D2.6 TECHNO-ECONOMIC MAP OF HEAT UPGRADE TECHNOLOGIES

V0.3

Grant agreement No: 101069689

From: Tecnalia

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Date: 30/06/2024

DELIVERABLE

Basic information on the deliverable	
Dissemination level	Public
Type	Report
Due date	M20 June 2024
Task	2.6
Task leader	TECNALIA
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VERSIONS

No.	Name	Partner	Contribution	Date
01	Cordin Arpagaus	OST	Review of Version V0.1	29/05/2024
02	Laura Alonso	TECNALIA	Second review	17/06/2024
03	Maider Epelde	TECNALIA	Final review	30/06/2024

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ABBREVIATIONS

AHT: Absorption heat transformer

CAPEX: Capital expenditure

CC: Carbon capture

CCU/S: CO_2 capture and utilisation/storage

COP: Coefficient of performance

DHN: District heating network

HP: Heat pump

HTHP: High-temperature heat pump

HUT: Heat upgrade technology

IEA: International Energy Agency

MVR: Mechanical vapor recompression

PUSH2HEAT: Pushing forward the market potential and business models of waste heat valorisation by full-scale demonstration of next-gen heat upgrade technologies in various industrial contexts.

QTHT: Qpinch thermochemical heat transformer

ROI: Return on investment

TDHP: Thermally driven heat pump

THT: Thermochemical heat transformer

VCHP: Vapor compression heat pump

VHTHP: Very high-temperature heat pump

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1. Introduction

Industry must play a major role in the energy transition to meet climate neutrality targets. Increased energy efficiency by recovering and upgrading waste heat is the first step towards decarbonization in the industrial sector. The PUSH2HEAT project aims to push forward the market potential and business models of Heat Upgrade Technologies (HUTs) by full-scale demonstration of heat upgrade systems in relevant industrial sectors with high waste heat recovery and upgrading potential, with supply temperature in the range of 90 to 160 °C.

This report provides a techno-economic map of the Heat Upgrade Technologies (HUTs) developed in the project. The objective of the report is to provide a complete overview of the most important techno-economic issues affecting these technologies to reach a wide public with the need or goal to understand how these systems work and can be integrated into the industry. Thus, this report can be useful for different stakeholders, such as industrial plant owners or energy managers, engineering companies, energy service companies, research entities, industrial associations, politicians, etc.

In **Section 2**, a general description of the HUTs of PUSH2HEAT is provided. Those technologies include vapor compression heat pumps (electrically driven), with two different compression technologies, piston compressor and turbocompressor, and thermally driven heat pumps, with two different technologies, the absorption heat transformer and the thermochemical heat transformer.

In **Section 3**, the energetic and environmental benefits of the HUTs are explained, supported by a theoretical comparison with common fossil-fuel-based heat generation technology in the industry.

Section 4 goes into more detail regarding the technical characteristics of the HUTs, explaining the basic thermodynamics and operation of the systems and the specific characteristics of each one.

Section 5 provides a table with the techno-economic characteristics of the HUTs from the manufacturers working in PUSH2HEAT.

Section 6 presents an analysis of the potential feasibility of the HUTs in different countries, considering the different energy costs and their impact on the techno-economic feasibility of integration of the HUTs under different reference conditions.

In **Section 7**, a description of the identified sectors and processes for the HUTs integration is provided. The waste heat sources usually available in the different sectors and the possible upgraded heat use in those sectors are discussed. Also, some possible integration schemes for the HUTs are provided in various processes of interest.

Section 8 presents real-world application examples of the four HUTs in PUSH2HEAT. It describes the HUT integration and the most relevant KPIs for those specific case studies.

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2. General description of Heat Upgrade Technologies

Waste heat recovery is a beacon of sustainability within industrial operations, representing the harnessing and upgrading of thermal energy that would otherwise dissipate unused into the environment. As industries strive for greater efficiency and environmental responsibility, waste heat recovery emerges as a cornerstone for resource optimization and reduced carbon footprints. Through innovative technologies and strategic implementations, it minimizes energy wastage and unlocks opportunities for cost savings and enhanced operational performance.

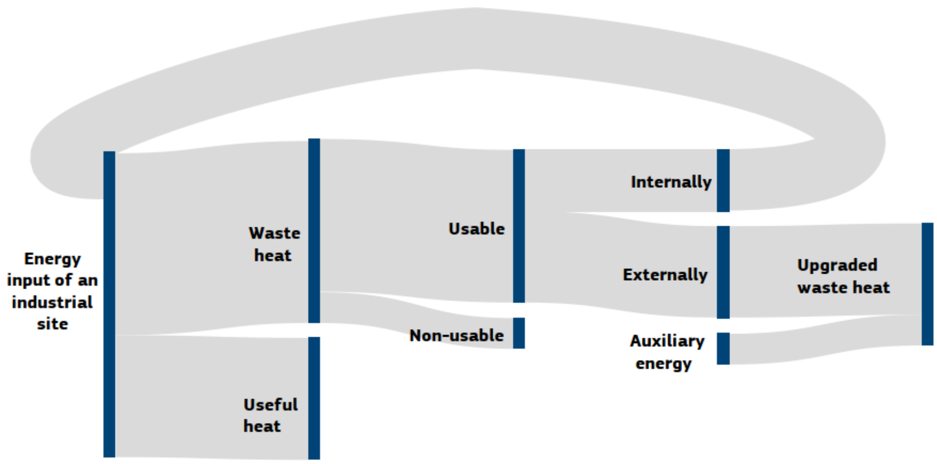

Figure 1: Potential waste heat flows at the industrial site level (Source: [1])

The initial waste heat assessment stage involves discerning internally and externally employable heat. Internally usable heat enhances on-site energy efficiency, and when upgraded with HUTs, it can also be utilized on-site or in other external processes. Subsequently, the second stage entails determining the portion of externally usable heat that couldn't be avoided or reclaimed for internal purposes.

Significant amounts of low-grade or waste heat are generated within industrial processes, often below 100 °C, and are frequently overlooked as a valuable resource. This is where HUTs come into play, offering a sustainable solution to capture and utilize this waste heat, transforming it into a useful resource. They are designed to transfer heat from a low-temperature source to a higher-temperature heat sink.

In industrial energy management, understanding the significance of waste heat recovery and the role of HUTs is pivotal. Two distinct approaches, open and closed systems, are viable solutions. Open systems utilize external heat sources or mechanical compression to upgrade low-grade heat streams. In contrast, closed systems rely on internal processes driven by electrical or thermal energy to upgrade heat without direct contact with external sources. By comprehending the fundamental differences between these systems, industries can optimize energy utilization and achieve operational excellence.

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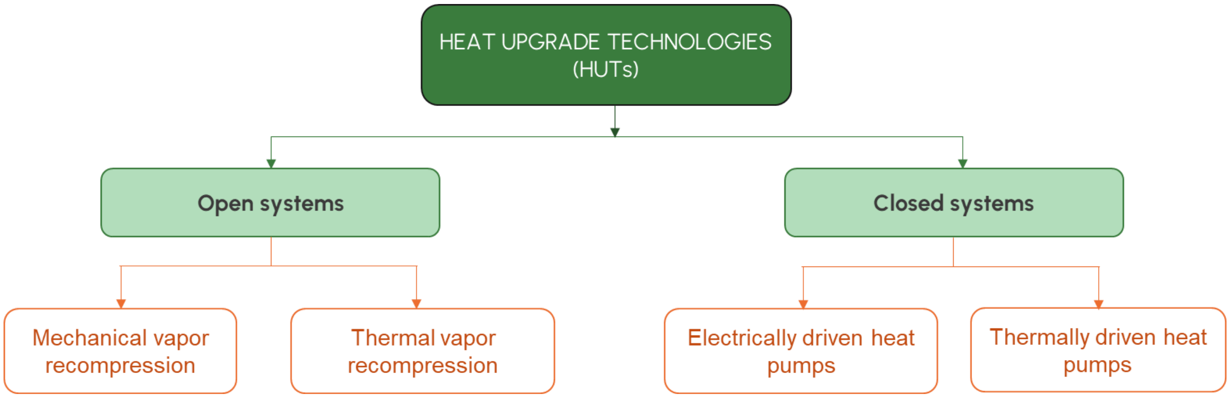

Figure 2: Types of heat upgrade technologies (open and closed systems)

2.1. Open Systems

Mechanical Vapor Recompression (MVR): utilizes a compressor to mechanically increase the pressure of a low-pressure vapor, raising its temperature. The high-pressure vapor then transfers its heat to the process requiring higher temperatures. This system is particularly suitable for applications involving low-temperature waste heat and moderate-temperature requirements.

Thermal Vapor Recompression (TVR): employs a high-temperature motive fluid, like steam or hot water, to drive a jet ejector. This jet ejector compresses the low-pressure vapor from the waste heat source, elevating its temperature. Compared to MVR, TVR offers simpler equipment but might require a readily available high-temperature motive fluid source.

2.2. Closed Systems

Electrically Driven Heat Pumps: This category facilitates the transformation of waste heat into usable energy forms through electrically driven compressors, contributing to overall efficiency gains and cost savings. These pumps offer versatility and precision control, making them suitable for various industrial applications.

Thermally Driven Heat Pumps (or Heat Transformers): by harnessing thermal gradients and differential temperatures, these technologies convert waste heat into usable energy, exemplifying sustainable solutions for industrial energy management. Examples include absorption heat pumps, adsorption chillers, and thermochemical heat transformers. These technologies offer sustainable heat recovery and utilization solutions by exploiting natural temperature variations or waste heat streams.

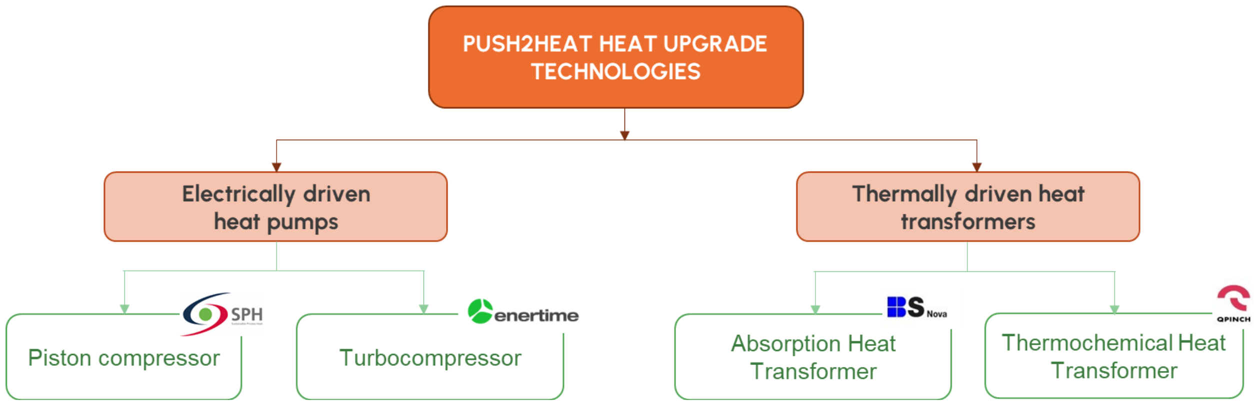

Figure 3: Scheme of Push2heat heat upgrade technologies

Thermally driven heat pumps (or heat transformers) are activated by thermal energy and have relatively low electrical consumption compared to compression heat pumps. Different thermally driven heat pumps exist based on their internal configuration and effect. Some types include absorption heat pumps (type I or type II, heat transformers), adsorption heat pumps, or thermochemical heat pumps.

The thermally driven heat pumps described in this report are heat transformers, and a basic scheme of their working principle when attending to the external heat inputs and outputs is shown in Figure 4, comparing the heat sources and sinks with the most widely known electrically driven heat pumps.

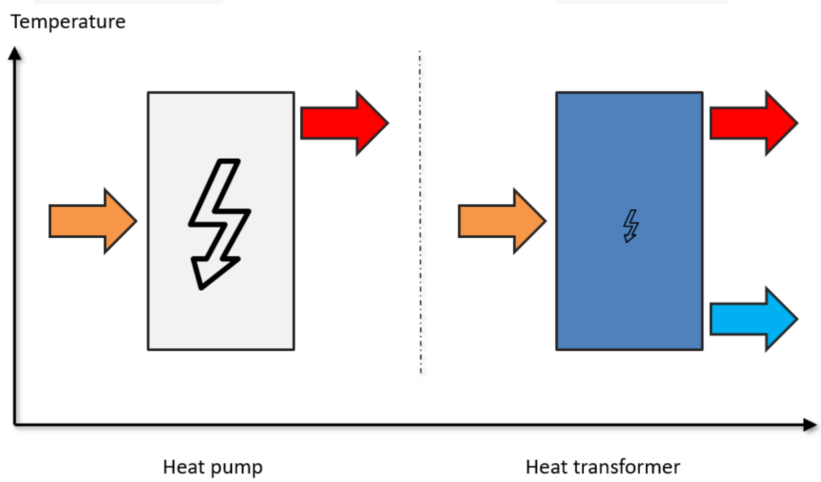

Figure 4. Comparison between an electrically driven heat pump and a thermally driven heat pump (heat transformer)

On the right of Figure 4, a conceptual diagram of a heat transformer is shown. Part of the driving heat is upgraded to a higher temperature level, with hardly any electrical consumption. However, the machine can upgrade only part of the driving heat, and the remaining part must be rejected at a lower temperature.

Applying a heat transformer makes it possible to recover waste heat that cannot be reused inside an industrial site due to its low temperature. The heat transformer elevates the temperature of approximately 50% of the residual energy to levels usable in the installation (simple effect units). In other words, it increases the exergy of 50% of the residual heat, to the detriment of the other 50%, but with minimal electricity consumption.

3. Energetic and environmental benefits of HUTs

In the industrial sector, heat demand is mostly covered (over 95%) by burning fossil fuels. Considering that a quarter of the global energy system CO_2 emissions derive from the industry (Including process emissions but not including indirect emissions from electricity used for industrial processes) [2], implementing decarbonization solutions in this area is key to meeting climate neutrality targets.

Increased energy efficiency by recovering and upgrading waste heat is the first step towards decarbonization. Industrial process heat has a significant weight in the total energy demand of the European industry. For applications up to 100 °C and from 100 °C to 200 °C, HP technologies could potentially deliver 730 TWh/a or 37 % of the process heat in industry [3]. Koller et al. [4] estimated an industrial HP market potential at 6,361 (1 MW-equivalent) units/yr based on a future scenario assuming a 30% share of used waste heat, 80 €/tn CO_2 carbon taxes and +20 % more expensive energy prices. The main benefits of using industrial HPs include:

- Reduction of energy costs
- Reduction of CO_2 emissions
- Improved energy efficiency
- Independency from fossil fuels
- Contribution to decarbonization of industrial heat demand

Given that the assessed HUTs have hardly been introduced in the industry up to 2024, more needs to be known about the dynamics of these systems once integrated. For this reason, the most reliable approach in the initial stage is to analyze the performance based on a steady-state point, using manufacturer or typical performance values.

Figure 5 shows a theoretical comparison of two types of HUTs: a Vapor Compression Heat Pump (VCHP) and a Thermally Driven Heat Pump (TDHP). Both technologies have been compared in specific operating conditions against the most common scenario, natural gas boilers, considering that around half of the industrial heat obtained from non-renewable energy sources comes from natural gas [3].

The studied HUTs require waste heat, plus electricity consumption, to drive either the mechanical compressor (in HTHPs) or circulation pumps or fans (TDHPs). To quantify the environmental impact of the HUTs, the indirect CO_2 emissions have been calculated depending on their electricity consumption. Their efficiency depends on the operating point and the temperature lift between the waste heat and the process heat.

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The comparison has been performed in Figure 5 assuming a waste heat temperature of 80 °C and a process heat temperature of 120 °C (which represents a temperature lift of 40 K). The reference thermal demand set is 1 MW. The absolute values in this scheme should be treated with caution since they depend on the operating point. Some technologies, such as TDHPs, are very sensitive to operating temperatures, and consequently, a detailed study is recommended before drawing general conclusions comparing the different HUTs. Nevertheless, as a first step, this presentation provides a glance at the potential benefits that can be achieved.

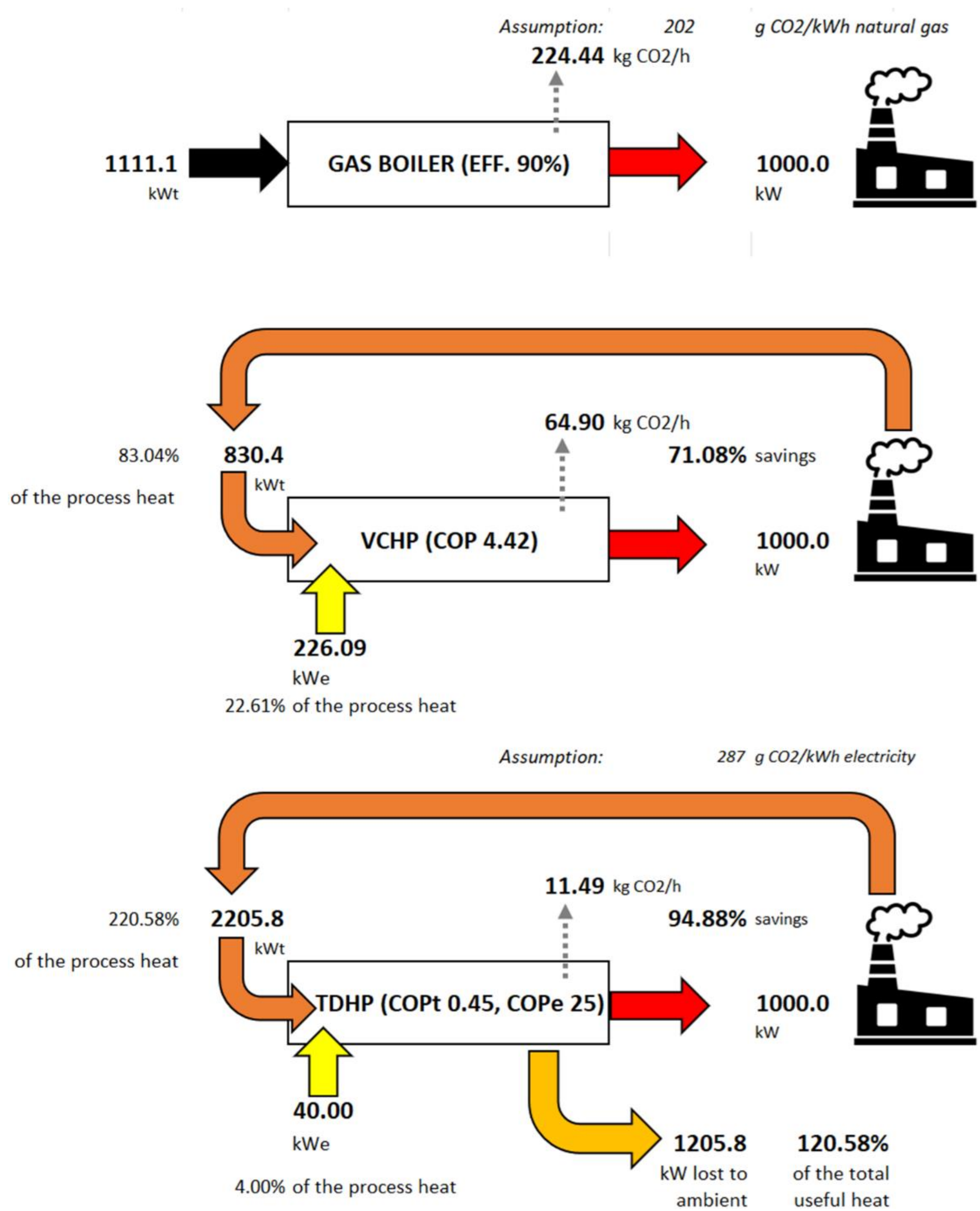

Figure 5. Simplified schemes comparing the performance of different HUTs

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The energy source in the reference scenario is natural gas (black arrow in Figure 5). The upgraded heat is represented with a red arrow. Orange arrows have been employed to represent either waste heat or heat rejection. Finally, a yellow arrow represents the electric power consumption of the HUTs.

Under the studied conditions, VCHPs help reach around 71% CO_2 emission savings, whereas TDHPs can save up to 94.9% due to the higher COP_{el}. The electricity consumption is expressed in Figure 5 as a function of the process heat so that the results can be extrapolated for other thermal demands as a first approach.

In mechanical compression systems, around 22.6% of the required process heat is electricity the compressor consumes. With thermally driven systems, only 4.0% is needed for the necessary auxiliaries (fans and pumps). Regarding the required waste heat, VCHPs only need around 83.0% of the process heat, compared to 220.6% in the case of thermally driven systems. In other words, thermally driven systems require around 2.2 units of waste heat for one unit of heat production and only 0.83 units with mechanical compression systems. TDHPs also require dissipating around 1.2 units to the ambient (generally performed with wet or dry cooling towers). Again, these results are only valid for the assumed temperature lift of 40 ºC between the waste heat temperature (80 ºC) and the upgraded heat temperature (120 ºC).

4. Heat Upgrade Technologies in PUSH2HEAT

4.1. Vapor compression heat pumps

This section provides the working principle of HPs. Then, a focus on HTHPs will be given, underlining their main characteristics, such as suitable refrigerants, type of compressors, typical efficiencies and challenges.

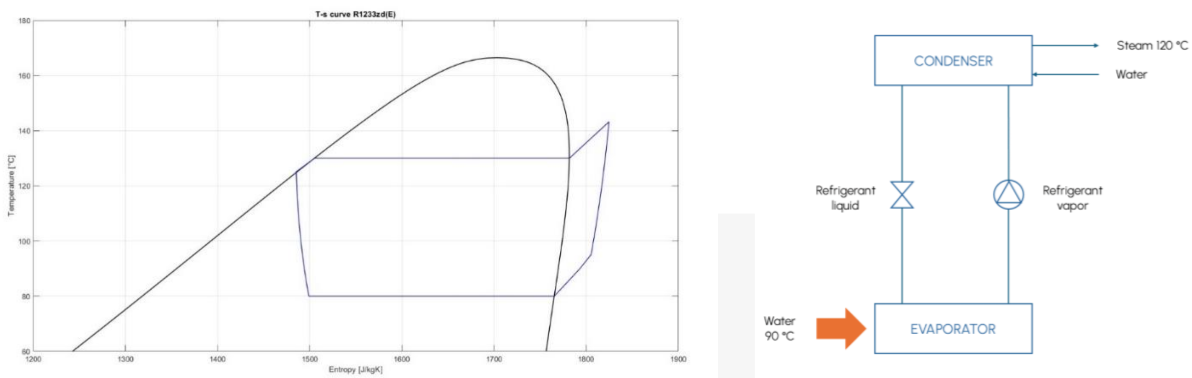
A HP machine upgrades heat from a cold reservoir (heat source) to a hotter reservoir (heat sink). Typical heat sources are excess (waste) heat from industrial processes, ambient heat from air, water bodies or the ground, heat from solar collectors, or district heating. Typical heat sinks include industrial processes, thermal energy storages, district heating supplies or building heating systems.

The heat pumping process can be achieved using various technologies:

- Vapor compression heat pumps (VCHPs)
- Absorption heat pumps
- Adsorption heat pumps
- Thermoacoustic heat pumps

VCHPs have been the core focus of pilot and demonstration projects related to HTHPs due to the high TRL of the technology for heat pumping and refrigeration applications. In all these projects, the common denominator preventing the fast rollout of the technology is the availability of high-capacity compressor technology that can operate reliably under the high temperatures required. Additionally, the electricity-to-gas price ratio and price stability represent a critical issue, especially considering the higher capital investment required to purchase and install a HUT compared to fossil-fueled systems.

VCHPs are built based on the indirect Rankine cycle. A schematic representation of the cycle layout and the T-s diagram are shown in Figure 6.



(a) (b)

Figure 6. Example T-s chart (temperature vs. entropy) (a) and cycle layout (b) of an indirect Rankine cycle working with R1233zd(E)

This cycle takes advantage of a working fluid, called refrigerant, which undergoes phase change during evaporation and condensation. In particular, the basic indirect Rankine cycle comprises the following transformations in the refrigerant:

- A compressor performs compression, increasing the pressure of the refrigerant from low to high. As a result, the temperature of the refrigerant increases while it passes from a saturated vapor (or slightly superheated vapor) to a superheated vapor at higher pressure.
- De-superheating and condensation are performed in one or two heat exchangers, which bring the refrigerant to the saturated liquid (or slightly subcooled liquid) state by rejecting heat to the sink along an almost isobaric transformation. The heat exchanged along this transformation is delivered to the high-temperature sink and represents the useful effect of the heat pump.
- Expansion, performed by an expansion valve (rarely through a turbine), reduces the pressure of the refrigerant leaving the condenser. This process causes a temperature reduction at the expense of the evaporation of part of the refrigerant.
- Evaporation is performed in a heat exchanger called evaporator. The refrigerant leaving the expansion valve at low pressure has a temperature low enough to receive heat from the low-temperature source. Usually, the refrigerant leaves the evaporator slightly superheated to prevent damage to the compressor due to the presence of a liquid fraction.

To obtain optimal VCHP performance, a waste heat stream at a suitably high-temperature level is required. Marina et al. [5] made a conservative estimate of the European (EU-28) industrial VCHP market potential. Their study used a bottom-up methodology to estimate the heat delivery potential for VCHPs up to 200 °C in the food, paper, chemical and refining sectors. The results showed that VCHPs, supplying heat up to 200 °C, can cover 614 PJ/a (171 TWh/a) in the EU-28, with the chemical sector having the largest opportunity (283 PJ/a). The corresponding estimated CO_2 reductions are 52.6 MT CO_2/a.

The efficiency of heat pumps strongly depends on the temperature lift, i.e., the difference between the heat sink (condenser) and heat source (evaporator) temperatures. The heat sink temperature depends on the industrial process's needs, while the heat source temperature depends on the availability of excess (waste) or ambient heat [6]. Given the different levels of the heat sink and source temperature, it becomes important to classify the types of heat pumps according to these operating parameters.

Classification of HTHPs

An industrial HTHP is designed to handle higher temperature lifts, typically 80 K to 150 K or higher. It requires robust components and materials to withstand elevated temperatures and pressures. These heat pumps are used in various industrial sectors, including food processing, chemical manufacturing, waste heat recovery, and other applications where high-temperature heat is required for industrial processes.

International Energy Agency (IEA) (2014) proposed a classification for heat pumps used in the industry according to their heat sink and heat source temperatures, represented in Figure 7. Therefore, while several studies mention high-temperature heat pumps (HTHPs) without establishing a specific operating range, according to ([7]; [8]; [9]), only heat pumps operating at heat sink temperatures of between 80 and 100 °C can be classified as HTHP. Consequently, according to IEA, a source of at least 40 to 60 °C is required to ensure efficient heat pump operation. Heat pumps below that temperature range are called conventional heat pumps (HP), and those above heat sink and source temperatures of 100 and 60 °C, Very High Temperature Heat Pumps (VHTHP).

More recent publications have extended this classification. A new generation of heat pumps generating steam is under development, able to achieve sink temperatures above 200 °C. At the same time, sink temperatures between 100 and 140 °C are achieved by many products currently on the market (see IEA HPT Annex 58), as demonstrated in the PUSH2HEAT project.

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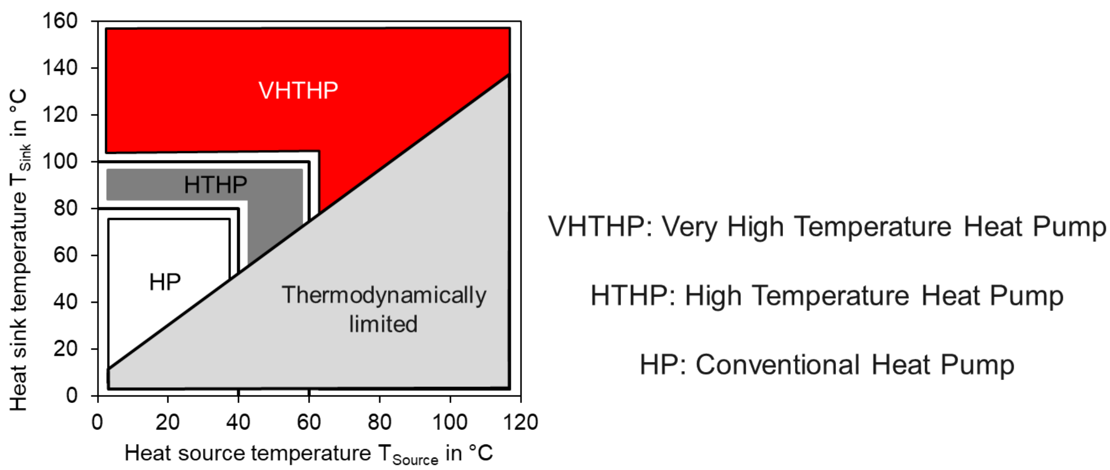

Figure 7. Heat pump classification based on operating temperature range (Source: [10])

System efficiency

The performance of heat pumps is measured through the Coefficient of Performance (COP), calculated as the ratio between the heating capacity delivered to the heat sink ($\dot{Q}_h$) and the work required for running the machine ($\dot{W}$), as expressed in the equation below.

$$COP_{heating} = \frac{\dot{Q}_h}{\dot{W}}$$

The theoretically maximal performance of such a heat pump is given by the COP of the Carnot cycle operating between two reservoirs at constant temperature:

$$COP_{Carnot} = \frac{T_{sink}}{T_{sink} - T_{source}}$$

Where T_{sink} and T_{source} are the temperatures (in Kelvin) of the heat sink and heat source, respectively.

However, heat pumps normally operate between two reservoirs with temperature variation during the heat transfer processes. In this case, it is more appropriate to evaluate the theoretically maximum performance of the heat pump by Lorenz COP:

$$COP_{Lorenz} = \frac{\hat{T}_{sink}}{\hat{T}_{sink} - \hat{T}_{source}}$$

Where $\hat{T}$ is the entropic mean temperature. The entropic average temperature is used for calculating the average temperature of a medium-changing temperature between states 1 and 2. The entropic average temperature is defined as the ratio of the difference in specific enthalpy h, over the difference in specific entropy s.

$$\hat{T} = \frac{h_1 - h_2}{s_1 - s_2}$$

For applications without temperature glide in the heat source and the heat sink, the Lorenz cycle equals the Carnot cycle [11].

This definition can be applied to all streams, including the case of steam supply with a combination of condensation at constant temperature and subcooling at varying temperature. For streams with a constant capacity, the entropic mean temperature can be approximated by the logarithmic mean temperature:

$$\hat{T}_{sink} = \frac{\Delta T_{sink}}{ln\left(\frac{T_{sink,out}}{T_{sink,in}}\right)}$$

Lorenz efficiency is a measure used to evaluate a heat pump's performance compared to the maximum achievable performance when the heat pump interacts with reservoirs at variable temperatures.

The efficiency of vapor compression machines based on the indirect Rankine cycle depends on several parameters, such as the cycle configuration [12], the heat exchangers dimensioning and the efficiency of the compressor. In particular:

1. Internal heat recovery can enhance the heat pump's performance. The most common heat recovery is obtained using a heat exchanger that sub-cools the refrigerant leaving the condenser while heating the vapor leaving the evaporator.
2. The size of the heat exchangers determines how close the refrigerant temperature gets to the temperature of the external fluid. Up to a certain dimension, larger heat exchangpfaers reduce the temperature differences and enhance efficiency at the expense of higher heat pump costs.
3. Compressor efficiency depends on the type of compressor, its capacity (larger compressors are usually more efficient), and the working conditions.

In Figure 8, the COP values of different commercial VHTHPs are summarized in a chart depending on the temperature lift between the sink and source [13].

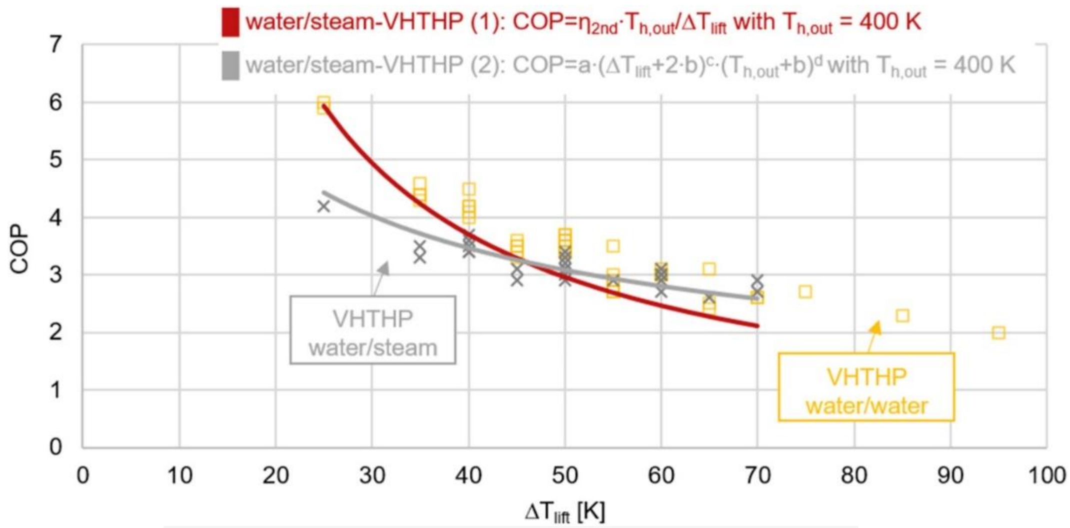

Figure 8. COP of commercial VHTHPs as a function of the temperature lift between the heat sink and source (Source: [13]**)**

Working fluids

Suitable working fluids for HTHPs are selected based on some preferable requirements:

- Reasonable pressure (possibly above atmospheric pressure and not too high) at the typical evaporation and condensation temperatures.
- Good heat transfer properties (low viscosity and high conductivity) and high latent heat of phase change.
- Low specific volume at the compressor inlet conditions.
- No flammability, zero ozone depletion potential, low global warming potential, safe and compatible with most materials.

Since no fluid meets all these requirements, compromises are usually made based on the conditions. Safety issues can be handled better in industrial applications than in residential applications. At the same time, given the high number of yearly working hours, the characteristics enhancing efficiency are more relevant.

The refrigerants currently used in HTHPs can be categorized as follows:

HydroFluoroCarbons (HFC), such as R-245fa or R-365mfc are commonly used. However, their GWP is comparatively high, and given the prevention of global warming (F-gas regulation [14]), these working fluids will be restricted in the foreseeable future.

Hydrofluoroolefins (HFO), such as R-1234ze and R-1336mzz(Z), are designed to replace HFCs thanks to their low GWPs. R-1336mzz(Z) [15] is particularly suitable for HTHP applications, offering high thermal stability and efficiency. HFOs provide similar performance as HFCs but with reduced environmental impact. Although slightly flammable (R-1234ze is safety class A2L), they require specific system designs to ensure safety. A major concern related to HFO is that, once released into the atmosphere, they undergo photo-oxidation to form trifluoroacetic acid (TFA). TFA then descends with rainfall to the earth, primarily accumulating in water and posing a hazard to humans[16]. Consequently, the European Parliament has proposed phasing out these refrigerants by 2050, although the issue has not yet been resolved [17]. However, the present F-gas regulation (F-gas regulation [14]), already bans some of the HFOs for certain applications, such as air-to-water monoblock systems.

Hydrochlorofluoroolefins (HCFO), such as R-1233zd and R-1224yd, are emerging as low-GWP alternatives for HTHP applications. R-1233zd is especially interesting for its performance in high-temperature applications, offering a good balance of efficiency, low flammability, and reduced environmental impact. **Natural refrigerants** are considered the alternative to synthetic working fluids thanks to the low GWP and good overall properties. Natural refrigerants suitable for HTHP applications are water (R-718), CO_2 (R-744), ammonia (R-717), and **hydrocarbons** (HC in Table 1, e.g., R-600, R-601). Among those, **water** is suitable for high-temperature ranges, while it has the drawback of sub-atmospheric operation when the evaporation temperature is below 100 °C. On the other hand, using **CO_2** implies high pressures, which may limit certain applications, but some manufacturers produce units with working temperatures around 120-130 °C, even 150 °C [18]. The same stands for **ammonia**, which is more suitable for refrigeration applications. Among these options, hydrocarbons are the most suitable for properties at typical operating conditions. However, they are characterized by high flammability (safety group A3), which can represent an issue in some contexts, especially for heat pumps of high capacity, employing high quantities of fluid. [19]. In Table 1, the main refrigerants suitable for HTHP applications are summarized, together with their main properties, while in Figure 9, the operating ranges of some refrigerants are reported.

Table 1: Properties of the main refrigerant for HTHP (Sources: [19], [20], [21])

Refrigerant	Type	T_{CRIT}	P_{CRIT}	ODP	GWP	safety class
		[°C]	[bar]	(R11=1)	(CO2=1)	
R245fa	HFC	154.0	36.5	0	858	B1
R1336mzz(Z)	HFO	171.3	29.0	0	2	A1
R1234ze(Z)	HFO	150.1	35.3	0	< 1	A2L
R514A	HFO	178.4	34.0	0	2	B1
R1233zd(E)	HCFO	165.6	35.7	0.00034	1	A1
R1224yd(Z)	HCFO	155.5	33.4	0.00012	< 1	A1
HC-601 (isopentane)	HC	196.6	3.4	0	5	A3
HC-600 (butane)	HC	152.0	3.8	0	4	A3
HC-600a (isobutane)	HC	134.6	3.6	0	20	A3
R-718 (water)	Natural	373.9	220.6	0	0	A1
R-717 (ammonia)	Natural	132.3	113.3	0	0	B2L
R-744 (CO_2)	Natural	31.0	73.8	0	0	A1

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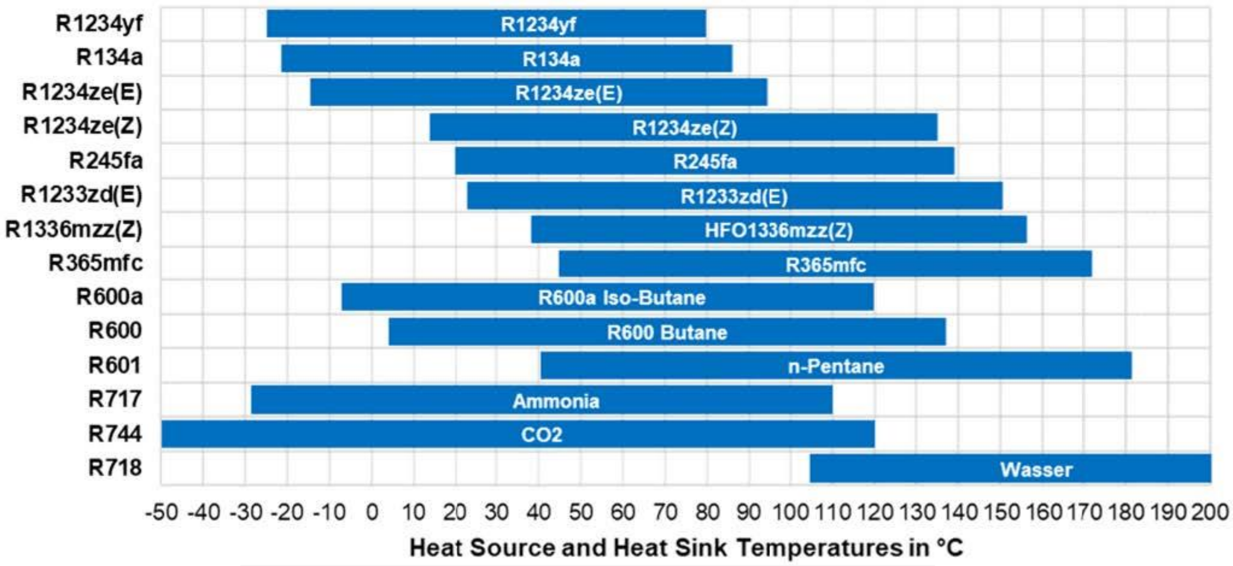

Figure 9. Operating ranges of common refrigerants for HTHP (Source: [21])

Compressor technologies

Compressors are the key component for HTHPs due to the high temperatures at the compressor discharge. In addition to being able to deal with high discharge temperatures, compressors need to handle the required pressure ratio and refrigerant flow rate imposed by the given application. At the same time, the compressor must operate efficiently since it is the component with the largest impact on the performance difference between the Lorenz efficiency and the actual heat pump efficiency. The compressors technologies commonly used and their main characteristics are summarized below:

- **Screw Compressors:** A screw compressor consists of two helical rotors that mesh to compress the refrigerant. They are known for their high efficiency and reliability, especially in industrial-scale applications, where large capacities and high temperatures are common requirements. Screw compressors offer good part-load performance and are less prone to issues related to liquid refrigerant carryover.
- **Centrifugal Compressors:** A centrifugal compressor relies on the principle of centrifugal force to accelerate the refrigerant and increase its pressure. It is highly efficient and capable of handling large volumes of refrigerant gas. Centrifugal compressors are often used in HTHPs for industrial processes and large-scale HVAC systems. However, they require precise control systems to maintain stable operation across varying conditions.
- **Reciprocating Compressors (or Piston Compressors):** A reciprocating compressor converts rotary motion into reciprocating motion, driving pistons to compress the refrigerant. They can deliver high pressures and are often used in HTHPs requiring high compression ratios. However, their efficiency can be affected by variations in load and speed.
- **Scroll Compressors:** These compressors are characterized by their smooth and nearly continuous compression process, which helps minimize energy losses associated with pulsation. They are well-suited for HTHPs because they can effectively handle varying load conditions. Scroll compressors offer good energy efficiency and reliability, making them popular in residential and commercial applications.

4.2. Thermally driven heat pumps

The following subsections describe the two types of thermally driven heat pumps developed in the Push2heat project: absorption heat pumps (or heat transformers) and thermochemical heat pumps (or heat transformers).

4.2.1. Absorption heat pump

An absorption heat transformer (or type 2 absorption heat pump) is a thermally driven heat pump [22] that works based on the concept introduced before. Its internal processes include the absorption and desorption of refrigerant in a sorbent. There are different working pairs of sorbent-refrigerant, but the technology developed in Push2heat works with water-lithium bromide salt (LiBr), the refrigerant.

The heat transformer, from the point of view of external heat sources and sinks, which are used to activate and obtain the machine's useful effect and dissipate heat, works at three temperature levels. Figure 10 shows the temperature levels and thermal fluxes in the cycle. The three temperature levels at which an AHT works and the main components involved include:

4. The driving heat is introduced in the evaporator and generator at a temperature level T_1.
5. The useful effect, the heat upgrade, occurs in the absorber due to the exothermic nature of the water absorption by the saline solution, and the driving heat is upgraded to a temperature level of T_2.
6. Finally, the condenser dissipates part of the driving heat at a temperature level T_0.

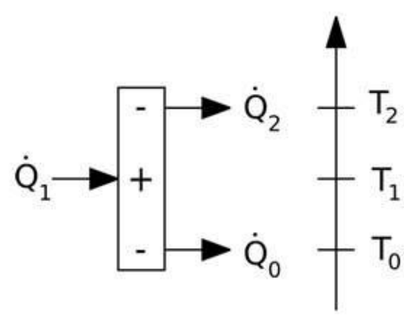

Figure 10. Heat flows in an AHT: Recovery (Q1), revaluation (Q2) and dissipation (Q3) at their corresponding temperature levels.

The temperature lift (ΔT_{lift}) of the AHT is the temperature difference between the upgraded heat temperature level (T_2) and the driving heat temperature level (T_1). On the other hand, the temperature thrust (ΔT_{thrust}) corresponds to the temperature difference between the driving heat temperature level (T_1) and the rejection heat temperature level (T_0).

For a specific design of an AHT, the heat upgrade capacity decreases when the high-temperature level T_2 increases. On the other hand, the heat upgrade capacity increases when the dissipation level T_0 decreases or when the driving heat temperature level T_1 increases. Finally, conditioned by the

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properties of the aqueous LiBr solution, which is the working fluid mainly used in this kind of heat pump technology due to its absorption capacity, single-effect transformers can work up with a maximum heat upgrade temperature of up to approximately 160 °C. Still, the maximal value will depend on the conditions marked by the temperatures T_1 and T_0.

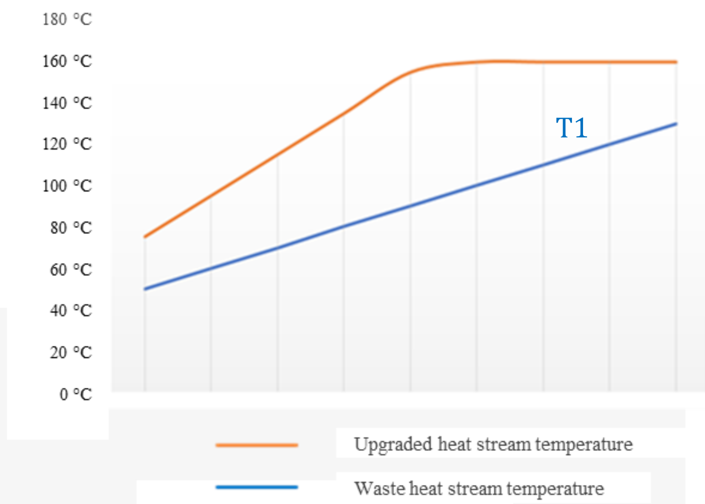

Figure 11. Estimated maximum upgraded heat temperature levels (orange) in an AHT based on residual heat temperature (blue) for dissipation at ambient level.

The AHT is the least known and used type of heat pump within the absorption technologies. Although the technology has been developed for a long time in universities, research institutes and companies, and although there are industrial facilities described in the bibliography, the system still needs to be discovered in the market and industry. The effect described on external streams is due to the exothermic absorption of water vapor by the commonly used aqueous solution of Lithium Bromide (LiBr).

Single-effect AHTs can increase the temperature of about 50% of the residual energy by about 50 K. Still, this temperature lift depends strongly on the difference between driving heat and rejection heat temperature levels. The AHT can be considered an absorption chiller that works in reverse, and it includes the same main components: a condenser, an evaporator, an absorber, and a generator. The difference between the absorption chiller and the AHT is that in the latter, the absorber and evaporator operate at high pressure, and the condenser and generator at low pressure. Figure 12 shows a schematic of an AHT.

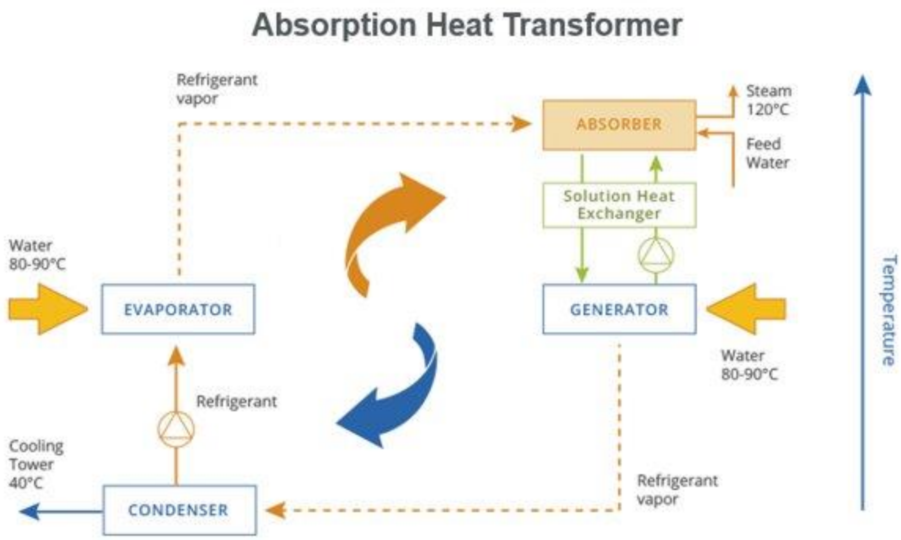

Figure 12. The thermodynamic cycle of an AHT

The operation of a LiBr/H_2O single-effect AHT has the following steps:

7. Driving heat activates the AHT cycle, separating the refrigerant water from the absorbent, an aqueous LiBr solution. This occurs in the generator.
8. The refrigerant vapor flows to the condenser, discharging its latent heat to a lower-temperature dissipation source, generally at ambient temperature.
9. The condensed refrigerant is pumped at a higher pressure and evaporated, with the driving heat from the heat source, as in the generator.
10. Finally, the refrigerant vapor is absorbed in the absorber by the concentrated LiBr solution from the generator. Due to the exothermic nature of the process, the absorption heat is released at a higher temperature, thus obtaining the revalued heat that is obtained from the AHT and will be delivered to the corresponding application.

The single-effect AHT cycle has been described as the industry's most common type of AHT. A double-lift AHT, as presented on the right-end side of Figure 13, increases the complexity and investment cost by adding an additional evaporator and absorber at a higher temperature level but allows for larger temperature lifts of up to 80 K. However, the ratio between the driving and upgraded heat is reduced to 30 to 34 % instead of 50 %.

Lubis et al. [23] reported steam generation at 170 °C using driving heat with temperatures between 80 and 90 °C and dissipation temperatures between 20 and 30 °C with a double-effect AHT. Cudok et al. [24] stated that only 5 out of 43 industrial applications reported by the authors of this review were double-lift AHTs.

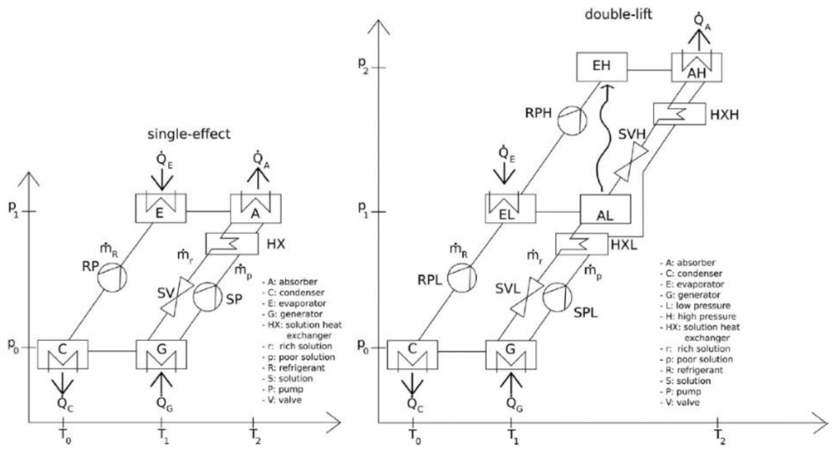

Figure 13. Single-lift (left) and double-lift (right) AHT cycles are represented in a p-T diagram [24]

The main operational risk in AHTs is the crystallization of aqueous LiBr solution, which may lead to the blockage of pipes, heat exchangers or even pumps. However, commercial heat transformers include technical protection against crystallization, and modern-day AHTs include control strategies that avoid operating in points that could lead to crystallization.

In addition, corrosion is one of the main risks for the operation of AHTs. The corrosive environment of the LiBr solution is particularly intense at high temperatures and with salt mass fractions higher than 60% [24]. However, safe and sustainable operation boosting heat up to 165 °C is demonstrated as state-of-the-art when the concentration of the corrosion inhibitor Li_2MoO_4 is properly maintained. Boosting to higher temperatures is possible, but a higher maintenance effort is needed. Another risk for AHT that can result in performance degradation is the presence of non-condensable gases within the vessels. Modern-day AHTs include the so-called purge systems that automatically or helped by maintenance can eliminate these gases.

Modern-day AHTs include automatic controllers that ensure the safe and smooth operation of the units, efficient operation for changes in either the driving heat or the dissipation temperature levels, and constant upgrade heat temperature.

Ayou et al. ([25] describe the main installations with AHT in recent years. For example, Thermax Ltd has developed equipment with a capacity of between 500 and 1000 kW, which can revalue up to a maximum temperature of 160 °C and have a COP of between 0.45 and 0.50. In the same way, Johnson Controls-Hitachi offers equipment between 150 and 2,475 kW, upgrading the residual currents to between 70 and 140 °C.

Cudok et al. [24] published a review of documented facilities. 26 out of 43 are installed in the chemical industry, 9 in the food industry, and the rest in various sectors, such as water treatment, pulp and paper, steel and machinery. In the rest, neither the industry nor the AHT installation process is specified. Despite the lack of detail, the documented facilities are in intensive sectors and processes.

Section 7 provides more information on specific sectors and processes for implementing AHT technology.

4.2.2. Thermochemical heat transformer

The general principle of THT

The thermochemical heat transformer (THT) follows the same general working principle shown in Section 4.2. The heat recovery technology is activated and almost solely driven by wasted heat at low to intermediate temperatures (80°C-120°C). The internal process converts this residual heat into two heat streams: useful process heat at high and rejected heat at lower temperatures. A negligible amount of electrical energy is used to circulate the working fluid. These energy flows are depicted in Figure 14 for the THT of the Belgium-based company Qpinch. This is functionally equal to the Absorption Heat Transformer.

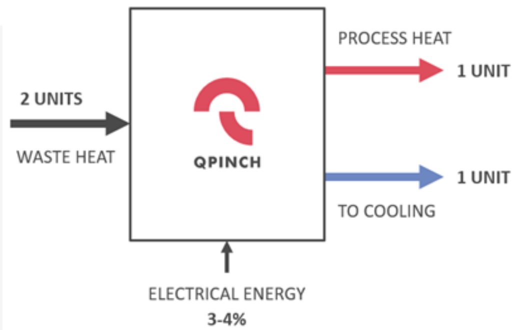

Figure 14. QTHT energy flows.[1]

The THT process exploits a reversible endo- and exothermal chemical reaction, resulting in larger temperature lifts to high temperatures. The technology behind the thermochemical heat transformers was put into practice and developed for industrial application by Qpinch. The Qpinch THT (QTHT) was inspired by the highly efficient reversible biochemical ATP-ADP cycle, which is crucial to the energy metabolism of all living cells. The QTHT uses inorganic, food-grade phosphoric acid (H_3PO_4) as a medium, forming its dimer and water in an endothermic reaction (Figure 15 left to right). In the reverse reaction, the dimer is hydrolyzed, regenerating the monomer while setting free heat at high temperatures (right to left). [26]

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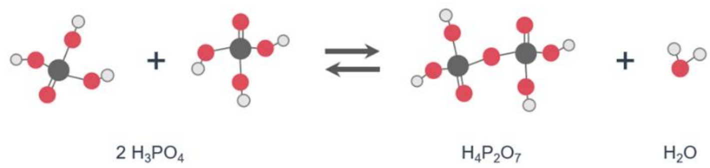

Figure 15. Dimerization of phosphoric acid.[2]

The working principle can be broken down into three steps, as shown in Figure 16:

1. Waste heat is captured in the cold reactor via indirect heat transfer.
2. Transformation of waste heat into process heat of higher temperature is realized in the QTHT internal process using the reversible physicochemical reaction.
3. Process heat is delivered to the industry via indirect heat transfer.

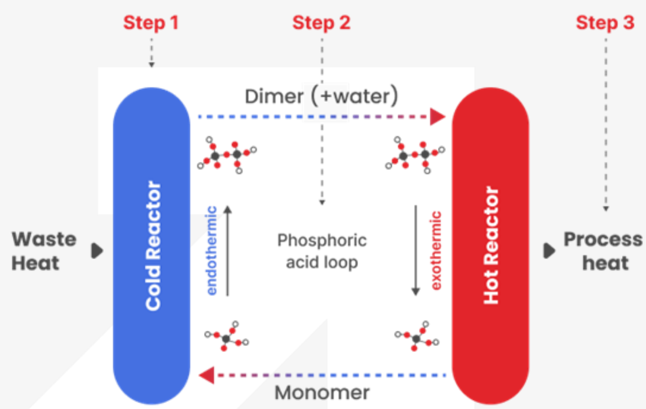

Figure 16. Process scheme of the Qpinch thermochemical heat transformer. [3]

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QTHT internal process

The internal QTHT process, as depicted in Figure 17, comprises the following chemical steps:

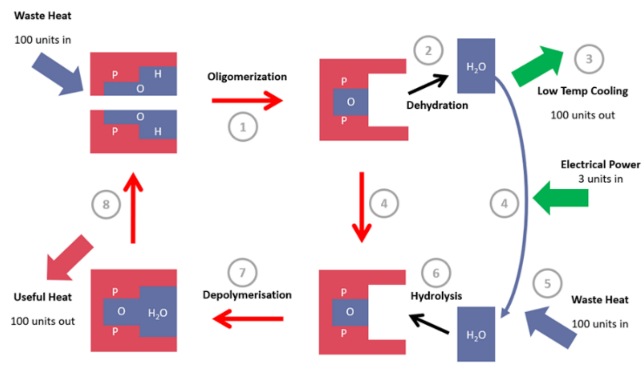

Figure 17. Chemical process scheme of the QTHT.[4]

- **Oligomerization:** the total waste heat source (200 units) is used in two separate spots of the process. Approximately half of it (100 units) is used in the cold reactor to oligomerize the monomeric phosphoric acid.
- **Dehydration:** molecular water is released when two phosphoric acid molecules react to form its dimer.
- **Condensation:** To maintain the driving force of the endothermic oligomerization, water vapor is condensed using cooling, and thus, 100 units of thermal energy are dissipated through cooling water.
- **Pressure increase:** Phosphoric acid and water pressures are increased using conventional liquid pump energy.
- **Evaporation:** the second part (100 units) of the waste heat source (mentioned in step 1) is used to evaporate the condensate to steam. This is an important differentiator compared to mechanical compression heat pumps, as waste heat is used to compress the refrigerant (instead of power), making it a thermally driven technology.
- **Hydrolysis:** after preheating the polymerized phosphoric acid with a recuperator to make the process as efficient as possible, the phosphoric acid is exposed again to the water vapor in the hot reactor.
- **Depolymerization:** The exothermic depolymerization reaction occurs in the hot reactor, setting free useful heat. The heat is typically transferred indirectly to a water loop with a flash vessel to generate steam at the required pressure.
- **Pressure decrease:** in the final step to close the thermal cycle, the monomerized phosphoric acid is sent through the recuperator to return to its original state in the cold reactor.

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Characteristics of the QTHT

The physicochemical reaction in the QTHT enables it to address the main challenges in heat upgrade for several industrial sectors.

- Output temperature

With a given waste heat source, the QTHT can realize temperature lifts between 40 K and 100 K in one step with a flexible temperature output setting. The state-of-the-art THT can reach a maximum steam output temperature of 210 °C. Figure 18 shows the operational window.

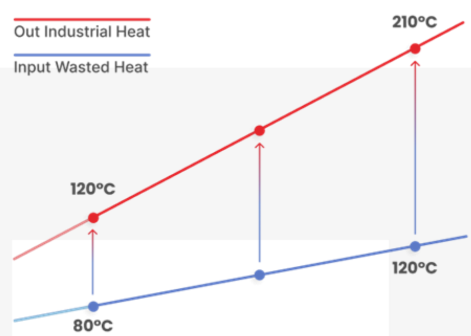

Figure 18. QTHT temperature jumps.[5]

- Capacity

The QTHT has a high scalability starting at MW-scale up to 10 MW and above. The current operational QTHTs are scaled between 1 and 2 MW. In addition, it has a large turndown ratio depending on the needs of the industrial customer and the available waste heat at a certain moment.

- OpEx

The process is fully driven by thermal waste energy and consumes marginal electricity, resulting in a low net OpEx.

- Process integration

The QTHT has high integration flexibility, meaning it is compatible as an add-on in most industrial processes and can handle multiple operating conditions. The flexibility regarding duty and temperature widens the technology's applicability. Depending on the application and the specific

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needs of the industrial client, the QTHT can be designed in series or a hybrid configuration with mechanical compression heat pumps.

Industrial examples of QTHT

The QTHT was designed with waste heat from (petro)chemicals and refineries in mind. Many of these processes require heat anywhere between 120 °C and 250 °C; some, like crackers, even several hundreds of degrees more. Waste heat typically becomes available below 200 °C, with the bulk of it below 130 °C. Referring to the operational window as visualized in Figure 18, the QTHT can cover the main part of the process heat demand with waste heat below 130 °C.

The current commercial QTHTs are situated in the port area in Antwerp, Belgium. Two of them are integrated into chemical plants, recovering waste heat from distillation overhead streams and reactor cooling water (one of them is described in Section 8). In addition, Qpinch operates an industrial-scale testing facility on its own premises. They have a capacity between 1 MW and 2 MW and upgrade waste heat between 90 °C and 140 °C to process heat between 140 °C and 185 °C.

5. Technical specifications of HUTs in PUSH2HEAT

The following table presents an overview of the specifications of Push2Heat HUT technologies.

Table 2 Push2heat HUT technologies specifications

		SPH	ENERTIME	BS NOVA	QPINCH
Refrigerants/ Working fluid		HFOs (R515B, R1233zd, R1336mzz-Z, …) HCs (R600 butane, R601 pentane)	HFOs (R1234ze(E), R1233zd(E))or Natural refrigerant (alkanes)	H_2O/LiBr (refrigerant being pure H_2O)	Refrigerant: H2O Absorber: phosphoric acid (H3PO4)
Range of operational temperatures	Source	10-120 °C	> 30 °C	>70 °C *	>80° C
	Sink (upgraded heat)	100-165 °C	typically from 90 °C to above 200 °C	Up to 150 °C	Up to 210° C
	Sink (heat rejection)	na	Na	< 40 °C	<40° C
	Range of ΔT_{lift}	20-120 K	35-120 K directly	20-60 K	40-100 K
Range of capacities		0,3-1,5 MW per Heat Pump, Up to 10 MW per Installation	3-15 MWth per Heat Pump	0.1 - 0.6 MW / unit	0.5 to >10 MW / unit
Compressor type		Piston compressor	Turbo compressors (Enertime OEM)	na	Na

* Minimal heat source temperature for low-temperature sink with 20˚C limits can be shifted depending on the other conditions and application

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	SPH	ENERTIME	BS NOVA	QPINCH
Specific investment cost (EUR/kWth)	300 - 1000	600-1200	300 - 1000	1000-2000
Expected lifetime	>20 years	>20 years	>20 years	>20 years
Efficiency	COP: 1,5 - 8	COP: 2 – 5	Thermal: 45-48% Elect. COP: 70 - 100 (only AHT) Elec COP (whole system): 25-30	Thermal: 45-48% Elect. COP: 70 - 100 (only HP) Elect. COP (whole system): 25-30

6. Techno-economic feasibility of HUTs in several countries

This section presents an analysis of the potential feasibility of the HUTs in the countries considered in the proposal stage for potential industrial demo sites.

Table 3 shows the country-dependent parameters employed in the calculations. All costs refer to the status in 2024.

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Table 3: Costs refer to the status in 2024 for Germany, Italy, Belgium, and Spain

	Gas price [€/kWh]	Electricity price [€/kWh]	Electricity-to-gas cost ratio	CO_2 emission factor (gas) [tn CO_2/kWh]	CO_2 emission factor (elec) [tn CO_2/kWh]	CO_2 emission price [€/tn CO_2]
Germany	0.047	0.076	1.62	0.000202	0.000287	90.8
Italy	0.042	0.119	2.83	0.000234	0.000247	94.2
Belgium	0.03	0.07	2.33	0.0002	0.000178	150
Spain	0.052	0.109	2.10	0.000182	0.000217	90.74

Given the previous country-dependent parameters, Table 4 shows the minimum waste heat temperature each technology needs to reach 120 °C and 150 °C on the heat sink (process heat) for a thermal demand of 1 MW. From a technical point of view, some technologies can work with lower waste heat temperatures. Still, a maximum payback period of 4 years has been fixed to ensure short-term investments, which are more likely to be introduced in the industry.

The first row of each country corresponds to the minimum waste heat temperature to operate the VCHP with a return period of less than 4 years. A further restriction has been considered on the second row, as the minimum thermal COP in practical TDHPs is 0.4. Thus, this second row represents the minimum waste heat temperature to obtain a maximum payback period of 4 years and a minimum thermal COP of 0.4 with the TDHP. In all the scenarios, the electrical COP of the TDHP has been fixed at 25, so only the thermal COP is shown.

This analysis has included different aspects: the operating temperatures, the industry location, and the size of each technology. The investment cost (CAPEX) was obtained from a correlation from IEA HPT Annex 58 [18] for VCHPs, and the characteristic equation method was used for the TDHPs [27]. The most relevant economic indicators are the return on investment (ROI) and the simple payback period.

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Table 4: Performance of HUTs for a thermal demand of 1 MW

1000kW process heat production										
	Twasteheat [C] to reach 120C		VCHP				TDHP			
	VCHP	TDHP	CAPEX [k€]	ROI [%]	Payback [years]	COP	CAPEX [k€]	ROI [%]	Payback [years]	COPt
Germany	47.5	-	796.1	27.6	4	2.44	-	-	-	-
	-	75	796.1	41.8	2.57	3.93	1,021.1	46.8	2.28	0.40
Italy	69.3	-	796.1	27.7	4	3.49	-	-	-	-
	-	75	796.1	31.8	3.44	3.93	1,021.1	45.1	2.37	0.40
Belgium	54	-	796.1	27.7	4	2.68	-	-	-	-
	-	75	796.1	38.1	2.84	3.93	1,021.1	43.1	2.49	0.40
Spain	57.3	-	796.1	27.7	4	2.82	-	-	-	-
	-	75	796.1	39.2	2.75	3.93	1,021.1	48.8	2.18	0.4
	Twasteheat [C] to reach 150C		VCHP				TDHP			
	VCHP	TDHP	CAPEX [k€]	ROI [%]	Payback [years]	COP	CAPEX [k€]	ROI [%]	Payback [years]	COPt
Germany	72	-	796.1	27.6	4	2.44	-	-	-	-
	-	89	796.1	35.9	3.03	3.12	1,016.6	47.1	2.27	0.40
Italy	95.5	-	796.1	27.7	4	3.49	729.9	63.2	1.66	0.46
	-	89	796.1	23.2	4.82	3.12	1,016.6	45.3	2.36	0.40
Belgium	79	-	796.1	27.8	4	2.68	-	-	-	-
	-	89	796.1	32.4	3.38	3.12	1,016.6	43.3	2.48	0.40
Spain	85.5	-	796.1	27.7	4	2.82	-	-	-	-
	-	89	796.1	31.7	3.46	3.12	1,016.6	49.0	2.17	0.4

For temperature lifts above 50 K, VCHPs have a wider operating range and can perform better. For instance, in Germany, a waste heat temperature of 47.5 ˚C is enough for a VCHP to reach 120 ˚C, whereas 75 °C is required with a TDHP. However, if the waste heat temperature is high enough to reach a reasonable performance with TDHPs (COPt > 0.40), shorter payback periods and higher ROI values can be achieved compared to VCHPs. However, TDHPs also require heat dissipation to the ambient and higher amounts of waste heat.

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Table 5: Performance of HUTs for a thermal demand of 500 kW

500 kW heat production										
	Twasteheat [C] to reach 120C		VCHP				TDHP			
	VCHP	TDHP	CAPEX [k€]	ROI [%]	Payback [years]	COP	CAPEX [k€]	ROI [%]	Payback [years]	COPt
Germany	54.2	-	447.8	27.7%	4	2.69	-	-	-	-
	-	75	447.8	37.3%	2.91	3.93	766.2	31.0%	3.54	0.40
Italy	74	-	447.8	27.7%	4	3.85	837.0	27.2%	4.07	0.37
	-	75	447.8	28.3%	3.91	3.93	766.2	29.8%	3.69	0.40
Belgium	61	-	447.8	27.7%	4	3.00	-	-	-	-
	-	75	447.8	33.9%	3.22	3.93	766.2	28.5%	3.88	0.40
Spain	62.5	-	447.8	27.6%	4.01	3.08	-	-	-	-
	-	75	447.8	34.9%	3.12	3.93	766.2	32.3%	3.39	0.40
	Twasteheat [C] to reach 150C		VCHP				TDHP			
	VCHP	TDHP	CAPEX [k€]	ROI [%]	Payback [years]	COP	CAPEX [k€]	ROI [%]	Payback [years]	COPt
Germany	79	-	447.8	27.6%	4.01	2.68	-	-	-	-
	-	89	447.8	31.9%	3.44		763.2	31.1%	3.53	0.40
Italy	100.5	-	447.8	27.6%	4.01	3.85	521.3	44.2%	2.43	0.48
	-	89	447.8	20.4%	5.48	3.12	763.2	29.9%	3.68	0.40
Belgium	86.5	-	447.8	27.7%	4	3.00	1,089.7	19.3%	5.8	0.30
	-	89	447.8	28.8%	3.84	3.12	763.2	28.6%	3.86	0.40
Spain	88	-	447.8	27.6%	4.01	3.07	842.0	29.3%	3.76	0.37
	-	89	447.8	28.1%	3.93	3.12	763.2	32.4%	3.37	0.40

Table **5** shows similar results, although for a smaller scale of 500 kW upgraded heat with the HUTs. Like before, VCHPs show a wider operating temperature range, except for Italy (due to the high electricity-to-gas cost ratio). As the capacity decreases, the specific CAPEX of both technologies increases. This aspect is more marked in TDHPs. In countries with a lower electricity-to-gas cost ratio, the payback is always better with VCHPs, and the opposite is that if the cost ratio is high, the payback is better with TDHPs. The economic feasibility is very dependent on the energy costs, and for this reason, the results should be treated with caution and analyzed case-by-case for other industries.

7. Identified sectors and processes of interest for HUT integration

The principal processes in which the PUSH2HEAT heat upgrade technologies work are within those considered low-temperature processes.

According to the classification by Arpagaus et al. (2018) [10], VHTHPs (compression heat pumps) provide heat until 160 °C. In recent years, research has been done on ever-higher temperature levels for revalued heat, but the focus in this section will be mainly on the objective temperature range of the PUSH2HEAT project: 90 °C to 160 °C. Regarding thermally driven heat pumps, the absorption heat transformer can upgrade heat until approximately 160 °C and the thermochemical heat transformer until 210 °C.

Figure 19 shows the heat consumption in two different temperature ranges per industrial sector in the EU. Focusing on the objective temperature range of Push2heat, the major heat consumption comes from the Food and Tobacco, Non-metallic minerals, Iron and steel and Chemical sectors.

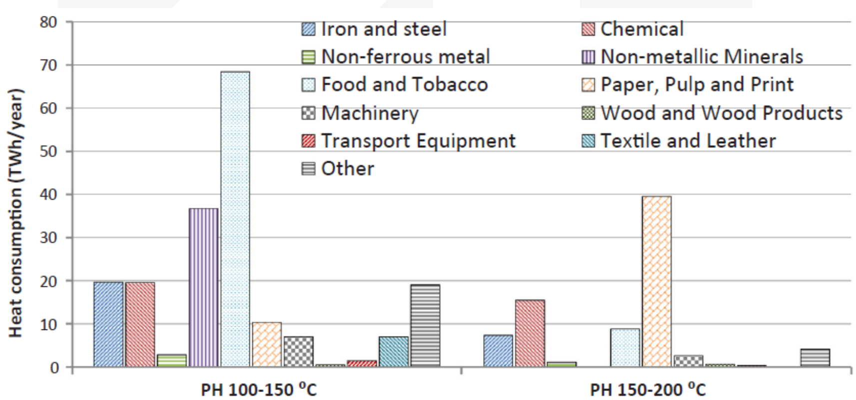

Figure 19. Heat consumption at two different temperature ranges per sector (Source: [28]**)**

Heat upgrade technologies in the range of 90 to 160 °C are of interest, especially in industries like the following ones:

- Chemical and pharmaceutical;
- Pulp and paper;
- Food and drinks;

- Refineries;
- Non-metallic mineral;
- Iron and Steel;
- Non-ferrous sectors.

Figure 20 lists processes in different sectors where HTHPs can be implemented. The processes are classified according to their temperature range.

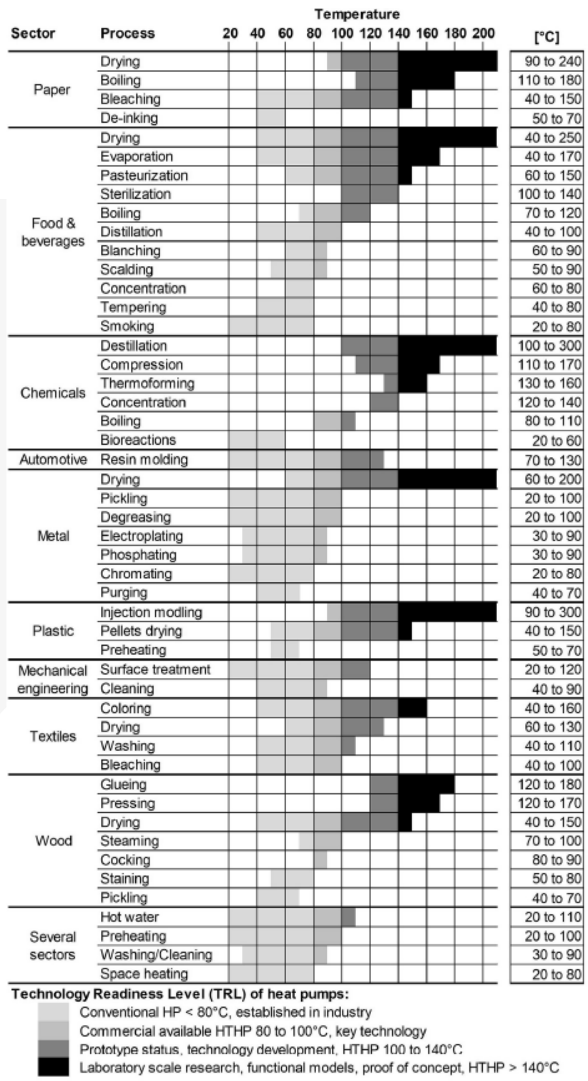

Figure 20. Processes in different industrial sectors structured by typical temperature ranges and Technology Readiness Level (TRL) of heat pumps in 2018 (Source: [10]**)**

7.1. Paper sector

As previously described, the pulp &paper sector is among those considered to have major potential for HUT integration. There are many pulp & paper plants in Europe with a significant annual excess of heat discharged into the atmosphere as water vapor. The analysis of this industrial sector is of great importance, in addition to the fact that some of the main companies in the industry are located in Europe. Below are the possible waste heat sources, processes of upgraded heat injection, and possible integration options.

Waste heat sources

The most energy-intensive process steps in the pulp & paper sector are the production of pulp and the further processing of this semi-finished product to the paper web. As steam is widely used in the paper industry, many waste heat recovery opportunities come from this heat carrier. For instance, steam from the cyclones could be used to separate the pulp from the vapor during the pulping process.

Another important waste heat carrier is the exhaust air from the paper machine. As can be observed in the Sankey diagram of Figure 21, a large proportion of energy comes out of the paper machine in the form of hot exhaust air. This energy is normally recovered to heat the supply air to the drying machine, process water, or space heating [29]. Still, extra waste heat can be used to feed HUTs to reevaluate another process stream.

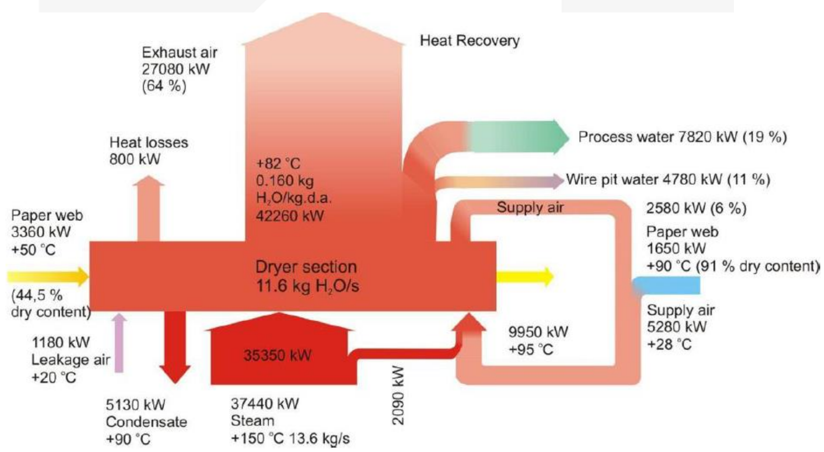

Figure 21. Sankey diagram of a paper machine (Source: [30]**)**

Possibilities for upgraded heat injection

Different possibilities exist for the upgraded heat that HUTs can produce. Steam generation by HUTs is considered one of the best options for the paper industry. The steam needs in the sector are described in D2.5 (Public Report in Push2Heat project, [31]). Some of the processes requiring steam in the pulp & paper sector are:

- Steam for cooking the pulp in chemical pulping processes (temperature: 130 to 150˚C).
- Heating with steam is used to recover the chemical content of the pulping process.
- Pulp drying with steam in non-integrated pulp mills.
- Heating of the pulp with steam in the bleaching process.
- Thermal drying with steam in the paper machine.

HUTs can produce low-pressure steam and, if needed, recompress it to a higher pressure using thermocompressors or mechanical vapor recompression (MVR). Thermocompressors are often used in the paper drying process, and they can be integrated to use exhaust vapor from separators [30].

Other opportunities apart from steam generation include heating water streams in processes and drying wet fuels or sludge.

Possible integration schemes

After analyzing the possible waste heat sources and upgraded heat injection opportunities, some options for integrating HUTs into the pulp & paper sector are described below.

Heat pump integrated into the drying machine of a paper plant

Figure 22 shows a possible integration scheme of a HTHP in the drying machine of a paper plant. The HTHP uses the exhaust air after preheating, producing steam which, after recompressing, is fed into the cylinders of the paper machine.

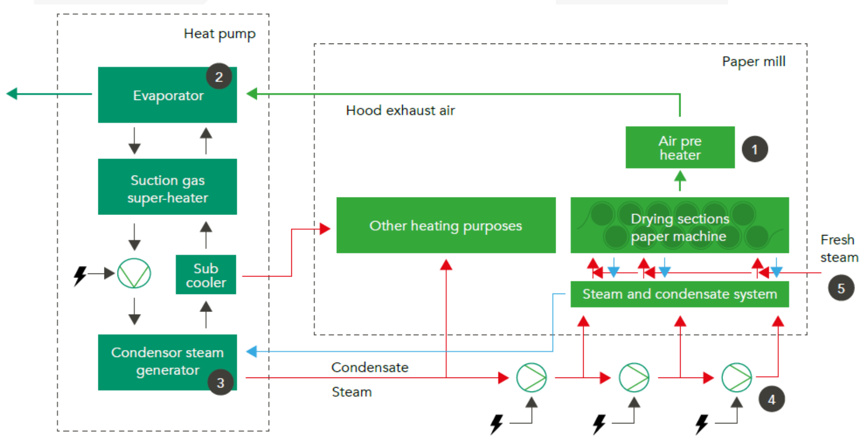

Figure 22. Possible integration scheme of a HTHP in a paper machine (Source: [32]**)**

Another scheme for integration of HUTs into the paper production process is shown in Figure 23 [33], including different pressure levels and the integration of thermal storage. The joint paper between CEPI and EHPA considers the inclusion of different types of thermal storage (hot water buffer tank, steam accumulator) into these kind of systems, in order to cope with the flexibility needed by the process.

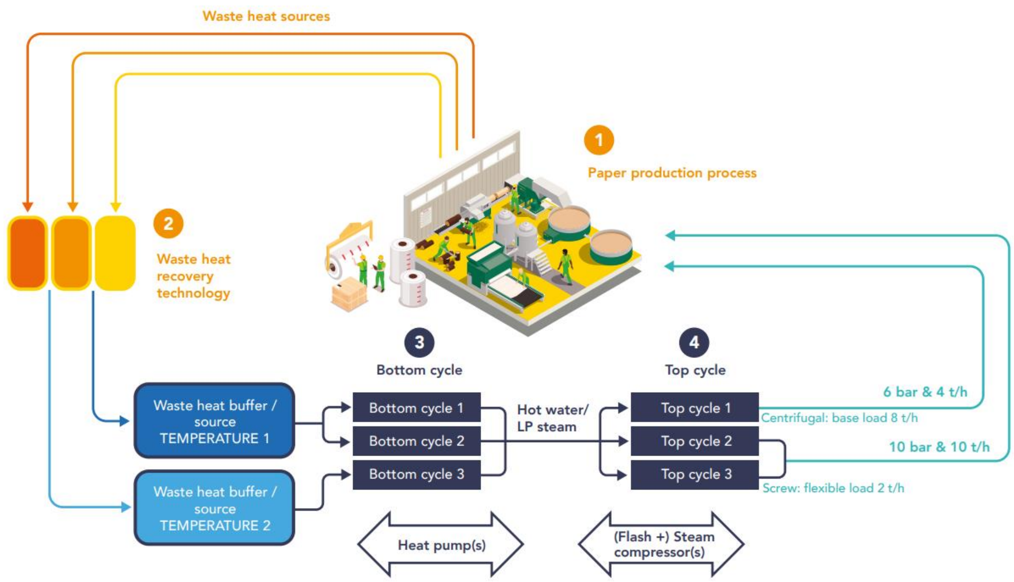

Figure 23. Scheme of integration of HTHPs into paper production process, including mechanical vapor recompression and thermal storage [33]

7.2. Chemical sector

Within the industrial sector, the biggest energy consumers in the EU in 2021 [34] were the chemical and petrochemical industry, the non-metallic minerals industry and the paper, pulp and printing industry. The three sectors with the highest final energy consumption were the chemical and petrochemical industry (2,159 PJ or 21.5 % [35] of the total final energy consumption in industry in 2021 in the EU)

This makes the need for change in the sector even more critical than in others. Greater resource use, especially when dealing with large quantities of energy, represents significant savings, enough to invest in innovation methods. Integrating the technologies described in this document is a promising and effective solution to taking the first steps in this change.

Waste heat sources

- Distillation and vulcanization processes in the rubber and plastic industry.
- Recovery of the sensible and latent (according to the temperatures) heat in the flue gases will heat a fluid (water) for the heat pump on the evaporator side in the plastic industry.
- Cooling compressors waste heat.
- Heat recovery from chillers for air conditioning.

Possibilities for upgraded heat injection

- Drying flows of process fluids. Industrial drying processes can be employed to produce high-quality steam.
- Steam generation for pharmaceutical companies [36]

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- Heat the diathermic oil in the plastic industry. In this sector, hot oils (also known as thermal fluids, heat transfer fluids and diathermic liquids) are mainly used for the following applications and purposes (see Table 6)

Table 6: Hot oil applications in plastics processing (Source: [37])

APPLICATION	PURPOSE
Blow molding	Barrel Cooling
Injection molding	Mold temperature control
Extrusion	Barrel Screw Heating and Cooling
Lamination (Composites)	Coating, Drying
PET Crystallization	Drying
Rubber	Drying and Curing

Possible integration schemes

In the rubber and plastic industry, there are processes where heat can be recovered using the HUTs of the Push2Heat project. One such process involves recovering both sensible and latent heat, depending on the temperatures available in the flue gases [38]. This recovered heat can be utilized to heat a fluid, typically water, on the evaporator side of a heat pump in the rubber/plastic industry. For instance, this waste heat could be employed in the diathermic oil heating process. The integration of the HUT can replace additional equipment, such as a secondary boiler.

In this industry, diathermic oil is used as the primary heat source. It is usually used to produce steam required for certain processes, provide hot water for heating systems during startup phases, and space heating and domestic hot water.

A prior heat recovery setup (waste heat recovery as depicted in the diagram) enables the retrieval of sensible and latent heat from the flue gases, preheating the process water before it enters the HTHP.

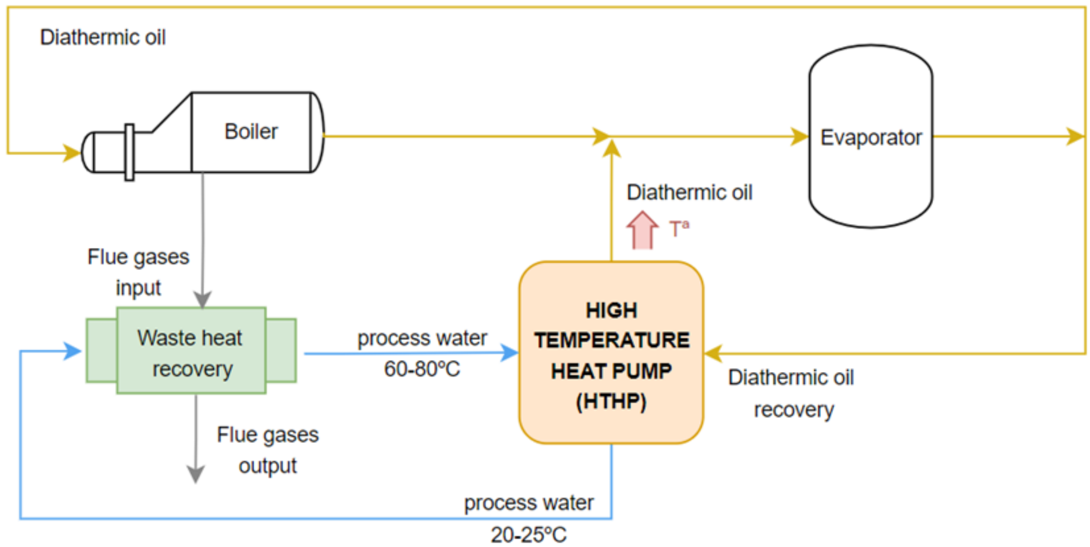

Figure 24: Integration scheme of a HTHP in chemical industry (Source: [39])

Figure 11 shows another possible integration scheme: a heat pump system is integrated to recover waste heat in the dyeing industry. The HTHP elevates the temperature of the dyeing liquid, thereby substituting the oil-fired heater used for heating crude oil. This concept can be replicated in **chemical fertilizer waste sources.**

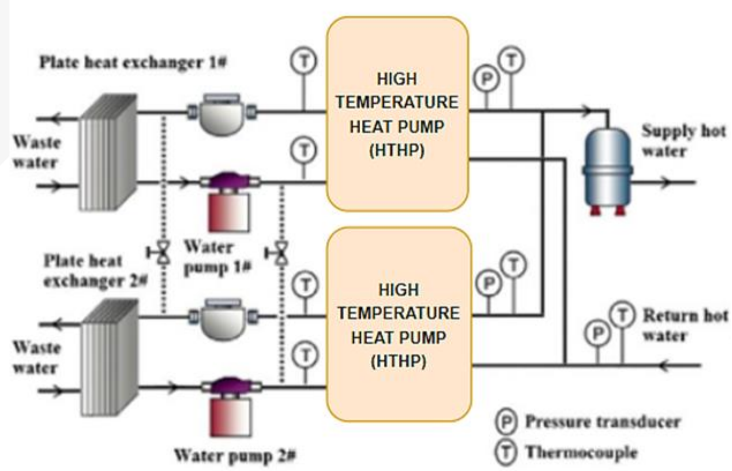

Figure 25: Integration of HTHP system to recover waste heat in the dyeing industry (Source: [40])

The last example presented is steam generation for pharmaceutical companies. The cold heat source is a heat recovery circuit that is transferred indirectly to the heat pumps. The heat pump uses this heat to heat a hot circuit that circulates over a steam generator. The steam generator uses this heat to generate steam that is fed to the plant's steam distribution circuit.

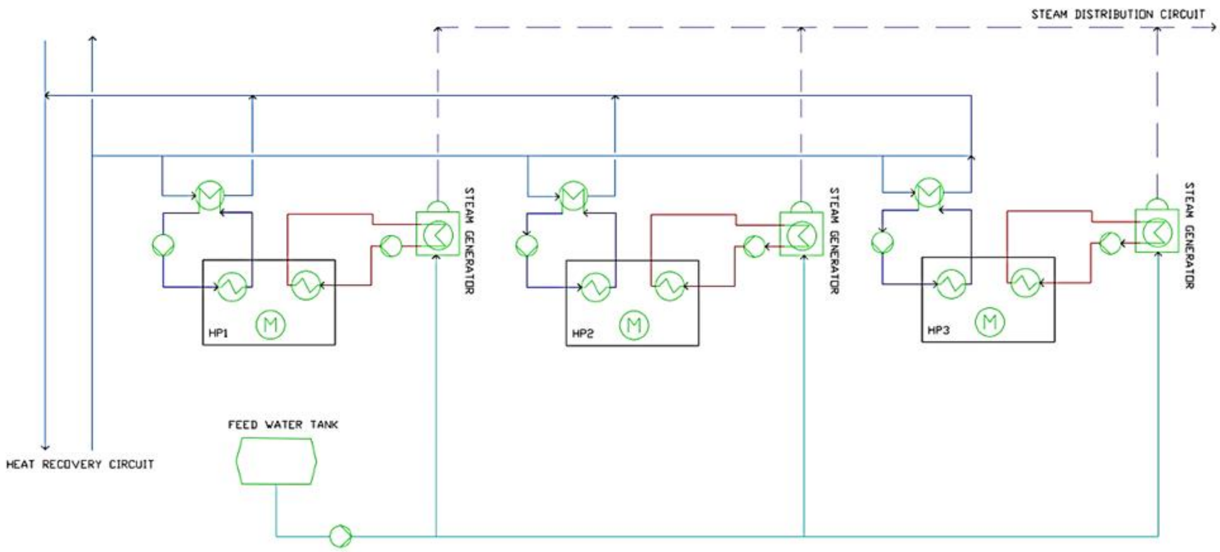

Figure 26: Simplified scheme of the installation of HTHPs in the pharmaceutical industry (Source: [41]**)**

7.3. Food & beverage sector

In today's food and beverage industry, reusing waste heat is paramount. HUTs play a pivotal role by enhancing energy efficiency, reducing costs, and promoting sustainability. By capturing and repurposing waste heat from processes like pasteurization and sterilization, companies can cut energy bills, comply with regulations, and gain a competitive edge through eco-friendly production.

Due to a continuously increasing global population, the demand for food and beverage products and, consequently, their production is expected to remain high in the future. As a result, there is a pressing need to emphasize reducing energy consumption by enhancing the energy efficiency of production processes. Many food manufacturing processes require a heat source, often sourced from the combustion of natural gas. Introducing HUTs in this sector would reduce the use of these types of fuels.

Waste heat sources

Some waste heat sources in the food & beverage industry include:

- The milk production process uses steam or hot water for sterilization and pasteurization, creating waste heat as not all thermal energy is utilized. This flow represents the waste heat source.

- Possibility of waste heat recovering system to generate DHW using the condensed water after the Sterilization-Pasteurization process in the autoclaves [42]
- Waste heat recovered from the vented steam in the legume industry.

Devices designed for heat recovery from venting systems are readily available in the market. The widespread presence of venting streams in all facilities utilizing steam for their operations significantly enhances the potential for waste heat recovery and its feasibility for implementation.

Possibilities for upgraded heat injection

- Pressurized hot water production in a milk production plant. A case study that uses waste heat from ammonia condensers is currently discharged by dry coolers and heat demand for process stream (pressurized hot water) at high temperature (115 °C) supplied by electric steam boilers. [43]
- Sterilization and pasteurization (milk production) [44]
- Pre-heat the combustion air used to produce the fuel-air mixer in baking ovens
- Production of steam in evaporation systems in different industrial processes used for drying, pasteurization, distillation and sterilization processes [43]
- The heat recovered from the vented steam in a legume industry can be used for various processes, such as preheating feedwater for the boiler or providing heat for industrial processes, thereby increasing overall energy efficiency.

Possible integration schemes

Figure 13 displays an overall system of residual heat injection into the HTHP process. It refers to the numerous processes within the food & beverage industry that could benefit from installing these innovative devices in their processes.

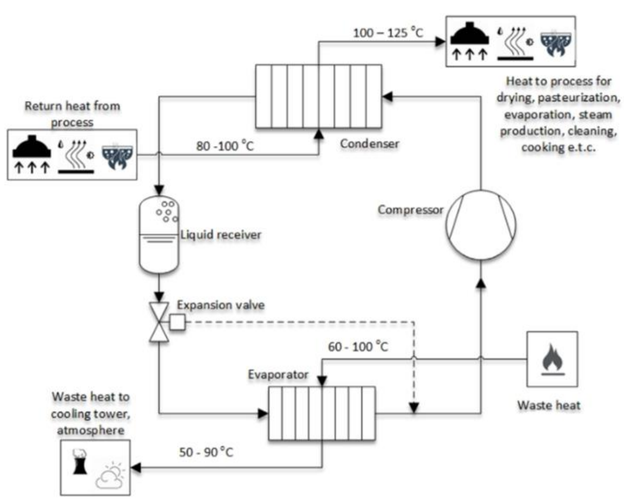

Figure 27: Schematic of a simple HTHP cycle for an industrial process working with waste heat (Source: [45])

An alternative potential application for reusing waste heat, aside from hot water production, involves preheating the air with any of the technologies proposed in this project based on the needs and conditions of the process. This process is also known as combustion air. Preheating combustion air has been successfully tested in other manufacturing industries, transport, and power generation fields.

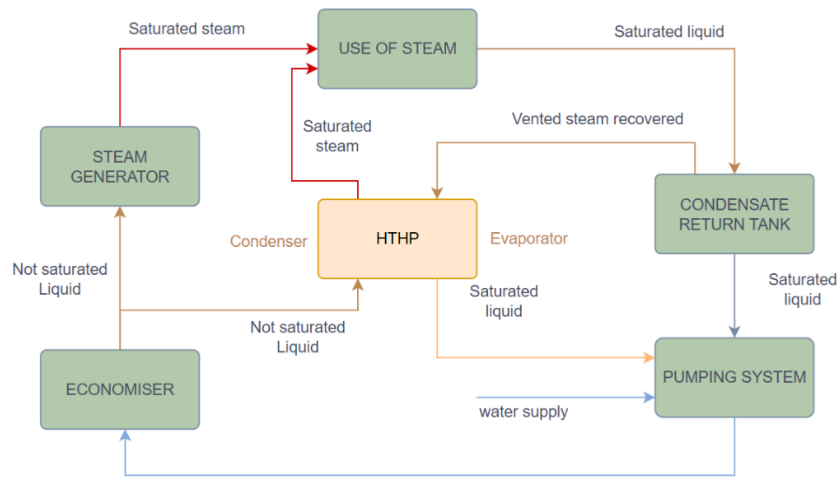

Figure 28: Integration of a HTHP for steam generation recovering WH from the vented steam (legume industry)

In this proposal, the condenser of HTHP is connected to the outlet of the economizer of the boiler (or any other steam generator) before entering the boiler itself. This can be replicated using the pumping system outlet before the boiler's economizer.
Devices for recovering heat from ventilation systems are already available in the market. Venting streams in all facilities utilizing steam enhances the potential and replicability of waste heat recovery.

7.4. Others

7.4.1. District heating

District heating involves generating heat in a centralized location and then distributing it to residences, businesses, and industries in a local area. They present significant opportunities for the efficient, economical, and adaptable utilization of low-carbon energy sources for heating purposes. Nevertheless, the potential for decarbonizing district heating remains largely unrealized, with approximately 90% of the heat generated in district networks originating from fossil fuels. This reliance on fossil fuels is particularly prevalent in the largest district heating markets, notably China and Russia. [46]

Considering the opportunities that this type of network can have and the HUTs presented in this document, it can be regarded as the important role of this kind of system for the recovery of heat in industrial sources that can be reused through these networks. By implementing HUTs, industries can capture excess heat produced during their operations and channel it into district heating networks. This approach minimizes waste and optimizes energy utilization, fostering sustainability in heating infrastructure. For this application, both HUT and Waste Heat to Heat technologies come into play [46].

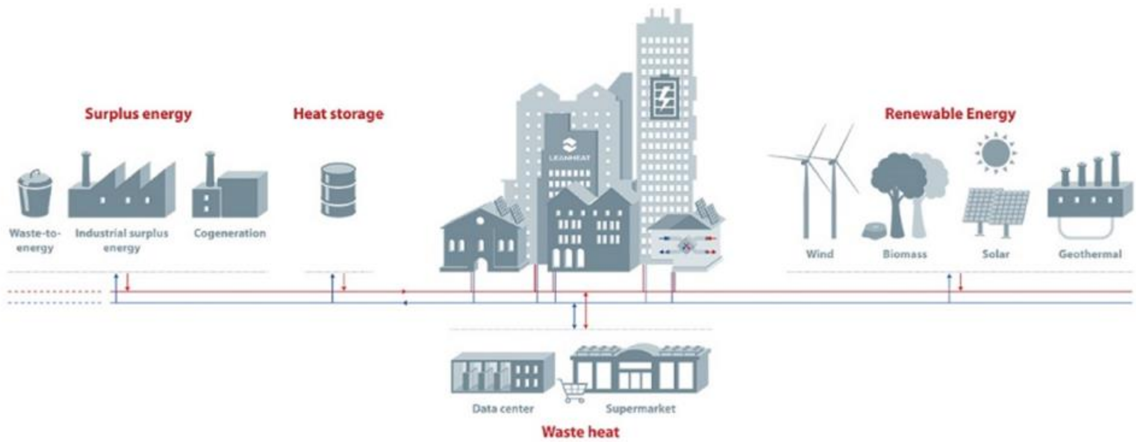

Figure 29: The district energy scheme. Red lines: distribution pipes with supply temperatures; Blue lines: pipes with return temperatures (Source: [47]**)**

In this context, the recovery of waste heat is a key strategy to enhance the efficiency and sustainability of district heating systems. It is important to note that the flow of waste heat can be applied in two ways in a district heating system:

11. **As a source of waste heat.** The district heating system provides a heat source for other applications or processes requiring additional thermal energy. This can be combined with the set of HUTs presented in this document to elevate its temperature and quality. This process allows the heat from the district heating system to be suitable for use in industrial processes that demand energy at higher temperatures.
12. **As a sink of waste heat.** In contrast, when the district heating system receives upgraded heat, it is a destination for excess heat generated by industrial processes or other sources. This upgraded waste heat is transferred to the district heating system to heat the water circulating through the urban heating network. In this case, the district heating system not only provides heating to end-users but also serves as an effective sink for upgraded waste heat, helping to improve the overall efficiency of the system by harnessing this resource that would otherwise be wasted.

Figure 29 presents an example of HUT integration for providing upgraded heat as a sink in a DH network.

This case study was introduced to partially utilize wastewater from Respia in Suji to prevent the depletion of the Seongbok stream and enhance the local scenery. This initiative aimed to reduce energy consumption and actively address the Convention on Climate Change by using unused wastewater energy as a heating source by installing and managing relevant facilities. [48]

Respia in Suji's district heating system provides steam at 100-110ºC to satisfy the heating demands of the Yong-in area via a boiler system. After circulation, hot water at 50ºC is recovered and returned to the boiler heat exchanger. The facility covers 124,573 m² and is situated 2 km from the heat source in Yong-in. Yong-in city planned to release treated sewage from the Suji sewage treatment plant into the upper Seongbok stream to prevent it from drying up and to improve the scenery. A heat pump was installed to use Suji Respia's unused energy as a heat source for district heating, which converts low-temperature, dispersed thermal energies into high-temperature, concentrated energy. The heat pump system can also produce hot and cold water simultaneously or independently. [48]

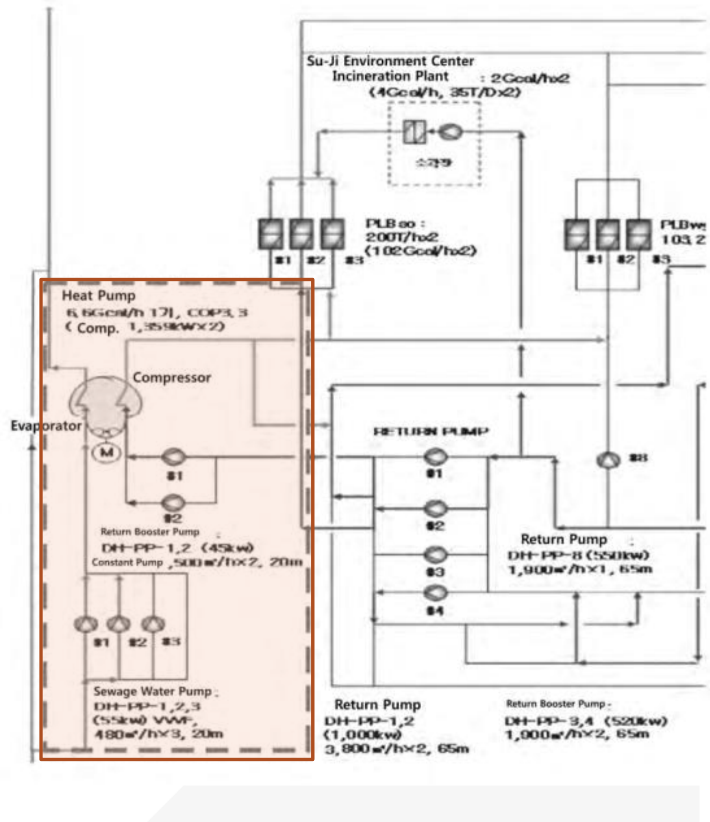

Figure 30: Process schematic diagram after improvement (Source: [48]**)**

Figure 29 shows that the recovered heat from the sewage-releasing place is transferred to the heat pump as a low-temperature heat source. The generated hot water is supplied to the heating demand placed in the Young-in area.

7.4.2. CCU/S

CO_2 capture and utilization/storage (CCU/S) will be vital in reaching climate neutrality and tackling the emission goals. The most developed post-combustion technology is an absorption process using amine or potassium carbonite. [49]

One of the main disadvantages of amine-based carbon capture (CC) technologies is the high energy consumption to drive these processes. Energy consumption varies between 2.5 to 4.0 GJ/ton CO_2 captured, which equals around 1.2 kg to 1.9 kg of steam per kg of CO_2 captured. In the absence of renewable heat, this will bring a significant extra CO_2 load, also known as the parasitic CO_2 load. If this heat is provided by natural gas to drive the CO_2 plant, an additional 30% of CO_2 needs to be captured. The specific energy consumption and operational costs can be significantly reduced by recovering waste heat from this process. An important benefit is a possibility of reducing the nominal load on which the CO_2 capture plant is being designed, leading to significant savings on capital investment.

A process flow scheme of a generic amine-based absorption carbon capture process is shown in Figure 31. Flue gas containing CO_2 is first washed & cooled. Next, it enters the absorption tower, where amines absorb the CO_2, resulting in a nearly CO_2-free gas stream that leaves the absorption tower. The CO_2-saturated amine flow is sent to the regeneration tower, where CO_2 is thermally removed from the amines by adding heat to the reboiler of the column (number 4 in Figure 31). The gas stream leaving the regeneration tower contains water and CO_2. Water is condensed in a heat exchanger against cooling water or air to separate it from the CO_2 stream. The pure CO_2 stream leaves the installation towards the next steps, such as compression, liquefaction, utilization or storage.

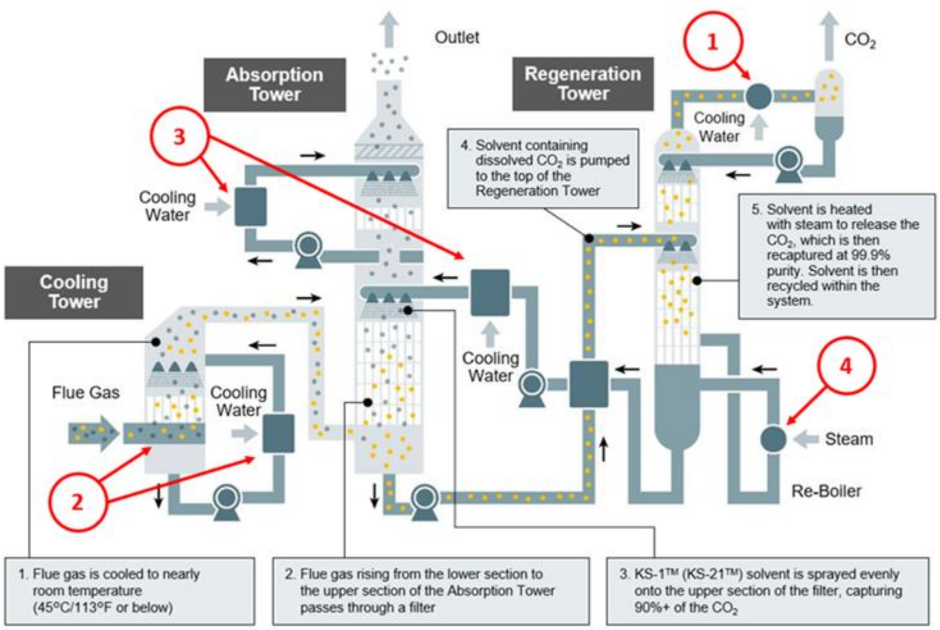

Figure 31: A generic amine-based carbon capture process flow scheme (Mitsubishi Heavy Industries. (n.d.). CO_2 capture technology: CO_2 capture process (Source: [50]**)**

Waste heat sources

Waste heat is emitted from the process at mainly three different spots:

1. From the overhead condenser of the regeneration tower (number 1 in Figure 31) with a temperature of 105 °C at the inlet and 88 °C at the outlet.
2. From the flue gas cooling & washing before entering the absorption tower (number 2 in Figure 31). The flue gas enters at 185 °C and is cooled down to 140 °C against water. Note

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that the flue gas will be further cooled to 45 °C in the flue gas cooling section of the amine CC plant.
3. From the cooling of amines before entering the absorption tower (number 3 in Figure 31). This heat is usually around 50 °C.

Possibilities for upgraded heat injection

The major heat consumer is the separation step in which CO_2 (number 4 in Figure 30) is thermally removed from the amines. This heat sink operates at a temperature of 136 °C. It accounts for almost all energy required per ton of CO_2 captured. Therefore, it is crucial that a carbon-neutral source provides this heat. This is an opportunity for HUTs. By using one or several of the three waste heat sources mentioned above as input, the upgraded heat could be used in the reboiler (number 4 in Figure 31).

8. Real cases. Techno-economic assessment

8.1. Vapor compression heat pumps

8.1.1. HTHP integrated into the recycling industry

Recycling of used materials and raw materials is becoming increasingly important. More and more new processes for recycling waste are being developed and implemented on an industrial scale. In the following process, conventional household waste is converted into a high-quality thermoplastic composite material. For this purpose, household waste, previously considered non-recyclable, is split into its basic components of lignin, cellulose, fibers, and sugar in a complex process and then reassembled into a new matrix, the thermoplastic composite material. This will be used in various applications in the future, e.g., vehicle interiors.

One process step in the production is drying the material. This requires temperatures of around 130 °C.

Boundaries

This project involves constructing the first industrial application to produce the new thermoplastic composite material. Fossil fuel was decided not to be an alternative, so a comprehensive heat utilization concept was developed to bundle various waste heat streams and use them as a source for an HTHP. The integration concept includes multiple cooling and heating circuits at different temperature levels, all of which are interconnected.

Integration

The HTHP is the last link in a series of heat pumps providing thermal energy at different temperature levels. The schematic in Figure 31 shows only a very rough concept focusing on the different heat pumps. In addition to these heat pumps are several other thermal exchangers, such as process heat exchangers or dry coolers for winter relief (delivering cooling water from cold outside temperatures instead of using the chiller) or even buffer storage. The circuit with the lowest temperature operates at 8 °C and is used to cool various process steps. This temperature is generated by a chiller, which condensing heat is used in a water circuit at about 35 °C. This level is used for cooling or heat recovery from warm material and exhaust air streams and preheating material streams. It then serves as a source for a medium-temperature heat pump that raises the temperature level to about 75 to 80 °C. This level, in turn, serves as a source for various process steps and a source for the HTHP. This then provides 130 °C hot water for the drying processes. Approximately 1.5 MW of heating power is required for drying. Two heat pump systems, each with two independent refrigeration circuits, are used here, each with a thermal output of approx. 1 MW, so that only three of the installed refrigeration circuits are in operation at any one time, and one circuit serves as redundancy or can cover power peaks in certain situations.

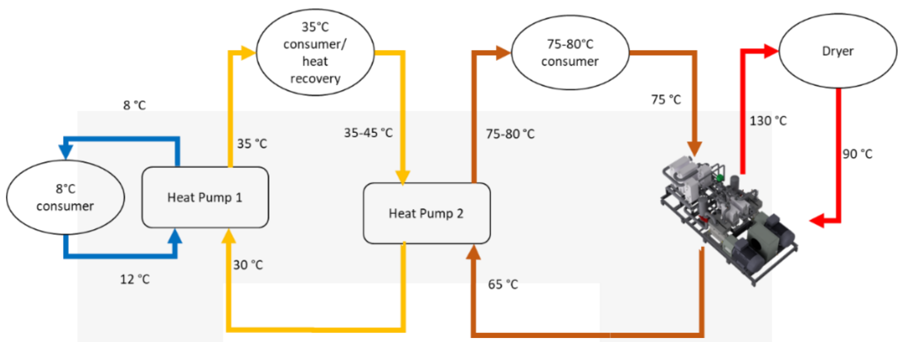

Figure 32. Thermal concept of the combination of cooling and heating circuits

High-temperature heat pump system

Since this application does not use steam as a heat transfer medium but hot water, the setup differs from the system shown in the previous application. Figure 33 shows the circuit diagram for the systems used.

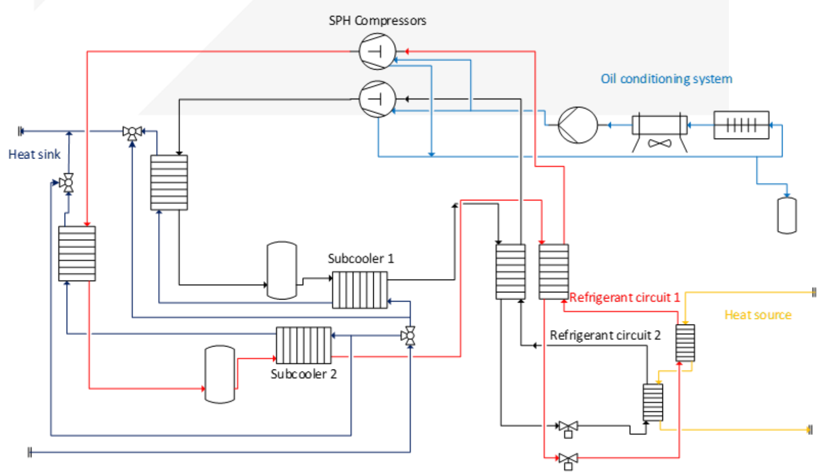

Figure 33. P&ID of the 2-circuit HTHP hot water system (Source: SPH)

The CAD model in Figure 33 shows the compact design with the two compressors on the outside and condensers and subcoolers placed in between. The evaporators are connected in series, and the internal heat exchangers are at the other end. The design data applicable to this application can be found in Table 4. Because of the series-connected evaporators, the two refrigeration circuits operate at different evaporating pressure levels. In the first circuit, the evaporating temperature is about 67 °C; in the second, it is about 62 °C. The condensing temperature, in turn, is very similar in both circuits at about 129 °C. To make optimum use of the large spread in the heat sink, a subcooler was placed downstream of the condenser in each case to subcool the refrigerant further and extract thermal energy. Due to the different evaporation temperatures, the two refrigeration circuits don't have identical power outputs.

To reach 130 °C sink water temperature at the condenser outlet in each refrigeration circuit, different heat sink water mass flows are needed. For this purpose, a distribution valve is integrated into the heat sink water circuit to distribute the water between the two refrigeration circuits. An additional distribution valve in each subpart of the water circuit helps to speed up the warm-up process if the complete water circuit is cold. In this case, only a small part of the flow goes through the subcooler and condenser to reach higher refrigerant temperatures in the condenser. This helps in the warm-up process due to higher temperatures on the high-pressure side of the internal heat exchangers, leading to higher superheat before the compressor and the possibility of higher evaporation temperatures earlier.

In the case of water as a heat sink, the Lorenz COP (2) is often used instead of the Carnot COP to assess the system's efficiency. Here, no individual process temperatures are used as a reference, but the entropic mean temperatures are used.

$$COP_{Lorenz} = \frac{\hat{T}_H}{\hat{T}_H - \hat{T}_L} \qquad (2)$$

The entropic mean temperatures are defined as follows.

$$\hat{T}_H = \frac{\Delta T_H}{\ln\left(\frac{T_{H,o}}{T_{H,i}}\right)} \qquad \hat{T}_C = \frac{\Delta T_C}{\ln\left(\frac{T_{C,i}}{T_{C,o}}\right)} \qquad (3)$$

With T_H, the temperatures are on the heat sink side, and TC is the temperatures on the heat source side.

In this application, the Lorenz COP is 9.6. With a designed and simulated COP of 4,4 for the high-temperature lift from 75 to 130 K, this means a Lorenz quality of approximately 46%. The system has been installed in the first half of 2023.

Table 7. Boundary conditions and simulated performance data for hot water heat pump

Parameter	Value
Heat Source Inlet	75 °C
Heat Source Outlet	65 °C
Heat Sink Inlet	90 °C
Heat Sink Outlet	130 °C
Thermal Output	1,017 kW
Cooling Power	809 kW
Electrical Consumption	229 kW
COP	4,4
Refrigerant	R1233zd(E)

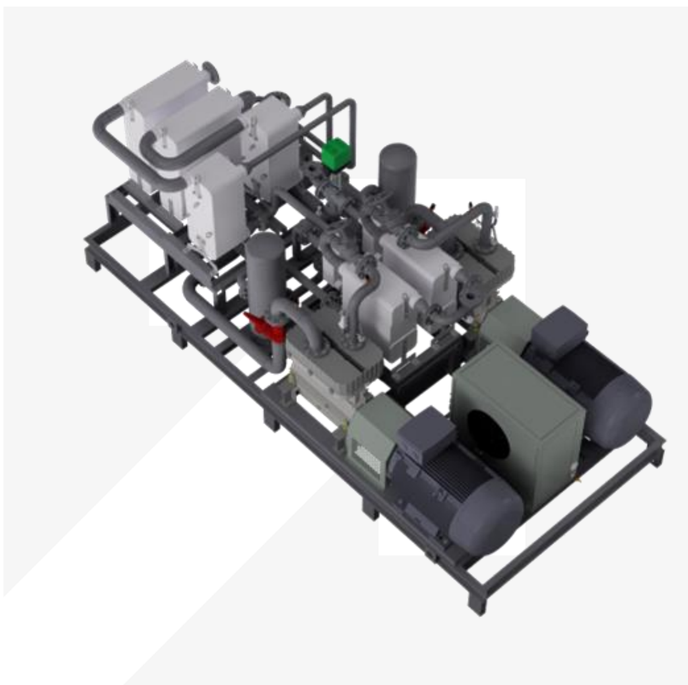

Figure 34. CAD model of the HTHP hot water system (Source: SPH)

Environmental impact

With a planned annual service life of approx. 8,000h, about 10.8 GWh of thermal process energy will be produced in the future. This corresponds to approx. 1.25 Mm^3 of natural gas, which will not be required using the heat pump. As the user consequently follows the principle of sustainability, only CO_2-neutral produced electricity is used in this project, so that approx. Compared to a natural gas-fired process heat production, 2,400 t CO2 per year is avoided yearly.

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8.2. Absorption heat pumps

8.2.1. AHT integrated in a refinery

Within the Indus3Es project [51], a successful demonstration of an AHT integrated into the petrochemical industry was developed. During the project, completed in 2020, an AHT was designed and installed at the Tüpras plant in Izmit (Turkey). All high-security requirements from the refinery, especially for explosive atmospheres (ATEX requirements), had to be considered for its installation.

The Izmit plant demonstrator uses steam from a condensate tank at approximately 100 °C as a waste heat source. This heat is transferred to a closed circuit, which feeds and activates the AHT at approximately 95 °C and is returned at 90 °C to the exchanger, closing the waste heat recovery circuit. On the other hand, the temperature of the stream to be revalued, demineralized supply water, is considered constant throughout the year and equal to 65 °C. Part of the waste heat source is used to preheat the demineralized water from the supply head from approximately 65 °C to 95 °C, to then raise it to 135 °C with the heat supplied by the absorber of the AHT.

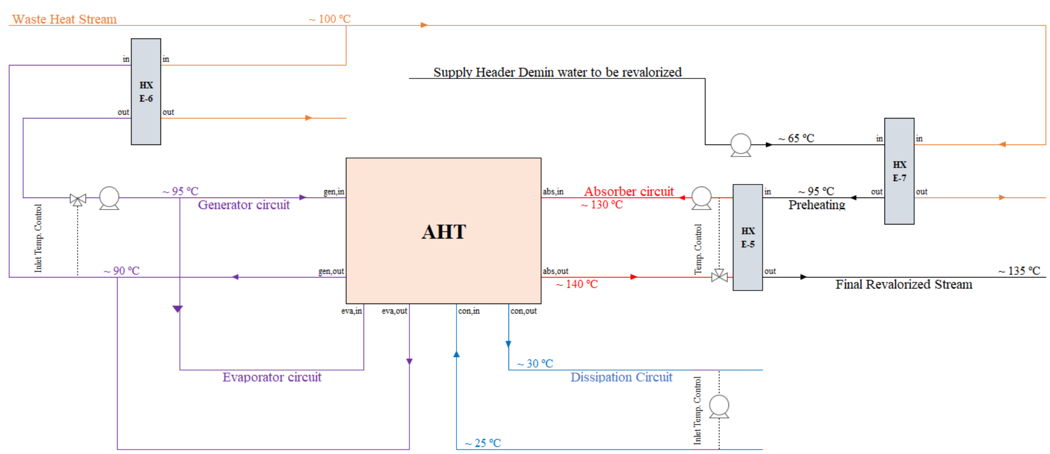

Figure 35. Schematic diagram of the AHT integrated in a refinery in Izmit (Turkey) (Source: [27])

The AHT demonstrated in the Izmit refinery has several innovations:

- Implementation of two adiabatic absorption modes of operation.

The equipment consists of a spray distribution system combined with a drip distribution system with an open tray to promote the adiabatic absorption of water vapor by the saline solution. Laboratory-scale measurements showed that these modes increase the revaluation temperature in the absorber. For demonstration and research purposes, the atomization mode can be turned on or off.

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- Innovative non-condensable gas purge system:

The presence of non-condensable gases drastically reduces the absorption process, which is critical for the AHT behavior. The system developed in the Indus3Es project collects non-condensable gases in a tank through continuous adiabatic absorption. These gases are periodically and automatically discharged into the environment. This solution, which can be considered simple and economical, optimizes the operation of the equipment and reduces maintenance efforts.

- Automatic control based on the "Characteristic Equation":

The control system has been designed especially considering the "Characteristic Equation Method" approach. In addition to procedures for automatic adjustment of optimal operation, new anti-crystallization modes have been considered, which are potentially riskier when compared to absorption chillers.

The equipment was monitored working in the two possible operating modes: non-adiabatic and adiabatic modes. Under nominal conditions, the AHT can revalue up to 198 kW during adiabatic mode, while the complete system, considering preheating, contributes approximately 268 kW. By using the adiabatic distributor, the capacity of the AHT is increased to about 214 kW. The thermal efficiency (thermal COP) of the AHT was approximately 50%.

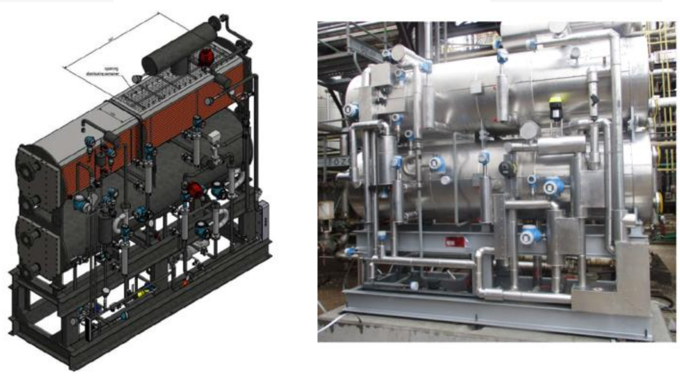

Figure 36. AHT developed in the Indus3Es project: design of the 3D model (left), and installation of the prototype at the Tüpras facilities (right).

Calculation of the relevant KPIs during a 20-year use phase leads to the following results:

- Saved fossil fuel consumption: 49,821,624 kWh
- Primary energy savings in fossil fuels: 51,844,382 kWh of primary energy
- Economic savings in fuel consumption: 1,634,221 €
- Savings in CO_2 emissions: 11,957 tons of CO_2

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The total consumption and the costs related to the operation are:

- Electricity consumption: 3,321,442 kWh
- Primary energy consumption: 6,551,544 kWh of primary energy
- CO_2 emissions: 1,451 tons of CO_2
- Electrical costs: 201,756 €
- Maintenance expenses: 356,840 €

With these results, net consumption and economic savings would be:

- Total primary energy savings: 45,292,838 kWh of primary energy
- Total savings in CO2 emissions: 10,506 tons of CO2
- Total financial savings: 1,752,047 €

8.3. Thermochemical heat pumps

8.3.1. THT integrated into the chemical industry

A commercial example of the Qpinch thermochemical heat transformer (QTHT) is located in the port of Antwerp area at Borealis. In this case, the QTHT transforms low-temperature heat from an exothermic ethylene polymerization (LDPE) reactor and a low-pressure steam vent into valuable medium and high-pressure steam (MPS & HPS).

The LDPE reactor produces over 40 recipes and requires different heat input levels, emitting highly fluctuating residual heat temperatures. To harvest all available waste heat and stably produce MPS or HPS, the QTHT thus has to show great flexibility, reliability and ease of operation.

Three different residual heat sources are combined via an intermediate hot water loop to use as a heat source for the QTHT. This heat is lifted to steam at 3 to 10 bar(g) with an output capacity between 400 kW and 1.3 MW. The unit is installed as an add-on to the reactor setup with minimal integration efforts. This way, close to 50% of the waste heat offered to the unit can be revalued. The integration scheme is shown in Figure 37 below.

Transforming waste heat via the QTHT brings value to Borealis in the following ways:

1. There is a significant direct energy cost saving on MPS and HPS since QTHT steam has marginal OpEx.
2. The CO2 emissions of the site directly decrease since the steam boilers need to produce less MPS and HPS.
3. The QTHT adds to the cooling capacity of the site.

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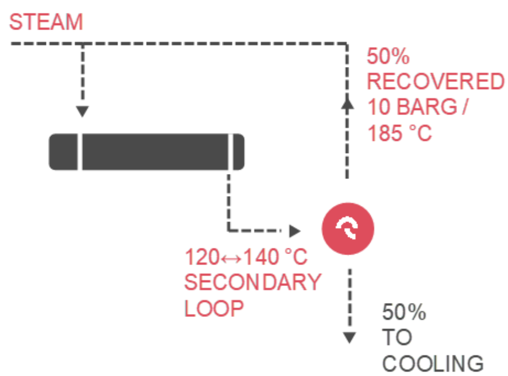

Figure 37. Integration of the QTHT at Borealis (the values in the scheme are given for one of several operating point).[6]

The QTHT unit is installed at the Zwijndrecht site of Borealis with a footprint of 4 x 6 m and a height of 15 m. It can easily be switched on and off without affecting the LDPE reactor operations. The Borealis QTHT is depicted in Figure **38**.

Figure 38**. Qpinch heat transformer at Borealis in Antwerp.**[7]

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