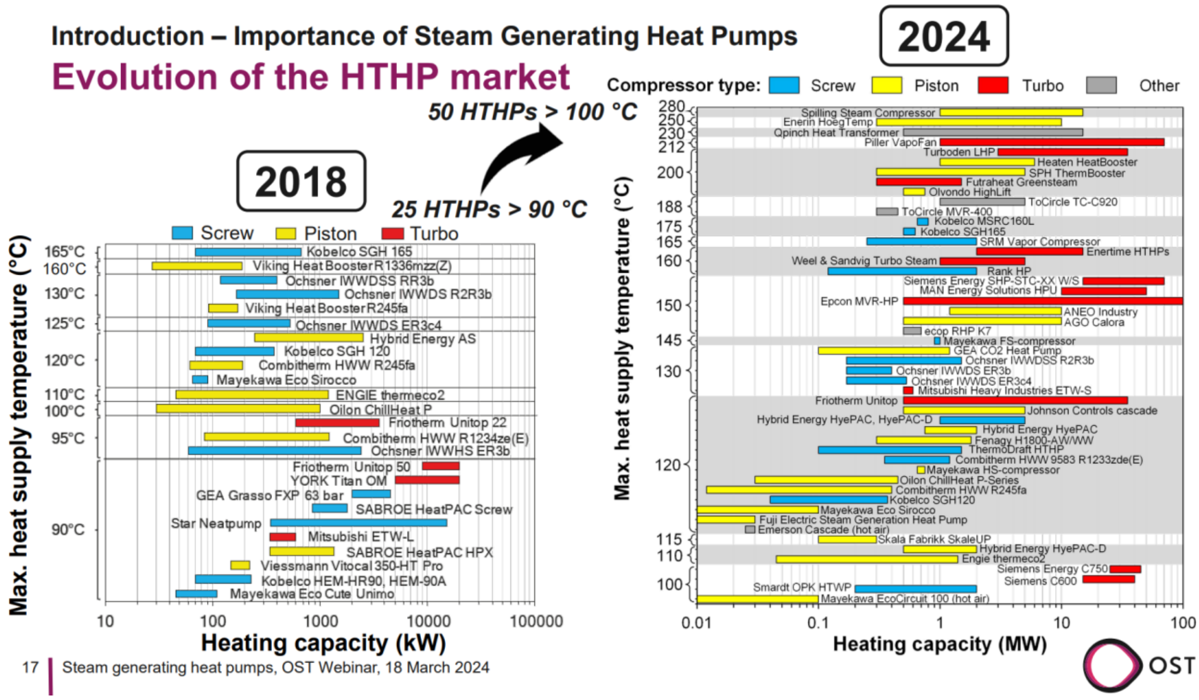


Figure 31: Evolution of the HTHP market regarding products from 2018 to 2024 (Arpagaus 2024).

HTHP technology offers a solution for the much-needed decarbonization in the industrial sector, up to about 200 °C. For the coming years, there will be a strong focus on bringing technologies into an application, demonstrating them in industrial applications and establishing supply chains, as well as increasing the variety of solutions and extending the range of applications. In parallel, industrial end-users will work on.

6.2 Future Development Perspective for HTHPs towards 2030

Figure 32 shows a **future development perspective for HTHPs towards 2030**. Various HTHP technologies are expected to become commercially available and implemented from 2024 to 2025 for supply at up to 120 °C, from 2025 to 2026 for temperatures up to 160 °C, and from 2026 to 2027 for even higher.

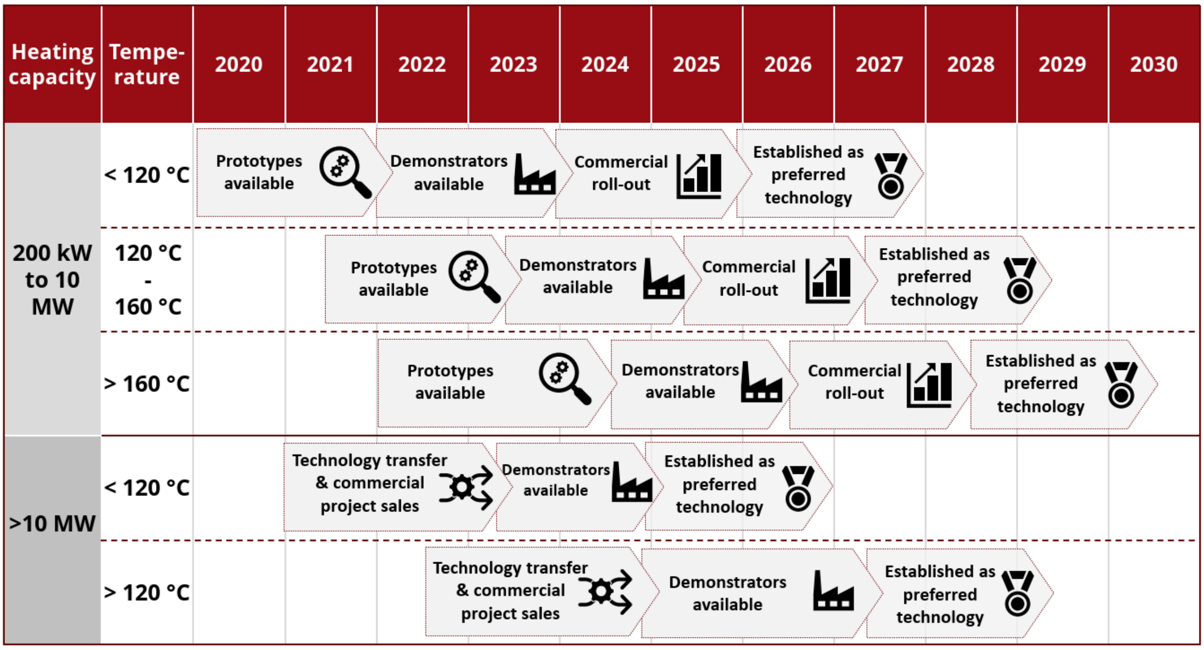


Figure 32: Development perspectives for HTHPs towards 2030. Source: IEA HPT Annex 58 Task 1 Report (IEA HPT 2023; Zühlsdorf 2024).

The development of HTHP technology towards market adoption also depends on the end users' acceptance and boundary conditions, which influence the business case (Figure 33). The availability and reliability of HTWP technology and its potential benefits are important. The end customer requires a rethink in designing and operating process heating from fossil fuels to electricity-based energy systems. Partnerships between HTHP technology providers, end users, R&D organizations, consultants, and policymakers are promising to reduce uncertainties and overcome barriers.

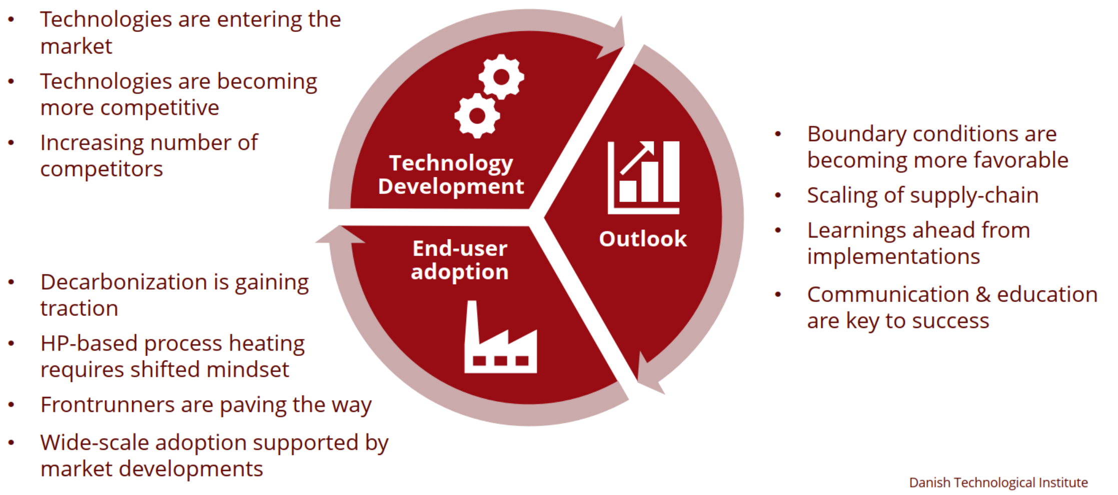


Figure 33: Aspects influencing the HTHP technology towards market deployment (IEA HPT 2023; Zühlsdorf 2024).

Education at all levels is needed to successfully transition to these new technologies: decision-makers, engineers, operators, etc. Given the number of competing technologies and configurations, operating conditions, uncertain utility and fuel prices, and the location of relevant parameters such as pinch points and process-to-process waste heat recovery potential, computational tools become crucial for helping in decision-making and reproducing hypothetical scenarios of heat pump energy integration.

External boundary conditions, such as fuel and greenhouse gas emissions costs, taxes, subsidies, and other market developments, impact end-users interests in tackling the conversion to decarbonized process heating and thereby implementing HTHPs. Favorable conditions are linked to fluctuating electricity-to-gas price ratio, carbon tax evolution, and efficient integration of HTHP. The scaling factor works in favor of large installations. Subsidies are currently offered to encourage the transition to these technologies.

A web-based tool can preliminarily address the selection of refrigerants, compressors, temperature, and pressure levels of a HTHP, bearing in mind its interaction with the process streams and other energy technologies. Such a tool can screen out less promising setups, allowing designers to focus on design that maximizes the return on investment and reduces industrial systems' energy consumption (and thus the associated CO_2 emissions).

Visualization tools are a more insightful way of comparing industrial case studies in which robustness to a wide operative range is desired. Thus, computational tools that can analyze and synthesize the PA results graphically and intuitively make the analysis more reproducible. Documentation is an important step in involving different actors in the discussions about design, installation, and investment, from operative technicians to stakeholders since all of them can access the most updated information about the industrial integration analysis.

7 Literature references

Adner R, Kapoor R (2010) Value creation in innovation ecosystems: how the structure of technological interdependence affects firm performance in new technology generations. Strateg Manag J 31:306–333. https://doi.org/10.1002/smj.821

Arpagaus C (2018) Hochtemperatur-Wärmepumpen: Marktübersicht, Stand der Technik und Anwendungspotenziale, 138 Seiten, ISBN 978-3-8007-4550-0 (Print), ISBN 978-3-8007-4551-7 (E-Book). VDE Verlag GmbH, Offenbach, Berlin

Arpagaus C (2024) Introduction to the Steam Generating Heat Pumps Webinar 2024. In: OST Webinar, 18 March 2024. https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Presentation_Cordin_Arpagaus_Introduction_Steam-Generating_Heat_Pumps_Webinar_2024_OST.pdf

Arpagaus C, Bertsch SS, Bless F, et al (2023a) Integration of High-Temperature Heat Pumps in Swiss Industrial Processes (HTHP-CH). In: 14th IEA Heat Pump Conf. 15-18 May 2023, Chicago, Illinois. https://etkhpcorderapi.extweb.sp.se/api/file/2573

Arpagaus C, Bless F, Bertsch S (2022a) Techno-economic analysis of steam generating heat pumps for integration into distillation processes. 15th IIR-Gustav Lorentzen Conf Nat Refrig June 13-15, Trondheim, Norw. https://doi.org/10.18462/iir.gl2022.0029

Arpagaus C, Bless F, Bertsch S (2022b) Techno-economic analysis of steam generating heat pumps for integration into distillation processes. In: 15th IIR-Gustav Lorentzen Conference on Natural Refrigerants, June 13-15, Trondheim, Norway

Arpagaus C, Bless F, Bertsch S, et al (2023b) Annex 58 HTHP-CH – Integration of HTHPs in Swiss Industrial Processes, Deliverable D1.2 (Q2/2023), Minutes of the workshop on High-Temperature Heat Pumps, 24 March 2023, DETEC Auditorium, Ittigen, Switzerland, SFOE contract number: SI/502336-01, 9 June 20. https://www.sweet-decarb.ch/events/event/high-temperature-heat-pump-event

Arpagaus C, Bless F, Bertsch SS (2024a) Übersicht zu Industrie- und Großwärmepumpen. In: 30. Tagung des BFE-Forschungsprogramms «Wärmepumpen und Kältetechnik» 26. Juni 2024, Eventfabrik Bern. https://www.fws.ch/fachpublikationen

Arpagaus C, Bless F, Bertsch SS (2022c) Techno-Economic Analysis of Steam-Generating Heat Pumps in Distillation Processes. In: 3rd HTHP Symposium, 29-30 March, 2022, Copenhagen, Denmark

Arpagaus C, Bless F, Bertsch SS, et al (2022d) HTHP-CH Integration of High-Temperature Heat Pumps in Swiss Industrial Processes. 28 Tagung des BFE-Forschungsprogramms «Wärmepumpen und Kältetechnik» 22 Juni 2022, BFH Burgd 1–9

Arpagaus C, Bless F, Paranjape S, Bertsch SS (2023c) Integration of High-Temperature Heat Pumps in Swiss Food Processes. In: ICR2023, 26th International Congress of Refrigeration, August 21-25, 2023, Paris, France. pp 1–12

Arpagaus C, Bless F, Uhlmann M, et al (2018) High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy 152:985–1010. https://doi.org/10.1016/j.energy.2018.03.166

Arpagaus C, Brendel L, Paranjape S, et al (2022e) High-Temperature Heat Pumps for Industrial Applications - New Developments and Products for Supply Temperatures above 100 °C. In: China Heat Pump Conf. (CHPC2022), Hangzhou, Zhejiang Prov. China, Oct. 24-27, 2022. https://www.youtube.com/watch?v=HvCEWrG4uR0

Arpagaus C, Paranjape S, Bless F, et al (2024b) Integration of a steam-generating HTHP in a Swiss meat factory, Poster presenation. In: High-Temperature Heat Pump Symposium, 23-24 January

2024, Copenhagen, Denmark

Arpagaus C, Paranjape S, Nertinger S, et al (2024c) Business Models for High-Temperature Heat Pumps. In: High-Temperature Heat Pump Symposium, 23-24 January 2024, Copenhagen, Denmark. pp 1–5

Arpagaus C, Sidharth P, Stefan N, et al (2023d) Review of Business Models for Industrial Heat Pumps. In: 36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2023). ECOS 2023, Las Palmas De Gran Canaria, Spain, pp 749–760

BFE (2021) Energiestrategie 2050. https://www.bfe.admin.ch/bfe/de/home/politik/energiestrategie-2050.html

BFE (2022) Analyse des schweizerischen Energieverbrauchs 2000 - 2021 nach Verwendungszwecken, Oktober 2022. In: Im Auftrag des BFE, Bern. https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/energieverbrauch-nach-verwendungszweck.exturl.html

Bhandari SB (2009) Discounted Payback Period - Some Extensions. In: Proceedings of ASBBS Annual Conference, Las Vegas, February 2009. pp 1–10

Bless F (2023) Guidelines for integrating industrial heat pump, IntSGHP Project (Contract number SI/502292), October 2023. https://www.sweet-decarb.ch/fileadmin/downloads/Methods_Guidelines/Guideline_IntSGHP_draftversion.pdf

Brunner F, Krummenacher P (2017a) Einführung in die Prozessintegration mit der Pinch-Methode, Handbuch für die Analyse von kontinuierlichen Prozessen und Batch-Prozessen, Zweite Auflage. 1–175

Brunner F, Krummenacher P (2017b) Introduction à l ' intégration énergétique de procédés par l ' Analyse Pinch: Manuel pour l ' analyse de procédés continus et de procédés batch. https://www.pinch.ch/docs/PDFs-Research-Publications/Manuel_Pinch_OFEN_2017.pdf

Calame N, Rognon F, Sari O (2017) High Temperature Heat Pumps for Industrial Processes - State of the Art and Research Needs. In: 23. Tagung des Forschungsprogramms Wärmepumpen und Kälte des Bundesamts für Energie BFE, 14. Juni 2017, Burgdorf. pp 1–17

Cortvriendt L, Flórez-Orrego D, Bongartz D, Maréchal F (2024) Data-driven systematic methodology for the prediction of optimal heat pump integration levels and refrigerants in process integration. In: 38th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2024, 30 June - 5 July, 2024, Rhodes, Greece

DAIKIN (2024) Reasons that Daikin Addresses the Environmental Impact of Refrigerants. https://www.daikin.com/csr/information/influence/protocol

Dardor D, Flórez-Orrego D, Terrier C, et al (2024) ROSMOSE: A web-based decision support tool for the design and optimization of industrial and urban energy systems. Energy 304:132182. https://doi.org/10.1016/j.energy.2024.132182

Davis LW (2024) The Economic Determinants of Heat Pump Adoption. Environ Energy Policy Econ 5:162–199. https://doi.org/10.1086/727881

De Kleijn Energy Consultants & Engineers (2018) Feasibility Check. www.industrialheatpumps.nl/en/feasibility_check

EECA (2019) MVR (Mechanical Vapour Recompression) Systems for Evaporation, Distillation and Drying. https://genless.govt.nz/assets/Business-Resources/Mechanical-vapour-recompression-for-evaporation-distillation-drying.pdf

European Commission (2021) EU Reference Scenario 2020 Energy, Transport and GHG Emissions - Trends to 2050. https://op.europa.eu/s/shWr

Florez-Orrego D, Dardor D, Ellen Ribeiro Domingos M, et al (2024) A web-based decision support tool for the design and integration of industrial high-temperature heat pumps. In: WP-Tagung, Bern, June 26, 2024. p Poster

Flórez-Orrego D, Domingos MER, Maréchal F (2023a) Techno-economic and environmental analysis of high temperature heat pumps integration into industrial processes: the ammonia plant and pulp mill cases. Sustain Energy Technol Assessments 60:103560. https://doi.org/10.1016/j.seta.2023.103560

Flórez-Orrego D, Domingos MR, Maréchal F (2023b) Heat pumping and renewable energy integration for decarbonizing brewery industry and district heating. Comput Aided Chem Eng 52:3177–3182. https://doi.org/10.1016/B978-0-443-15274-0.50507-2

Flórez-Orrego D, Domingos Ribeiro MEG, Maréchal F (2022a) A systematic framework for the multi-time integration of industrial complexes and urban systems. In: 7th International Conference on Contemporary Problems of Thermal Engineering, CPOTE 2022, 20-23 September 2022, Warsaw, Poland. pp 1–23

Flórez-Orrego D, Pina EA, Ribeiro Domingos M, et al (2022b) High temperature heat pumps applications for industrial separation and drying processes. In: Proceedings of ECOS 2022 - The 35th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, July 4-7, 2022, Copenhagen, Denmark. pp 1001–1009

Florez Orrego DA, Dardor DZO, Ribeiro Domingos MEG, et al (2024) Continuous training program: process engineering for decarbonization of the Swiss industry. https://infoscience.epfl.ch/entities/publication/b2068b52-7f91-4b89-9f48-889f6f888698

FOEN (2022) CO2 levy. https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/reduction-measures/co2-levy.html

FWS (2023) Statistik 2023, Fachvereinigung Wärmepumpen Schweiz. https://www.fws.ch/statistiken

IEA (2022) The Future of Heat Pumps. In: Futur. Heat Pumps. https://www.oecd-ilibrary.org/energy/the-future-of-heat-pumps_2bd71107-en

IEA (2014) Annex 35: Application of Industrial Heat Pumps, Final Report, Part 1, Report No. HPP-AN35-1. https://etkhpcorderapi.extweb.sp.se/api/file/543

IEA HPT (2022) IEA HPT Annex 58 about HTHPs (Website), Task 1: Technologies - State of the art and ongoing developments for systems and components. https://heatpumpingtechnologies.org/annex58/task1/

IEA HPT (2023) Annex 58 High-Temperature heat Pumps, Task 1 - Technologies, Final Report, August 2023, Report no. HPT-AN58-2. https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2023/09/annex-58-task-1-technologies-task-report.pdf

IEA HPT (2024a) Annex 58 High-Temperature heat Pumps, Task 2 - Integration Concepts, Task Report, April 2024, Report no. HPT-AN58-3. https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2024/04/annex-58-task-2-integration-concepts-report.pdf

IEA HPT (2024b) Final Webinar: Outcomes on HPT TCP Annex 58 “High Temperature Heat Pumps”, 18.4.2024. https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2024/04/finalwebinarannex58-1.pdf

IEA HPT (2024c) Annex 58 High-Temperature Heat Pumps Task 4 - Definition and Testing of Heat Pump Specifications, Task Report, March 2024, Report no. HPT-AN58-5. https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2024/04/annex-58-task-4-report-definition-and-testing-of-hp-1.pdf

IEA HPT (2024d) Annex 58 High-Temperature heat Pumps, Task 3 - Applications and Transition, Task Report, March 2024, Report no. HPT-AN58-4. https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2024/04/annex58task3report.pdf

Jakobs RM, Stadtländer C (2020) Final Report, IEA HPT Annex 48 (Industrial Heat Pumps, Second Phase), Heat PumpsTechnology Collaboration Programme on Heat Pumping Technologies (HPT TCP). https://heatpumpingtechnologies.org/publications/final-report-annex-48-industrial-heat-pumps-second-phase/

Kemp IC (2007) Pinch Analysis and Process Integration: A User Guide on Process Integration for the Efficient Use of Energy. Elsevier, Oxford, UK

Linnhoff B (1993) Pinch Analysis - A State-of-the-Art Overview. Trans IChemE 71:503–522

Linnhoff M (1998) Introduction to Pinch Technology. https://www.ou.edu/class/che-design/a-design/Introduction to Pinch Technology-LinhoffMarch.pdf

Mai TT, Jadun P, Logan JS, et al (2018) Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States. In: Natl. Renew. Energy Lab. https://www.nrel.gov/docs/fy18osti/71500.pdf

Myclimate (2024) Förderprogramm für nachhaltige Wärme in der Industrie. https://www.myclimate.org/de-ch/aktiv-werden/klimaschutzprojekte/detail-klimaschutzprojekte/schweiz-industriewaerme-7835/

Pisecky J (2012) Milk powder handbook, GEA Process Engineering A/S

Písecký J (2005) Spray drying in the cheese industry. Int Dairy J 15:531–536. https://doi.org/10.1016/j.idairyj.2004.11.010

Salman M, Flórez-Orrego D, Maréchal F, Grégoire L (2024) Superstructure-based Approach to Assess the Heat Pumping and Renewable Energy Integration Potential in the Sugar Industry. In: 38th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2024, 30 June - 5 July, 2024, Rhodes, Greece

SFOE (2023) Energy perspectives 2050+, Objectives for a climate-neutral Switzerland by 2050. https://www.bfe.admin.ch/bfe/en/home/policy/energy-perspectives-2050-plus.html/

Solenis (2024) Cleaning in place systems and equipment, Website

Spilling (2024) Steam compression, Website. https://www.spilling.de/applications-steam/steam-compression.html

VDI (2024) VDI 4646: Anwendung von Großwärmepumpen, Mögliches Erscheinungsdatum: 2024-02, Verein Deutscher Ingenieure. https://www.vdi.de/richtlinien/details/vdi-4646-anwendung-von-grosswaermepumpen

Wallerand AS, Kantor I, Maréchal F (2020) Integrated industrial heat pump systems: Background, software development & Swiss potentials, Final Report 30/07/2020. https://www.aramis.admin.ch/Dokument.aspx?DocumentID=66431

Wallerand AS, Kermani M, Kantor I, Maréchal F (2018) Optimal heat pump integration in industrial processes. Appl Energy 219:68–92. https://doi.org/10.1016/j.apenergy.2018.02.114

Wojtan L (2016) Industrielle Abwärmerückgewinnung auf hohem Temperaturniveau. In: News aus der Wärmepumpen-Forschung, 22. Juni 2016, HTI Burgdorf. pp 1–34

Zogg M (2008) History of Heat pumps: Swiss Contributions and International Milestones. https://www.zogg-engineering.ch/publi/HistoryHP.pdf

Zühlsdorf B (2024) High-Temperature Heat Pumps - How to bring them into application. In: 30. Tagung des BFE-Forschungsprogramms «Wärmepumpen und Kältetechnik» 26. Juni 2024, Eventfabrik Bern. https://www.fws.ch/fachpublikationen

Appendix

Appendix 1: Overview of HTHP products

Table 11: Overview of HTHP products, Status 2024, structured by TRL (Technology Readiness Level) (IEA HPT 2023), Friotherm (Wojtan 2016). Only products with TRL 9 are market ready.

Supplier	Compressor Type	Working Fluid	Capacity [MW]	$T_{max,supply}$ [°C]	TRL Indication	Specific Investment Costs [EUR/kW]
Enertime	1 or 2 stage centrifugal	R1336mzz(Z), R1224yd(Z), R1233zd(E)	2-10	160	4-8 (depending on concept)	300-400
Weel & Sandvig	Turbo	R718	1-5	160	4-9	150-250
Mayekawa Europe (FC comp.)	Screw	R601	1.0	145	5	720
SRM	Screw	R718	0.25-2.0	165	5	n/a
Fenagy	Reciprocating	R744	0.3-1.8	120	5-6 (concept study)	250-425
Emerson	Scroll and EVI scroll	R245fa, R410a, R718	0.03	120	6	n/a
Pars Makina	Rotary vane	R1233zd(E)	0.015-0.48	150	6	n/a
Futraheat	Centrifugal	R1233zd	0.3-1.5	150	6	250-400
Ecop	Centrifugal compression	Ecop fluid (He, Ar)	1	150	6-7	700
ToCircle	Rotary vane	R717+R718	1.0-5	188	6-7	250-430
Sustainable Process Heat	Piston	HFOs	0.3-5	165	6-8	150-1000
Mayekawa Europe (HS comp.)	Piston	R600	0.75	120	7	450
Enerin	Piston	R704	0.3-10	250	7	600-800
Skala Fabrikk	Piston (semihermetic)	R290+R600	0.3	115	7 (proto. demo)	500-700
Rank	Screw	R245fa, R1336mzz(Z), R1233zd(E)	0.12-2	160	7 (prototype demo.)	200-400
Aneo Industry	Centrifugal fan and piston	R717, R718	1.2-10	150	7-8	n/a
MAN Energy Solutions	Centrifugal turbo with integrated expander	R744	10-50	150	7-8	300-500
Johnson Controls	Reciprocating	R717+R600 (cascade)	0.5-5	120	7-8 (for HC top cycle)	n/a
Heaten	Piston	HFO and HC	1-8	200	7-9	280-450

GEA Refrigeration Netherlands	Semi-hermetic piston	R744	0.1-1.2	130	8	200-300
Mayekawa (EcoSirocco)	Reciprocating	R744	0.1	100	8-9	n/a
AGO	Piston, screw	R717/R718	0.7-10	160	8-9	800-1600
Piller	Turbo	R718	1.0-70	212	8-9	850
Fuji Electric	Reciprocating	R-245fa	0.03	120	9	n/a
Mayekawa (EcoCircuit)	Reciprocating	R1234ze(Z)	0.1	120	9	n/a
Kobelco (SGH120)	Two stage twin-screw	R245fa	0.37	120	9	n/a
Mitsubishi Heavy Ind.	Two-stage centrifugal	R134a	0.6	130	9	n/a
Kobelco (SGH165)	Twin-screw	R245fa+R134a (mixture), R718 for steam comp.	0.62	175	9	n/a
Kobelco (MSRC160)	Twin-screw	R718	0.8	175	9	n/a
COMBITHERM GmbH	Screw	HFOs	0.3-3.3	120	9	200-400
Hybrid Energy	Piston, screw	R717 and R718	0.5-5	120	9	200-600
Olvondo	Piston (double acting)	R704	5.0	200	9	1200
Spilling	Piston	R718	1.0-15	280	9	100-400
Epcon	High-pressure centrifugal fan; positive displacement blower	R718	0.5-100	150	9	200-400
Qpinch	Chemical adsorption heat transformer (no compressor)	Water, H3PO4 and derivatives	> 2.0	230	9	1000-2000
Turboden	Centrifugal (IGCC)	Hydrocarbons, R1233zd, R718	1.0-40	250	9 (MVR 5)	300-1000
Siemens Energy	Turbo (geared-type or single-shaft)	R1233zd(E), R1234ze(E)	8.0-70	160	9 (up to 90 °C), pilot plant at 120 °C being built	250-800
Friotherm	Turbo Unitop	R1234ze	0.5-35	90	9	900-1000

Appendix 2: Impact of integration level on KPIs

Table 12: Impact of the level of integration on KPIs (Key performance indicators).

KPI (Key Performance Indicator)	Level of integration: Process stream	Level of integration: Unit (process)	Level of integration: Utility (global or restricted perimeter)	Level of integration: Sector	Comments
Efficiency (small temperature lift <-> high COP)	**+ +** Most generally lowest temperature lift (case of mechanical vapour recompression)	In principle, unit level integration leads to higher efficiency, since it avoids/reduces the cascade of temperature drop and corresponding efficiency degradation of utility networks. However, the required temperature lift depends on the selected sink(s) and source(s) within the process. The GCC may reveal that the load of heat source(s) and/or the temperature level may be too low for an efficient operation. In this case, check the availability, in other nearby units, of appropriate heat source(s) at higher temperature (as long as these heat source(s) cannot be used more efficiently in their respective units, e.g. in case of large imbalance of GCC	**− −/+** Low to very low efficiency if heat from cooling water must be upgraded to low to middle pressure steam ! To improve the efficiency, check if a subset of large heat sources (cooling requirements) can be collected separately at a higher temperature to prevent heat degradation and efficiency loss when mixing in the flow of the cooling water network (determine the temperature at the process side of the corresponding cooler as an indicator of the maximum temperature). And/or check for a subset of substancial heat sinks with significantly lower temperature requirements than the present supply temperature of the utility (determine the temperature at the process side of the corresponding heater as an indicator of the minimum temperature). As a rule, don't let a single temperature-peaking process imposes the operation temperature of the utility network and of the heat pump (this can be identified on a residual GCC). As much as possible, supply local high temperature heating requirements with a dedicated HTHP (which evaporator can be supplied the main utility network operated at a lower temperature to match the majority of supplied processes).	Depending on temperature lift needed. The lift can be high in case of waste heat of an industrial site supplying a district heating newtork (integrate condenser preferably in the return line)	The focus should not be on the individual efficiency of a particular heat pump, but on the overall efficiency (of heat recovery and heat upgrading of all heat pumps). Don't forget to take into account the savings (electricity and OPEX) associated with the decrease of the heat load on active cooling systems). This is difficult task, as it is site specific (depends on the reference case, and on the optimisation strategy: 1) operation at reduced speed of cooling tower fans at same cooling water temperature setpoint (same compressor discharge pressure) , or 2) optimisation of setpoint temperature to operate at minimum total consumption (chiller compressor + cooling tower fans). Utility level integration: the feasibility of lowering the operating temperature/pressure of a utility network is a complex topic that requires many aspects/issues to be addressed.
Implementation	**− −** Often difficult to implement in or close to the process area (lack of space, requiresa a separate room with special safety measures depending on refrigerant used (fire hazard, toxicity, …), or at extra costs		**+ +** Usually much easier to implement in the utility area. Extra costs needed for piping if cold utility or selected heat sources not close to the HP and hot utility		Refer to Part B / Chapter 2
Degree of simultaneity	**+ +**		**−/+**		
Annual operation duration (equivalent number of hours of operation at rated load, or [kWh heat supplied / kWcapacity]	**−/+** Annual duration limited to the operation of the process unit. Practical recommendation: ask operators for the number of operating hours. Cross-check the given value with nominal capacity and annual production data. Large discrepancies are often noted and this has a direct impact on the amortization duration		**−/+** Although the total duration of operation may be up to over 8'000 h/year, the equivalent duration of operation at total rated load may be less than that of the HP integrated at process level. Use a classified load duration curve to design the HP systems with several units, and let peak load be produced by backup systems (and/or heat storage). As for improving efficiency, check if a subset of sources and/or sinks could be selected to achieve a higher equivalent duration without significant reduction of decarbonation.		Depends on the degree of simultaneity between sources and sinks. The respective time profiles of heat sources and heat sinks respectively can have a significant impact on the equivalent number of hours at rated capacity: the load can be either limited by the sources available at a given time or by the sinks.
Capacity / economy of scale	**− −** The heat load of sink(s) may be too limited to find a suitable HP on the market (the larger the cacpaity, the larger the choice of suppliers and technologies, and possibilities to split the total capacity into several modules)		**+ +/+** Low specific CAPEX [CHF/kW] for HP(s) thanks to large capacity, but the split of the the total heat load capacity into several units, control, thermal storage to ensure optimal and flexible operation can offset the advantage of low specific CAPEX		
Amortization of CAPEX expenditures	**−/+** Better flexibility (reduced sensitivity to changes into processes), longer lifetime		**+** Requires a sufficient equivalent duration of operation at rated load		Good amortization requires large equivalent duration of operation at rated load and low specific CAPEX (good economy of scale). Amortization duration must in any case be shorter than project lifetime
Flexibility, lifetime of HP system	**− −** Specifications of HP tailored to process characteristics. Limited without efficiency degradation. Process lifetime ahead has to be large to ensure amortization.		**+ +** Better flexibility (reduced sensitivity to changes into processes), longer lifetime	**+** Flexibilty possibility restricted (long-term contract)	

Appendix 3: Accessing the EPFL virtual machine and installing ROSMOSE

To access the virtual machines at EPFL and execute the ROSMOSE environment, installing and running the Cisco AnyConnect application on the computer is necessary. This application can be downloaded and installed from the following link:

https://www.epfl.ch/campus/services/en/it-services/network-services/remote-intranet-access/vpn-clients-available/

Select the adequate architecture and run the installer:

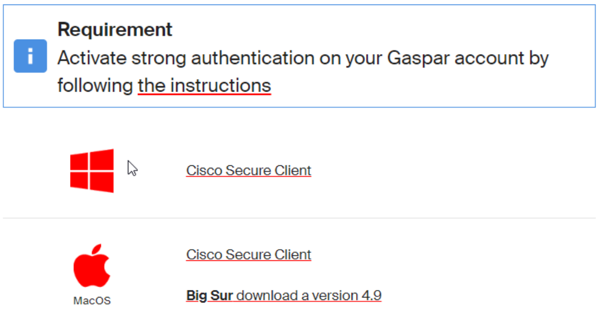


Figure 34: Downloading the installer of VPN connection software.

The following window will appear after installing and executing the application. Type 'vpn.epfl.ch', click connect and insert your credentials:

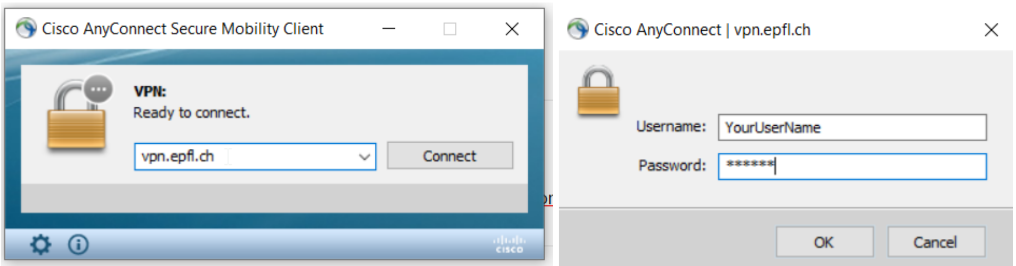


Figure 35: Connecting to Cisco AnyConnect VPN.

Next, a security code will be requested as part of the two-step authentication process recently introduced by EPFL to deal with the increasing internet attacks:

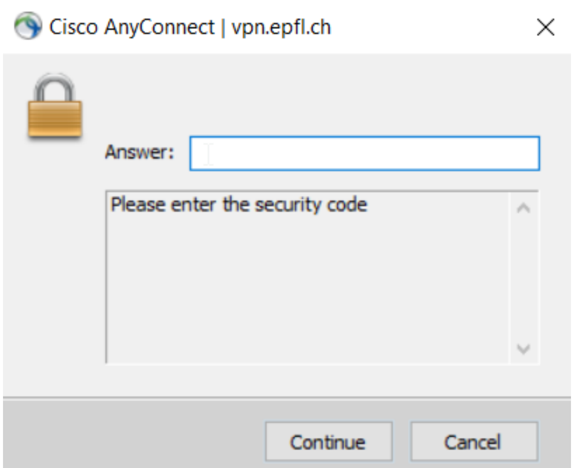


Figure 36: Double authentication process to access EPFL VPN.

To have access to this authentication code, it will be necessary to install Google Authenticator (recommended), as it is explained in this link:

https://www.epfl.ch/campus/services/en/it-services/authentication-gaspar/strong-authentication/activate-strong-authencation-on-smartphone/

- For Android: https://play.google.com/store/apps/details?id=com.google.android.apps.authenticator2&hl=fr_CH&gl=US
- For iPhone: https://apps.apple.com/us/app/google-authenticator/id388497605?l=fr
- To configure Google Authenticator, go to Gaspar platform, available from the link: https://gaspar.epfl.ch/

and click in 'login', enter your credentials and, if not activated, enable the Strong Authentication > Configure smartphone:

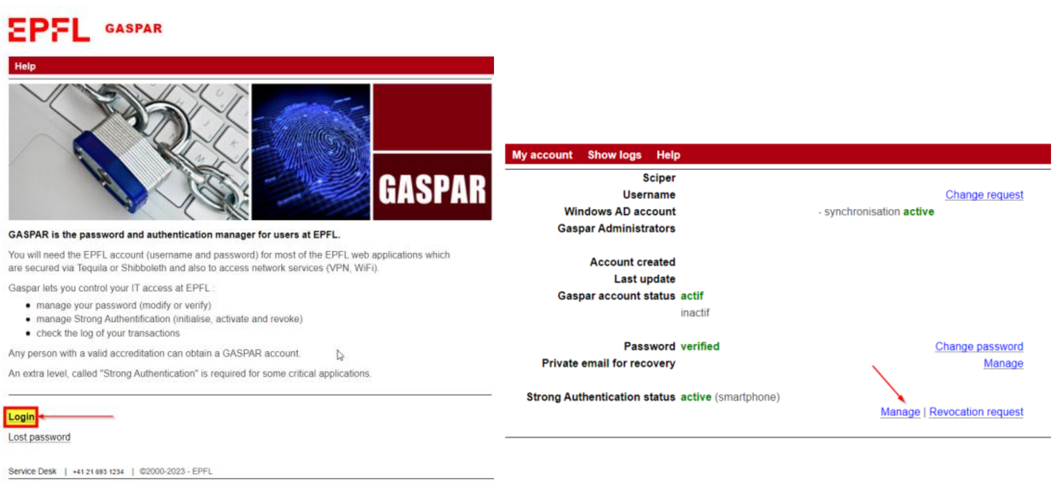


Figure 37: Gaspar platform at EPFL website.

On the mobile, open Google Authenticator and scan the QR code displayed on the Gaspar account page:

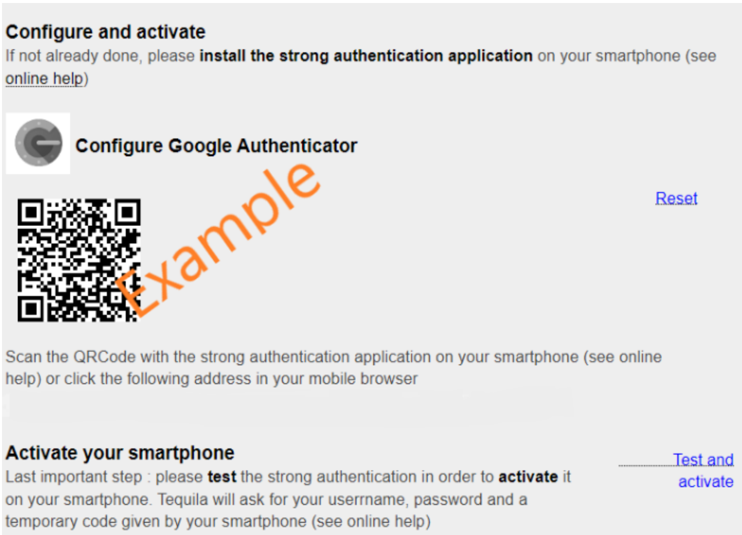


Figure 38: Configuring and activating the strong authentication in Gaspar website.

Next, click “Test and Activate”, click Login (link at the bottom of the page on the left), and once logged in, if the status is not “Active”, refresh the page.

A dynamically generated authentication code will be generated every few seconds in Google authenticator.

The following link, https://ipese-internal.epfl.ch/vm.html, describes how virtual machines can be accessed. Go to the “Start” menu in Windows and type Remote Desktop connection, which opens a window as shown below:

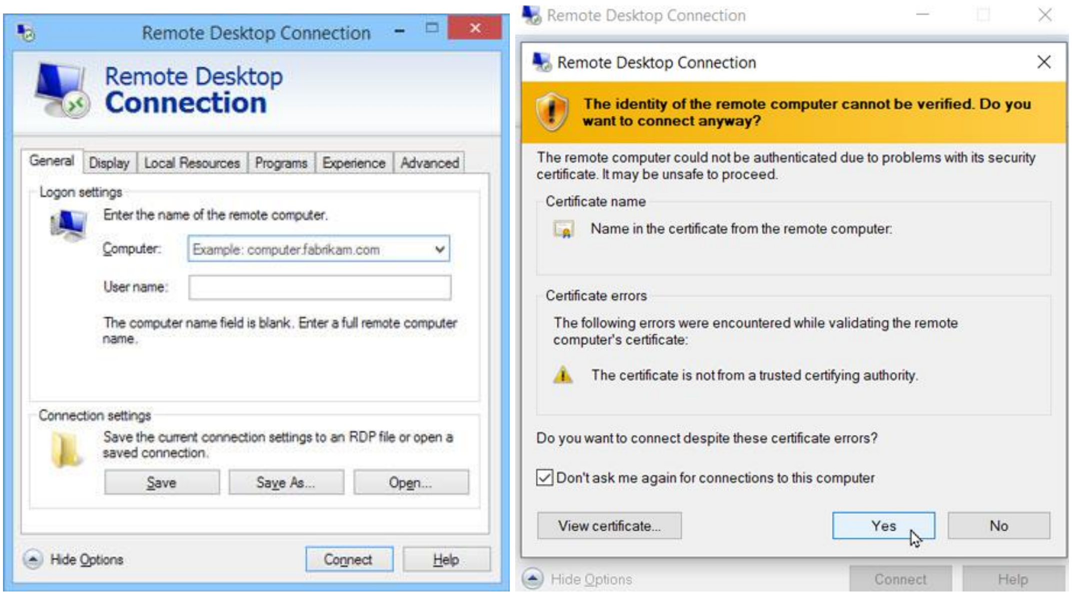


Figure 39: Remote desktop connection in Windows OS.

In the Computer field, type the name of your virtual machine: “ipesevm-YOURUSER.epfl.ch”, and in the User name field add: “intranet\YOURUSER”. Then, accept the certificate. Whenever a password is requested, use the provided password, which is generally a generic one created by EPFL. This password can be modified in the Gaspar platform, but it is not mandatory for this tutorial. If everything works fine, the remote virtual machine should pop up in a maximized window of the host computer. It can be closed from the floating menu that appears at the top of the screen when hovering with the mouse cursor.

Figure 40: Remote desktop in the EPFL virtual machine.

Finally, clone the following repository in Gitlab: https://gitlab.epfl.ch/ipese/mas/masbook/-/tree/integrationreportMASDFOdev?ref_type=heads. Note that sharing the source code of the web-based tool with industrial partners and interested collaborators is as simple as providing access to this repository. Gitlab is a software development and versioning control tool and website that not only allows the storage of the source code of the ROSMOSE tool but also provides the option for hosting static web pages (webbooks). Other authors can download the open-source code and suggest edits that can be later incorporated into the original development.

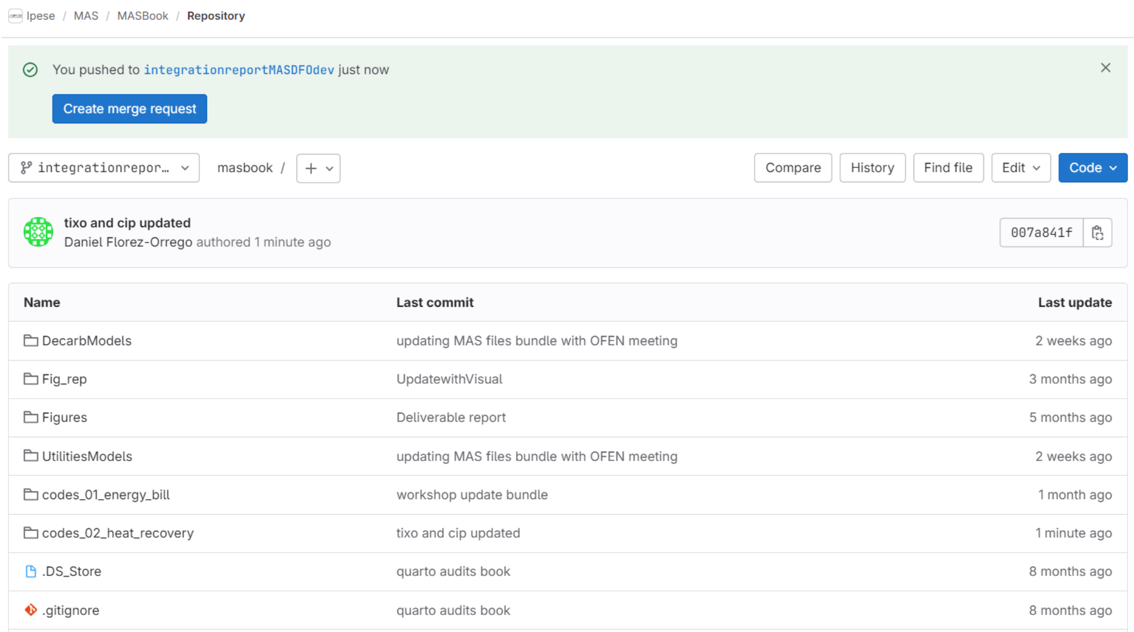


Figure 41: Repository of ROSMOSE tool used for the case studies analyzed in this report.

These steps must be followed to ensure that all the dependencies are installed in the VM and that the case studies can be rendered:

1. Open the terminal in VS code.
2. Install Quarto. More information about Quarto can be found here.
3. Verify that a connection to EPFL network, either directly or via the VPN, is active.
4. Verify the installation of R and Python in the computer, e.g. executing the command python --version
   5. Run the .bat script provided with the Gitlab repository that defines the CRAN repository and also installs some important packages:

For mac:

- Run ./installation/install_R_mac.sh in the terminal in order to *install R, set environment variables and install important packages.*

For windows:

- Verify the installation of R in C:\Program Files\R\<version installed>\bin.
- In the environment variables, open the variable PATH under System Variables and add the previously copied new path.
- Test R by running R --version in the command line
- Run installation/install_R_win.bat as administrator to *set environment variables and install important packages.*

6. Run in the terminal quarto render to build the book or quarto preview to open it directly on your browser.

To install ROSMOSE, execute the following chunk of R to source external R scripts:

```
```{r}
source("https://ipese-internal.epfl.ch/rscripts/rosmose-setup.R", local = knitr::knit_global())
```
```

Appendix 4: Structure of directories and files of the ROSMOSE tool

The frontend is the main script that contains all the information about which processes and utilities are to be included in the optimization problem, and it is the first file to run. Further details about the content and configuration of the frontend. The Rmd file will be discussed later on this section. When running the frontend, some folders are generated automatically, such the images and the result folders. Those folders contain the images for the report and the results in. json format that are generated automatically by ROSMOSE tool.

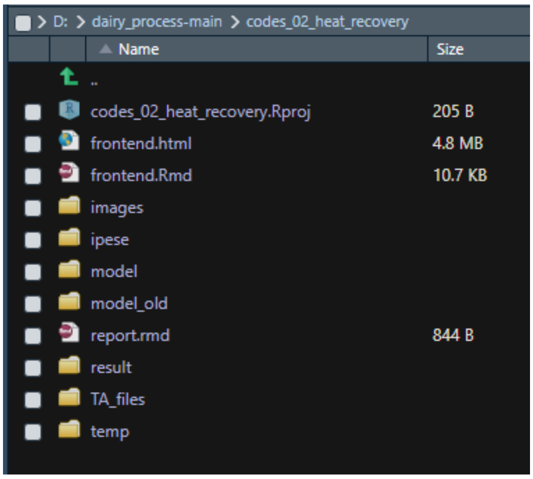


Figure 42: Folders are generated automatically, and other folders are manually modified (e.g., models) in ROSMOSE.

The building blocks of any ROSMOSE project are the energy technology (ET) models. Several input and output tags can define each ET, have multiple units, and be connected through layers to other ETs and their associated units. The layer concept in the ROSMOSE tool can be interpreted as the pipe through which similar streams flow, and it is characterized by a name, a quality and a physical unit. In addition, each unit of an ET can be classified as a process or utility. The main difference is that the size of the former is fixed in the optimization problem, as it represents the specified energy requirements that must be satisfied by the variable utility systems (Figure 43).

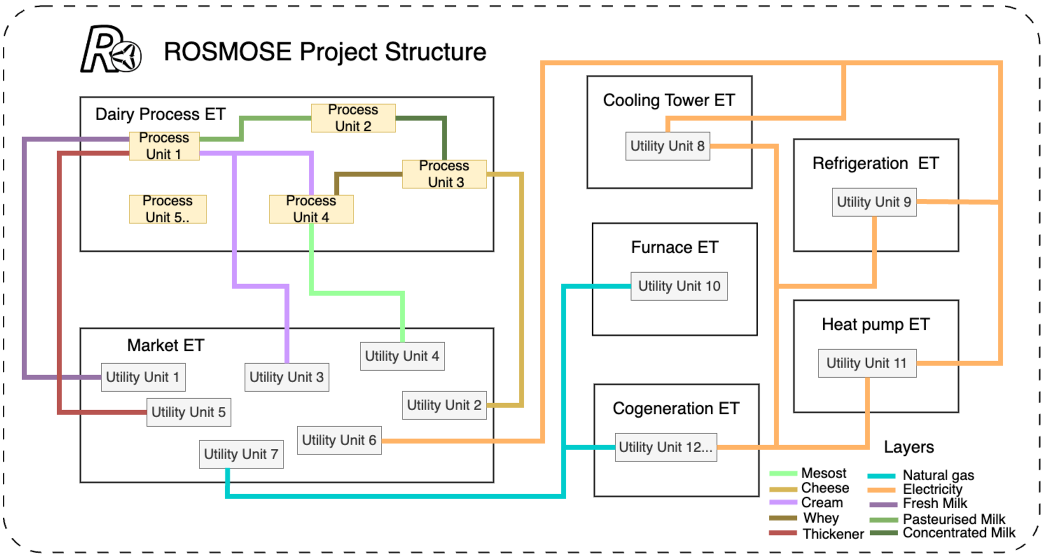


Figure 43: ROSMOSE project structure with sample ETs, units, and layers in a dairy process.

The process and utility models can be tailor-made, combined or adapted from existing ones to create more complex energy technologies (ETs). The `model` folder is virtually the only one that needs to be modified by the end-user. Figure 44 shows the content of the `model` folder, in which various case studies can be created to apply the pinch method. An energy integration superstructure typically contains the energy technologies and market grids necessary to supply the heating and cooling demands and other electricity and mass demands of the industrial processes.

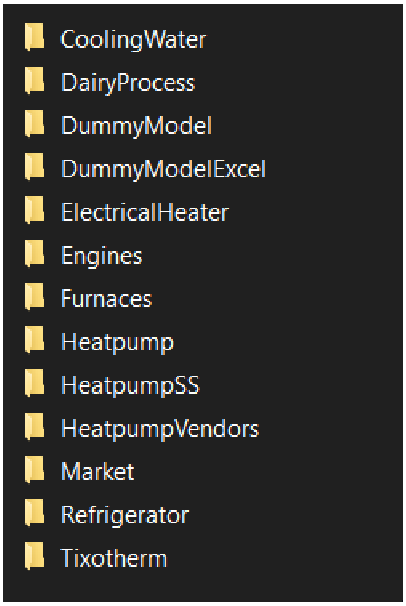
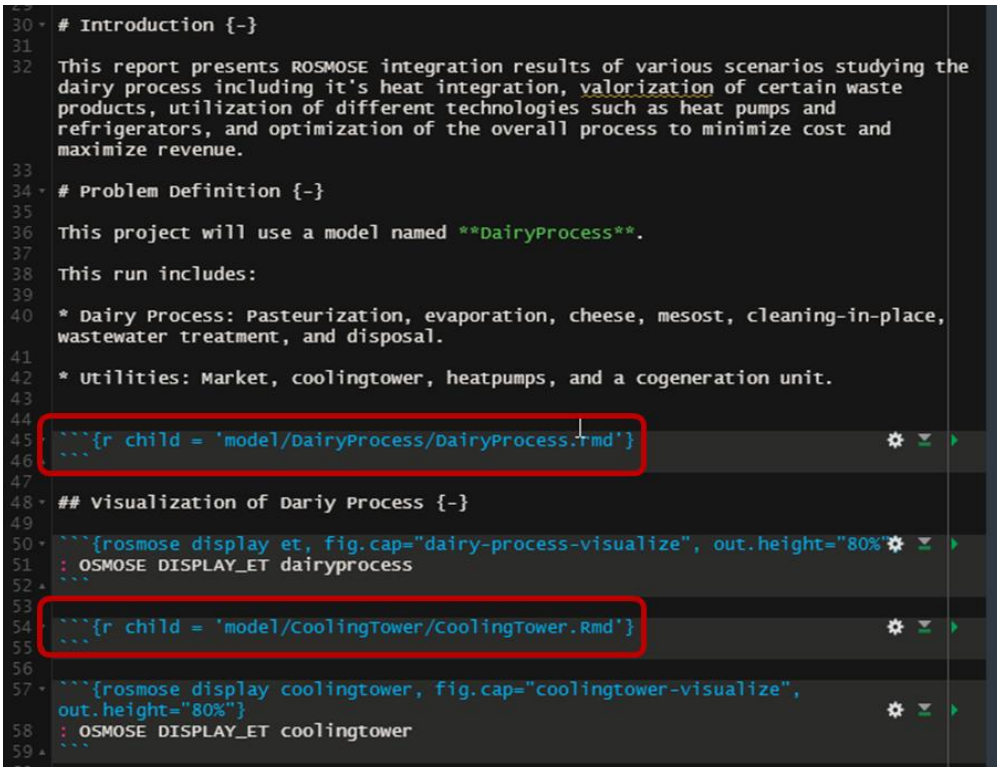


Figure 44: Content of the `model` folder in the ROSMOSE tool.

The frontend file must be executed to call the energy technologies available in the ‘model’ folder. The frontend file is a combination of text and code chunks, and it is the core file that contains all the elements that will be included in the report. The `frontend.Rmd` file can be regarded as a canvas, in which all the results retrieved by the execution of ROSMOSE tool can be summarized and documented, to be eventually rendered when building an .html book.

It is important to highlight the “`child`” functionality shown in the frontend, which is used to insert .Rmd code available in other .Rmd files in the specified position of the frontend. For instance, DairyProcess and CoolingTower.Rmd files, which contain the respective models of those energy systems, can be enabled from the frontend to be included in the optimization problem.

Moreover, any text (preceded or not by #) corresponds to plain text that will be rendered together with the code enclosed by the triple inverted quotation marks ```{r}```, thus producing a rich report with meaningful descriptions of the optimization results.



````
# Introduction {-}

This report presents ROSMOSE integration results of various scenarios studying the
dairy process including it's heat integration, valorization of certain waste
products, utilization of different technologies such as heat pumps and
refrigerators, and optimization of the overall process to minimize cost and
maximize revenue.

# Problem Definition {-}

This project will use a model named **DairyProcess**.

This run includes:

* Dairy Process: Pasteurization, evaporation, cheese, mesost, cleaning-in-place,
wastewater treatment, and disposal.

* Utilities: Market, coolingtower, heatpumps, and a cogeneration unit.

```{r child = 'model/DairyProcess/DairyProcess.rmd'}
```

## Visualization of Dariy Process {-}

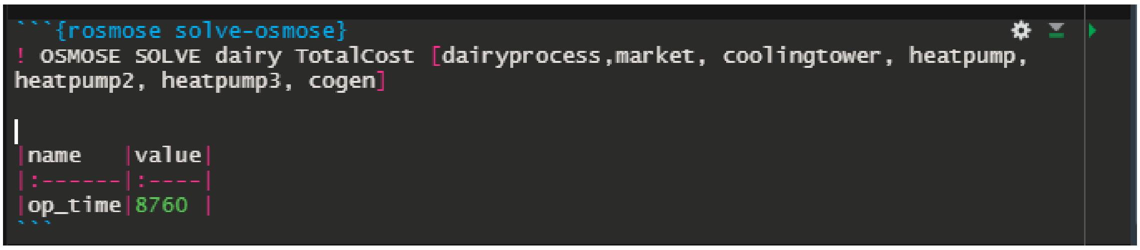
```{rosmose display et, fig.cap="dairy-process-visualize", out.height="80%"}
: OSMOSE DISPLAY_ET dairyprocess
```

```{r child = 'model/CoolingTower/CoolingTower.Rmd'}
```

```{rosmose display coolingtower, fig.cap="coolingtower-visualize",
out.height="80%"}
: OSMOSE DISPLAY_ET coolingtower
```
````

Figure 45: Structure of the frontend file: calling the models of the energy systems.

In the frontend, it can also be found the command `SOLVE-LOCAL` followed by a given objective function, such as `TotalCost or MER`, which calls OSMOSE in the backend. The project must have a codename (e.g. "dairy") provided after the command `SOLVE`, followed by the list of the models or ETs previously enabled in the frontend. The number of operating hours needs to be also defined.



````
```{rosmose solve-osmose}
! OSMOSE SOLVE dairy TotalCost [dairyprocess,market, coolingtower, heatpump,
heatpump2, heatpump3, cogen]

|name   |value|
|:------|:----|
|op_time|8760 |
```
````

Figure 46: Structure of the frontend file: solving the optimization process using the models.

In ROSMOSE, there is a functionality called "serialization" that helps experienced developers to debug more complex convergence issues. Serialization allows verifying that the OSMOSE engine is receiving correctly the information that the end-users are willing to transfer, and it is not mandatory to be enabled to use the ROSMOSE tool. An example of a serialization command is shown in Figure 47.

````
```{rosmose}
! OSMOSE SERIALIZE_PROJECT test-project TotalCost [dairyprocess,market,
coolingtower, heatpump, heatpump2, heatpump3, cogen]
#! OSMOSE SERIALIZE_PROJECT test-project TotalCost [et1, coolingtower, market,
furnace, refrigerator]
```

```{rosmose}
! OSMOSE SERIALIZE_ET [dairyprocess,market, coolingtower, heatpump, heatpump2,
heatpump3, cogen]
#! OSMOSE SERIALIZE_ET [et1, coolingtower, market, furnace, refrigerator]
```
````

Figure 47: Example of serialization command to generate OSMOSE lua files.

Next, the schema of the .Rmd files that represent the energy technologies is described in more detail. Firstly, each ET needs to have a name, which is defined at the beginning of the .Rmd file using a triple inverted quotation marks notation (```{ }```) to create an ROSMOSE chunk. Note also the "# Cooling Tower" text at the beginning, which only inserts a title header in the .Rmd file, but is not related to any ROSMOSE chunk of code.

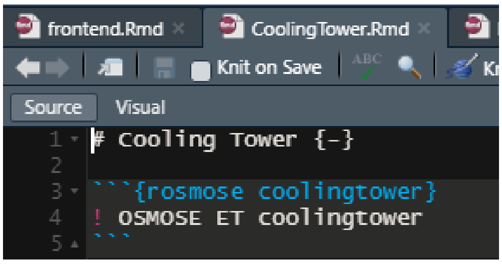


Figure 48: Naming of a `coolingtower` ET in a CoolingTower.Rmd file.

After creating the ET, a series of variables can be defined as tags in order to declare the user defined or the calculated parameters, representative of the operating conditions, design parameters, and other characteristic of the energy technologies. In ROSMOSE, a tag is an object containing:

- a name,
- a value,
- a physical unit, and
- a description.

````
```{rosmose}
Cool_Tin = 15 [C] #Cooling tower inlet temperature
Cool_Tout = 30 [C] #Cooling tower outlet temperature
Cool_Qmax = 1000 [kW] #Cooling tower reference heat load
Cool_Elec = 0.021 [kW/kW] #Cooling Tower electricity input kWel/kWth
dtmin_liq = 5 [C] #delta Tmin of the cooling water (w/ liquid streams)
deltaH = 62.8 [kJ/kg] #Enthalpy change for cooling water @1 bar between 15 to 30°C
Twetbulb = 12.17 [C]
n = 40.0 [yr] #lifetime of a cooling tower
i = 0.06 [-] #interest rate
CEPCI_2020 = 596.2 [-] # actual CEPCI
CEPCI_2008 = 575.4 [-] # CEPCI 2008
```

```{rosmose}
E_ref_CT = %Cool_Elec%*%Cool_Qmax% [kW] # Electricity consumption
deltaT_CT = %Cool_Tout%-%Cool_Tin% [C]
approach = %Cool_Tin%-%Twetbulb% [C]
water_flow = %Cool_Qmax%/%deltaH%*3600 [kg/h] #water flow rate
watermu_CT = 0.000851*%water_flow%*(%Cool_Tout%-%Cool_Tin%) [kg/h] #makeup water in
the CT system
Annuity = (%i%*(1+%i%)**%n%)/((1+%i%)**%n%-1) [-] #annualization factor
CTCost = 746.49/0.066*((%water_flow%/1000)**0.79)*(%deltaT_CT%**0.57)*(%approach%**-0.
9924)*(0.022*%Twetbulb%+0.39)**2.447 [Euro]
Cinv2_CT = %CTCost%*(%CEPCI_2020%/%CEPCI_2008%)*%Annuity% [Euro/y]
```
````

Defined tags, such as operating parameters, economic indicators, physical constraints, etc.

Calculated tags (note the %_% symbols for enclosing previously defined values)

Figure 49: User-defined or calculated parameters in ROSMOSE.

Each ET may enclose one or more units linked to each other and to other units of other ETs by mass and energy balances, using a concept previously defined as `layer`. In addition, each unit in an ET can be classified either as a `process` or as a `utility`. Process units are characterized by fixed operating data of industrial processes (e.g. flows, supply and target temperatures, composition, energy demands etc.). In contrast, utility units can be enabled or disabled, and sized to meet the energy demands of the process unit(s). To this end, each utility unit has bounds of minimum and maximum sizing factor, and have associated both variable and fixed investment and operating costs. All these objects, namely, layers, units, and unit parameters can be defined in the ROMOSE tool as shown in Figure 50.

````
```{rosmose}
: OSMOSE LAYERS coolingtower

| Layer      | Display name | shortname  | Unit  | Color  |
|:----------|:------------|:----------|:-----|:------|
|ELEC       |Electricity  |elec       |kW    |yellow |
|WATER      |Water        |water      |kg/h  |blue   |
```

**Cooling tower unit of the Cooling Tower ET**

```{rosmose}
: OSMOSE UNIT coolingtower

| unit name |type    ||
|:----------|:------|
| CoolTower |Utility|
```

**Parameters of the Cooling Tower unit**

```{rosmose CoolTower_params}
: OSMOSE UNIT_PARAM CoolTower

|cost1  |cost2  |cinv1  |cinv2       |imp1   |imp2   |fmin   |fmax   |
|:------|:------|:------|:----------|:------|:------|:------|:------|
|0      |0      |0      |%Cinv2_CT% |0      |0      |0      |100    |
```
````

Figure 50: Definition of layers, units, and unit parameters in ROMOSE.

Two types of streams may be assigned to any `process` or `utility` units, namely:

- *Resource streams*, which are linked to only one of the defined layers and require an indication of their direction about the unit, for instance, in (for consumption) or out (for production) (Figure 51)
- *Heat streams* correspond to thermal energy flows and require the definition of supply and target temperatures, inlet and outlet enthalpies (or heat capacities), the minimum temperature approach contribution and heat transfer coefficient (Figure 52).

````
*Resource Streams*

```{rosmose CoolTower_rs}
: OSMOSE RESOURCE_STREAMS CoolTower

|layer      |direction|value                |
|:----------|:--------|:--------------------|
|ELEC       |in       |%E_ref_CT%           |
|WATER      |in       |%watermu_CT%         |
```
````

Figure 51: Definition of the Resource streams in ROSMOSE tool.

```
*Heat Streams*

```{rosmose CoolTower_hs}
: OSMOSE HEAT_STREAMS CoolTower

|name           |Tin        |Tout       |Hin |Hout          |DT min/2       |alpha  |
|:--------------|:----------|:----------|:---|:-------------|:--------------|:------|
|cooltowerheat  |%Cool_Tin% |%Cool_Tout%| 0  | %Cool_Qmax%  | %dtmin_liq%   |1      |
```
```

Figure 52: Definition of the Heat streams in ROSMOSE tool.

In summary, by defining the input and calculated parameters, the layers, the units and their cost and bounding parameters, as well as the resources (mass or electricity) and heat streams, the simplest ET can be completely defined. All the other ETs are programmed similarly and can be called in the frontend.Rmd to determine the best combination of energy technologies that satisfy the constraints and minimize the objective functions.

Appendix 5: Access to OSMOSE framework (backend)

OSMOSE stands for Multi-Objective Optimization of Integrated Energy Systems (OptimiSation Multi-Objectif de Systèmes Énergétiques Intégrés). It is a process integration tool that has been developed at the Industrial Process and Energy Systems Engineering (IPESE) group in EPFL. It has been used for over two decades in research projects and teaching activities, and undergoes continuous development and addition of new features (Flórez-Orrego et al. 2022a). As a computational platform, OSMOSE combines metaheuristics (e.g., genetic algorithm) and deterministic optimization (e.g., mixed integer linear programming) for simultaneous heat and mass integration. This framework aids in the decision-making of the design and operation of various energy systems, either industrial or urban, while considering thermodynamic, environmental, and economic targets. Among the strengths of OSMOSE engine is its flexibility in integrating various software and tools, such as database handling routines (.csv and .json), process modelling and simulation suites (Aspen, Vali), deterministic optimization suites (AMPL/GLPK), data visualization (GNU Plot, d3js Sankey), and metaheuristics software (Dakota).

After the pinch analysis is applied to determine the maximum potential for waste heat recovery, OSMOSE selects the best available energy technologies and utility systems to supply the energy demands with a minimum overall production cost, including capital and operational expenditures. Due to the existence of various process integration routes, competing utility systems, and possible operating conditions, numerous scenarios arise. The variation of the operating conditions due to different production routes in a single plant leads to different utility demands. Thus, the systems needed to satisfy those demands can also change, entailing a growing list of alternatives and arrangements. For this reason, OSMOSE Lua is used to handle the MILP problem that determines the best combination of technologies and operating conditions that reduce the total cost.

OSMOSE tool can be used to calculate the minimum energy requirements (MER) of the process by applying pinch analysis techniques. It can provide the best combination(s) of energy technologies and their corresponding operating conditions that reduce the total cost. To this end, the MILP problem shown in Eq. (1) is handled and solved by the OSMOSE engine using AMPL suite:

$$min\ Cost_{tot} = \sum_{u \in Units}\left[\sum_{t \in Time}\left(Cop1_u \cdot Y_{u,t} + Cop2_u \cdot M_{u,t}\right) \cdot \Delta t + Cinv1_u \cdot Y_u + Cinv2_u \cdot M_u\right] \quad (1)$$

- $Cost_{tot}$ is the total annual cost of the industrial energy system [€/y],
- $Cop1_u$ is the fixed operating cost of unit u [€/hr],
- $Y_{u,t}$ is the integer variable related to the presence or absence of each unit u at time t [-],
- $M_{u,t}$ is the corresponding continuous load of a unit u at time t [kg/hr or kW],
- $Cop2_u$ is the variable operating cost of unit u [€/kg or €/kWh],
- Δt is the annual operating time of unit u [hr/y],
- $Cinv1_u$ is the fixed annualized investment cost of unit u [€/y],
- Y_u is an integer variable related to the presence or absence of a unit u in the system; the maximum value of $Y_{u,t}$ [-],
- $Cinv2_u$ is the specific annualized investment cost of a unit u [€/kg or €/kWh],
- M_u is the corresponding maximum load of the unit u [kg/y or kWh/y].

This objective function is subject to multiple constraints (unit existence and load boundary conditions):

$$Y_{u,t} \cdot Fmin_u \leq M_{u,t} \leq Y_{u,t} \cdot Fmax_u \ ; \qquad \forall u \in Units,\ \forall t \in Time \quad (2)$$

$$M_{u,t} \leq M_u \quad (3)$$

$$Y_{u,t} \leq Y_u \quad (4)$$

Mass and energy balance constraints:

$$\sum m_{Input\ streams} = \sum m_{Output\ streams}\ ; \qquad \forall\ Layer,\ \forall\ Time \qquad (5)$$

Power production or consumption constraints:

$$\sum_{w=1}^{N_w} M_w \cdot w_{w,utilities} + \sum_{Processes} W + W_{import} - W_{export} = 0 \qquad \forall\ Time \qquad (6)$$

Heat cascade constraints, balance at the temperature interval *r*:

$$\sum_{w=1}^{N_w} M_w \cdot q_{w,r} + \sum_{i=1}^{N} Q_{i,r} + R_{r+1} - R_r = 0\ ; \qquad \forall\ r = 1 \ldots.. N \qquad (7)$$

And solution feasibility:

$$R_1 = 0, R_{N+1} = 0,\ R_r \geq 0 \quad ; \ W_{import} \geq 0,\ W_{export} \geq 0 \qquad \forall\ r = 1 \ldots.. N \qquad (8)$$

- *N* is the number of temperature intervals based on supply/Target temperatures of all streams [-]
- *Q* is the heat exchanged between process streams [kW],
- *R* is the heat cascaded from higher (r+1) to lower (r) intervals of temperature [kW],
- N_w is the number of utility units available,
- $q_{w,r}$ is the specific heating or cooling flow supplied by any utility unit w within an interval *r* [kWheat/kW or kWheat/kg],
- *W* is the power produced or consumed by the utility systems, the unit processes, or imported from or exported to the grid [kW].

Additional thermodynamic and environmental indicators can be determined to compare and rationally represent scenarios in non-dominated Pareto plots. A weighted combination of multiple objective functions, such as costs and impact factors, may also be used to govern the optimization problem.

ROSMOSE triggers the execution of the routines in the OSMOSE engine, which writes the respective *.run*, *.mod,* and *.dat* files in AMPL language. Those files contain the equations of the optimization problem and the parameters of the ET models. The mathematical formulation of the problem can be solved using any open-source MILP solver compatible with the AMPL® community edition. Once the optimization problem is solved, results are dumped into an output file (JSON format) and parsed to extract and structure the data. Post-compute functions are next used to:

- Calculate performance indicators (e.g., costs, environmental impact, energy efficiencies, etc.).
- Display graphical representations of relevant results (e.g., composite and integrated curves).
- Calculate objective functions for multi-objective optimization scenarios.
- Carry out post-optimization analyses and issue recommendations.

According to the current European market, the costs of all input and output streams in the ROSMOSE tool can be assumed (Table 13).

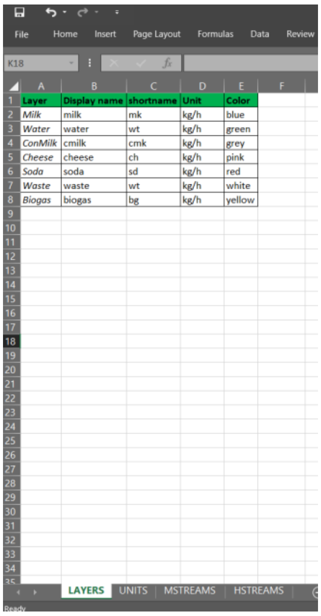
Table 13: Mass and energy input costs assumed for generic case studies.

Stream	*Unit*	*Cost*
Water	€/m^3	3.0
Electricity	€/kWh	0.2
Natural gas	€/kWh	0.07
Biogas	€/kWh	0.08
CO_2 tax	€/t	100
CO_2 marketed	€/kg	0.008

Appendix 6: Template for data input using Excel software

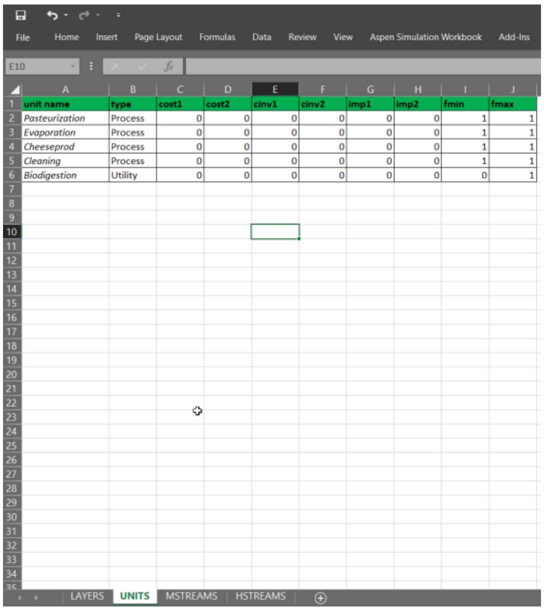
The practicality and expediency of the web-based tool must be balanced with the extensibility and transparency of the source code. Many practitioners and researchers, especially newer generations, prefer more control over the modeling, simulation and reporting steps, which calls for a more flexible execution. The possibility of programming in Python or R language ensures that the web-based tool will not be limited to the generation of Pinch Analysis but could connect and execute external software. Extensibility of the modeling and optimization processes by modifying the source code is crucial for achieving a lasting community of end-users and contributors.

On the other hand, considering that Excel® is one of the most widespread office suites and a lot of data generated in industries is stored in this and related formats, the ROSMOSE tool incorporates a function to read the content of an Excel file and automatically build the ET in the ROSMOSE syntax. The name of the Excel file is the same as the ET, which contains four tabs for inputting layers (LAYERS), units (UNITS), resource streams (MSTREAMS) and heat streams (HSTREAMS) (Figure 53 to Figure 56):



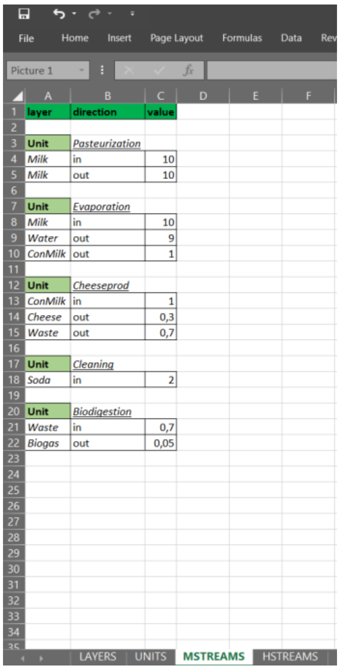
Layer	Display name	shortname	Unit	Color
Milk	milk	mk	kg/h	blue
Water	water	wt	kg/h	green
ConMilk	cmilk	cmk	kg/h	grey
Cheese	cheese	ch	kg/h	pink
Soda	soda	sd	kg/h	red
Waste	waste	wt	kg/h	white
Biogas	biogas	bg	kg/h	yellow

Figure 53:. Schematic of the LAYERS tab.



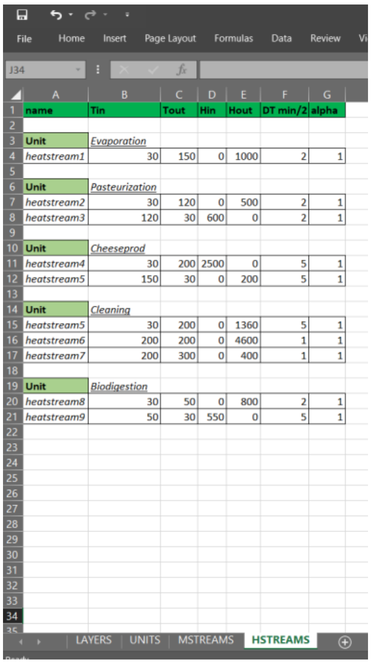
unit name	type	cost1	cost2	cinv1	cinv2	imp1	imp2	fmin	fmax
Pasteurization	Process	0	0	0	0	0	0	1	1
Evaporation	Process	0	0	0	0	0	0	1	1
Cheeseprod	Process	0	0	0	0	0	0	1	1
Cleaning	Process	0	0	0	0	0	0	1	1
Biodigestion	Utility	0	0	0	0	0	0	0	1

Figure 54: Schematic of the UNITS tab.



layer	direction	value
Unit	Pasteurization	
Milk	in	10
Milk	out	10
Unit	Evaporation	
Milk	in	10
Water	out	9
ConMilk	out	1
Unit	Cheeseprod	
ConMilk	in	1
Cheese	out	0,3
Waste	out	0,7
Unit	Cleaning	
Soda	in	2
Unit	Biodigestion	
Waste	in	0,7
Biogas	out	0,05

Figure 55: Schematic of the MSTREAMS tab.



name	Tin	Tout	Hin	Hout	DT min/2	alpha
Unit	Evaporation					
heatstream1	30	150	0	1000	2	1
Unit	Pasteurization					
heatstream2	30	120	0	500	2	1
heatstream3	120	30	600	0	2	1
Unit	Cheeseprod					
heatstream4	30	200	2500	0	5	1
heatstream5	150	30	0	200	5	1
Unit	Cleaning					
heatstream5	30	200	0	1360	5	1
heatstream6	200	200	0	4600	1	1
heatstream7	200	300	0	400	1	1
Unit	Biodigestion					
heatstream8	30	50	0	800	2	1
heatstream9	50	30	550	0	5	1

Figure 56: Schematic of the HSTREAMS tab.

Specialized predefined ETs based on comprehensive superstructure models, such as the heat pump and steam network superstructures, require a slightly different number of input parameters, as discussed in the next Appendix.

Appendix 7: Template for data input to the HTHP superstructure

A Python wrapper for the CoolProp library is used in an equation-oriented (EO) modeling approach to simulate two main superstructures of utility systems. The HTHP superstructure builds upon the combination of multistage compression and throttling systems, along with saturator, economizers, and subcooling equipment. The user sets the pressure and temperature levels by examining the industrial processes' grand composite curve. The user can also list the fluids among which one or more can be chosen by the optimization problem solved using the ROSMOSE tool.

````
```{rosmose}
: OSMOSE FLUIDS heatpump_ssTixo

|Fluid        |
|:------------|
|IsoButane    |
|Methane      |
|Ethylene     |
|water        |
|Ammonia      |
|n-Propane    |
|R1234yf      |
|Propylene    |
|R32          |
|Ethane       |
|CarbonDioxide|
|R245fa       |
|R1233zd(E)   |
|R1234ze(Z)   |
|R1234ze(E)   |
|R365MFC      |
|n-Pentane    |
|Isopentane   |
|n-Butane     |
|R134a        |
|R152a        |
```
````

Figure 57: Definition of the list of refrigerant fluids to be considered.

Next, the input parameters to the heat pump superstructure, which can be classified as mandatory or optional, are briefly presented. In the temperatures table, it is necessary to define the temperature-related parameters as rows, where:

- Temperatures [C]: Evaporation and condensation temperatures in descending order, as many temperatures as desired.
- SuperheatDT [C]: Superheating temperature difference corresponding to the temperature level.
- SupercoolingDT [C]: Supercooling temperature difference corresponding to the temperature level
- DT [C]: Minimum temperature difference contributes to the temperature level.

```
```{rosmose}
: OSMOSE TEMPERATURES heatpump_ssTixo

|Parameter    |T1    |T2   |T3   |T4   |T5   |Unit |Comment                                 |
|:------------|:-----|:----|:----|:----|:----|:----|:---------------------------------------|
|Temperatures |117.15|50   |30   |20   |-10  |C    |Evaporation and condensation temperatures|
|SuperheatDT  |20    |0    |0    |0    |0    |C    |Superheating temperature difference     |
|SubcoolingDT |64    |0    |0    |0    |0    |C    |Minimum temperature difference contrib  |
|CompressorDT |0     |2    |19.5 |20   |2    |C    |Superheating temperature difference     |
|DT           |2     |2    |2    |2    |2    |C    |Minimum temperature difference (dTmin/2) |
|MixForceUse  |0     |0    |0    |0    |0    |-    |Sensible heat contained                 |
```
```

Figure 58: Definition of the temperature-related table.

Next, it is mandatory to define a layer of electricity and the option to enable/disable the supercritical fluid states:

```
**Layer type and supercriticality**

Define the layer of electricity and the possibility to have supercritical fluid states.

```{rosmose}
: OSMOSE LAYER heatpump_ssTixo

|Balance_type     |LayerOfElec  |Supercritical|
|:----------------|:------------|:------------|
|ResourceBalance  |Electricity  | no          |
```
```

Figure 59: Definition of the layer type of electricity and criticality.

Next, it may be defined the sizing and economic parameters of the compressor (Inv2 is REQUIRED, all the other three are OPTIONAL), where:

- Fmin: Minimum load factor [-];
- Fmax: Maximum load factor [-];
- Inv1: Fixed cost coefficient [Eur/y];
- Inv2: Variable cost coefficient [Eur/kW/y];

```
```{rosmose}
: OSMOSE COMPRESSORS_PARAMS1 heatpump_ssTixo

|Fmin |Fmax |Inv1  |Inv2  |
|:----|:----|:-----|:-----|
|0    |100  |0     |0     |
```
```

Figure 60: Definition of the parameters of the compressor component.

The following parameters can be set by default or changed by experts to help convergence (OPTIONAL). For instance, the number of compressors allowed per fluid, per model and cluster, the efficiency of the compressor and other bounds:

- size: min and max size of compressor [kW], note the difference with the Fmin/Fmax, as this defines the bounds of compressor for design.
- pressure: min and max pressure levels [bar]

- ratio: min and max pressure ratio [-]

```
```{rosmose}
: OSMOSE COMPRESSORS_QUANTITY heatpump_ssTixo

|Per_fluid |Per_model |Per_cluster |
|:---------|:---------|:-----------|
|4         |4         |4           |
```

```{rosmose}
: OSMOSE COMPRESSORS_EFFICIENCY heatpump_ssTixo

|Efficiency|
|:---------|
|0.8       |
```

```{rosmose}
: OSMOSE COMPRESSORS_SIZING heatpump_ssTixo

|Param   |Min     |Max     |Unit| Comment          |
|:-------|:-------|:-------|:---|:-----------------|
|size    | 7      |500     |kW  |Compressor size   |
|pressure| 0.5    | 20     |bar |Range cost linear |
|ratio   | 1.2    | 7      |-   |Pressure ratio    |
```
```

Figure 61: Definition of additional design parameters of the compressor component.

Next, define the sizing and economic parameters of the heat exchangers (OPTIONAL), where:

- Fmin: Minimum load factor [-];
- Fmax: Maximum load factor [-];
- Inv1: Fixed cost coefficient [Eur/y];
- Inv2: Variable cost coefficient [Eur/kW/y].

```
```{rosmose}
: OSMOSE HEX_PARAMS1 heatpump_ssTixo

|Component  |Fmin  |Fmax  |Inv1  |Inv2  |
|:----------|:-----|:-----|:-----|:-----|
|Evaporator |0     |100   |     0|     0|
|Condenser  |0     |100   |     0|    70|
```
```

Figure 62: Definition of sizing bounds and economic parameters of heat exchangers.

```{rosmose}
: OSMOSE HEX_PARAMS2 heatpump_ssTixo
|

|Param    |Value    |Unit   | Comment                                                     |
|:--------|:--------|:------|:------------------------------------------------------------|
|U        | 1       | W/m2K | Heat transfer coefficient                                   |
|dT       | 10      | K     | Minimum temperature difference                              |
|a        | 500     | Euro  | Cost multiplication coefficient                             |
|b        | 0.8     | -     | Cost power coefficient                                      |
|Min      | 100     | kW    | Minimum size of heat exchangers                             |
|Max      | 1000    | kW    | Maximum size of heat exchangers                             |
|force    | 0       | -     | Binary {0,1} to force the sizing of HEX                     |
|DSH      | 0.2     | -     | Percent use of desuperheating % of a condensation level    |
```

Figure 63: Definition of additional parameters of heat exchangers.

Finally, define the bounds of the valves pressure drop, as differential pressure [bard] (OPTIONAL)

- Min: Minimum absolute pressure drop [bard]
- Max: Maximum absolute pressure drop [bard]

```{rosmose}
: OSMOSE VALVES_PARAMS heatpump_ssTixo

|Min  |Max  |Unit |Comment              |
|:----|:----|:----|:--------------------|
|0.5  |20   |bard |differential pressure|
```

Figure 64: Definition of parameters of throttling valves.

and define maximum and maximum multiplication factors of vessel units (OPTIONAL), where

- Fmin [-]: Minimum load factor
- Fmax [-]: Maximum load factor

```{rosmose}
: OSMOSE VESSELS_PARAMS heatpump_ssTixo

|Vessel |Fmin    |Fmax    |Comment      |
|:------|:-------|:-------|:------------|
|FlaD   |0       |100     |Flash Drum   |
|MixS   |0       |100     |Mix separator|
|DSHQ   |0       |100     |Desuperheater|
```

Figure 65: Definition of parameters of flash drums, mixers and de-superheaters.

The HP superstructure approach has been successfully applied in several works (Salman et al. 2024). More recent works aimed to extend the capabilities of the ROSMOSE tool by using a data-driven systematic methodology for predicting optimal heat pump integration using machine learning (Cortvriendt et al. 2024). This approach is still undergoing further development.