Push2Heat

D.2.5 Process integration and steam production in industrial processes

V0.3

Grant agreement: No. 101069689

From: TECNALIA

Prepared by: Laura Alonso & collaborators.

Date: 15/12/23

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Push2Heat

DELIVERABLE

DELIVERABLE	
Dissemination Level	Public
Type	Report
Due date of deliverable	M15 (December 2023)
Work Package	WP2 Full Scale Development and Optimization of Heat Upgrade Technologies
Task	Task 2.5 Process integration and steam production
Task Leader	TECNALIA
Authors	Jose Luis Corrales Ciganda, Laura Alonso, Mehdi Aminyavari, Francesco Sala, Glenn De Cordt, Dalia Janicki, Bernd Van Den Bossche, Bruno De Jonckheere, Tim Hamacher, Golnoosh Moghtadaei
Type	Report

VERSIONS

No.	Name	Partner	Contribution	Date
V0.1	D.2.5 Process integration and steam production in industrial processes	TECNALIA	First complete draft	20/11/23
V0.2	D.2.5 Process integration and steam production in industrial processes	OST	Review	3/12/23
V0.3	D.2.5 Process integration and steam production in industrial processes	TECNALIA	Final document after review from OST	15/12/23

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

ABBREVIATIONS

AHP: Absorption Heat Pump

AHT: Absorption Heat Transformer

CAPEX: Capital Expenditures

CCS/U: Carbon Capture and Storage/Utilization

CDU: Crude oil Distillation Unit

CHP: Combined Heat and Power

HP: Heat Pump

HTHP: High-Temperature Heat Pump

HUT: Heat Upgrade Technology

MVR: Mechanical Vapor Recompression

OPEX: Operational Expenditures

PM: Particulate Matter

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

SGHP: Steam Generating Heat Pump

UHT: Ultra High Temperature

VCHP: Vapor Compression Heat Pump

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

LIST OF FIGURES

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

PARTNERS

TECNALIA

BS NOVA

SPH

QPINCH

ENERTIME

BONO

TABLE OF CONTENTS

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

1. INTRODUCTION

The use of steam is widespread in many industrial processes, being used in many different sectors and for a variety of purposes. The development of Heat Upgrade Technologies (HUTs), which can deliver steam, can contribute to the decarbonization of the industry, and research efforts in this field have been increasing in the last few years. There are different possibilities for producing steam with HUTs, this will be demonstrated in the PUSH2HEAT project, integrating different HUTs in demonstration sites producing steam. This report presents a general overview of steam generation, distribution, and use in the industry, its use in different industrial sectors, and the status of steam-generating Heat Upgrade Technologies.

Contents of the deliverable

The contents of the deliverable are as follows.

In Section 2, a general view of steam generation, distribution, and use in the industry is presented. The equipment and elements normally used in steam installations are described, and some energy efficiency measures in steam generation and distribution systems are presented.

This section also describes some processes that use steam in different sectors: paper, chemical, food & beverage, oil & gas, carbon capture, etc.

Section 3 provides an overview of how steam can be produced with Heat Upgrade Technologies (HUT). State-of-the-art of steam-generating heat pumps and heat transformers are presented. Also, the methods of producing steam with those HUTs are explained, differentiating between indirect (externally from the HUT) and direct (directly inside the HUT) steam generation. The necessary equipment for steam generation with HUTs is described. Finally, the challenges of steam-generating HUTs and their integration into the processes are presented.

Section 4 discusses the process integration methods, focused on integrating HUTs within the industry.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

2. STEAM USE IN INDUSTRY

2.1 Steam generation and distribution systems

In this section, the steam generation and distribution systems in the industry will be described, focusing especially on saturated steam use. In many industrial applications, steam is the main heat source in production. Nowadays, steam generation is widely a combustion-based process. The cycle starts with water, properly treated through degasification or softening plus osmosis, that is converted into steam inside the boiler.

Generally, we can find two typical circuits in steam networks:

- Closed loop: steam generated is used at several different enthalpy levels down to the condensation of steam into water. This means condensate can usually be used to restart the cycle with a small amount of make-up water (10 to 15 %).
- Open loop: where steam generated is not recoverable, no condensation is possible since steam is somehow injected in the process.

Due to classical design principles, steam is often considered a "cheap" medium to keep a system at high temperature. The electrical consumption related to its distribution is usually low. This leads to a large distribution system that becomes the first user of the steam produced from the boiler. The condensation in pipes is the main cause, and steam trap systems usually have high OPEX costs. The challenge for the energy transition will be to re-think the distribution systems to place the steam generation closer to the final user. Heat upgrade technologies, such as HTHPs, can provide an interesting opportunity since electric power is easier to deliver closer to process steam consumers than gas.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

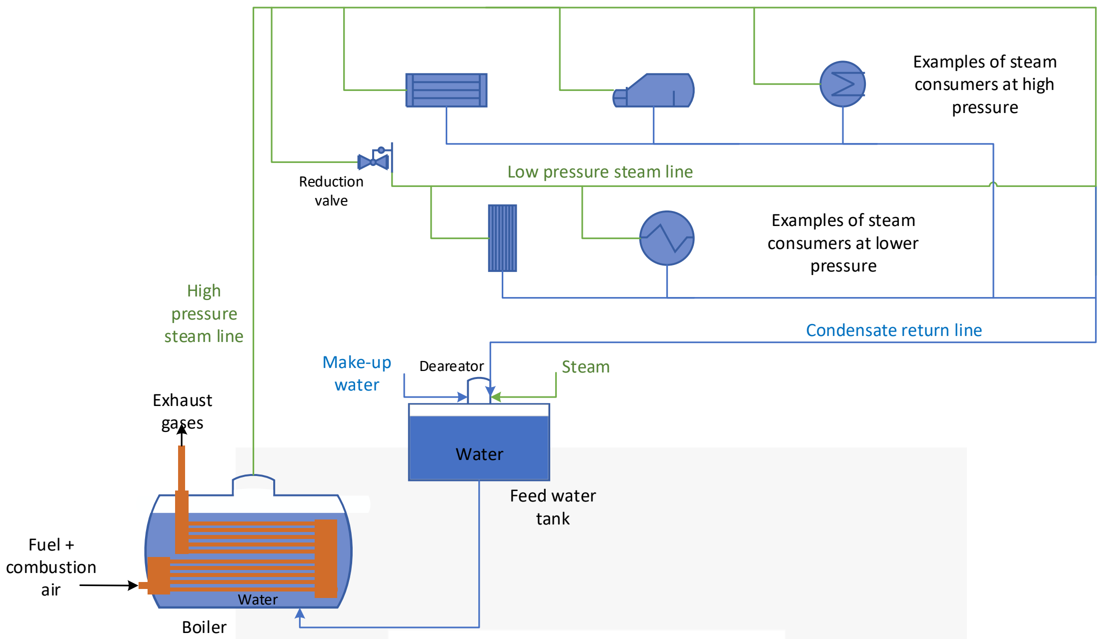


Figure 1. Closed loop steam generation and distribution system scheme.

A typical closed-loop steam installation is shown schematically in Figure 1. The scheme shows a fire-tube boiler (more information in Section 2.1.1 Steam generation) with its water feed tank, the distribution of steam at different pressure levels to the consumers (more information in Section 2.1.2 Steam distribution) and the schematic representation of various steam consumers (more information in Section 2.1.3 Steam consumption in the processes).

2.1.1 Steam generation

Industrial steam is generally produced in a fuel boiler inside a boiler room. The boilers can be pyro-tubular/fire-tube (gases pass inside the tubes) or aquatubular/water-tube (gases pass outside the tubes).

Fire-tube boilers are normally used for saturated steam generation and smaller capacities, although water-tube boilers can also be used for that purpose, due to their higher production cost, they normally will be used for high-pressure and high-capacity ranges. Instead, fire tube boilers have a limited operational pressure (25 to 30 bar) as the water is inside the shell; the higher the pressure, the higher the thickness of the shell and combustion chamber, which leads to limit the technology and cost-effective production. The principal application of saturated steam is heating

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

many different processes by condensing the steam into water, providing the latent heat to the process to be heated (see Section 2.2 Use of steam and needs in relevant sectors). Both water tube and fire tube boilers can also produce superheated steam up to limits indicated by standards for different tube materials, which depend on the operating pressure and creep rupture strength of the material. However, since the principal application of superheated steam is power generation in turbines, the water-tube boilers that can reach higher pressure superheated steam are the most common for this purpose in the industry.

In fire-tube boilers, combustion gases pass inside the tubes, and water is heated and evaporated in the shell side of the vessel. The tube bundle is covered with water, and the steam occupies the upper part of the vessel, feeding the principal steam distribution line. Water is provided to the boiler from the feed water tank. After the steam has released its latent heat to the processes, the condensate returns to the feed water tank. There is also a make-up water entrance to the feed water tank. The feed water tank includes a deaerator, which removes gases from the water, such as O_2, CO_2 or other non-condensable gases, using some steam consumption. Figure 2 shows a scheme of the fire tube boiler and the water feed tank.

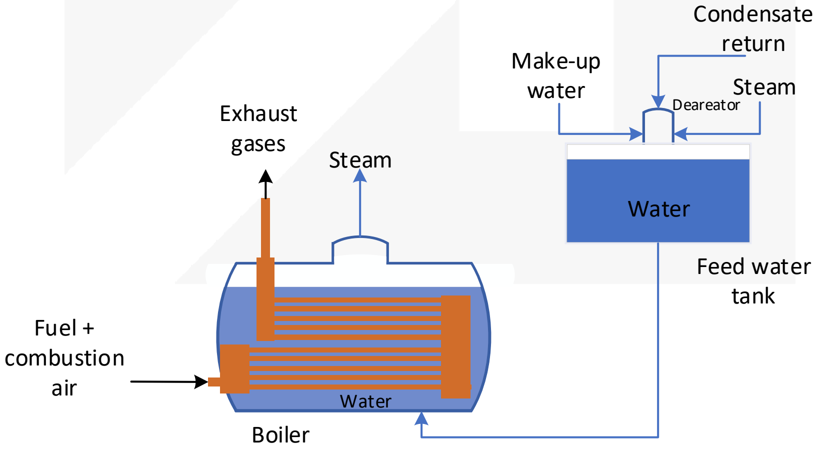


Figure 2. Steam fire-tube boiler and feed water tank scheme.

There are also electrical boilers, which can provide heat to the water using electric resistors inside the boiler shell (resistance boiler) or by means of 3-phase connected electrodes partially

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

immersed in water (electrode boilers). Resistance boilers are more convenient for lower load ranges (up to 5 to 6 MW), and electrode boilers are more economically attractive for higher loads.

Feed water needs to be treated to avoid corrosion on the surfaces of the boilers. A blowdown valve is included at the bottom of the boiler to remove solids and other impurities. A level control system is needed to ensure a constant water level in the boiler and to prevent bare tubes from being in contact with the water. That situation could cause overheating and the failure of the boiler tubes, with the possibility of explosion. On the other hand, if the water level in the boiler is too high, water can be entrained in the steam distribution system.

Industrial boiler feed water external chemical treatment involves the application of various chemicals to enhance the quality and conditioning of the water before it enters the boiler system. This treatment process is crucial for maintaining optimal boiler performance, preventing corrosion, minimizing scale formation, and ensuring efficient heat transfer. The external chemical treatment typically includes the addition of chemicals such as oxygen scavengers, alkalinity builders, scale inhibitors, and pH adjusters. Oxygen scavengers remove dissolved oxygen to prevent corrosion, alkalinity builders maintain the desired pH levels, scale inhibitors prevent the formation of mineral deposits, and pH adjusters regulate the water's acidity or alkalinity. These chemicals are carefully selected and dosed according to the specific requirements of the boiler system, ensuring the water is chemically balanced and conductive for safe and efficient operation. By employing effective external chemical treatment, industrial boilers can operate reliably, efficiently, and with extended lifespan, ultimately contributing to enhanced productivity and reduced maintenance costs.

The feed water to the boiler coming from the deaerator and the water inside the boiler should meet the standards indicated by EN standards for water-tube and fire-tube boilers. Very detailed characteristics of feedwater and boiler water of firetube boilers can be found respectively in tables 5.1 and 5.2 of EN 12953-10:2005 [1]. In contrast, for water tube boilers, similar information can be found in tables 5.1 and 5.2 of EN 12952-12:2005 [2].

Steam has a much higher specific volume than water, but the higher the pressure, the lower is its specific volume. Thus, the steam is generated at higher pressures, and normally, the pressure is reduced at or near the consumption points. This way, smaller steam generators or boilers and

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

smaller diameter steam distribution lines can be used. The steam pressure can be defined based on the maximum temperatures needed in the processes.

Different types of steam are produced depending on their purity grade. A classification from the least pure steam to the purest steam grades is as follows:

- Plant steam
- Filtered steam
- Clean steam
- Pure steam

For instance, the highest purity grade steam is used in food and pharmaceutical applications. Steam can have solid, liquid or gaseous impurities. The solids most frequently found in steam systems are sodium salts. There are several ways of measuring steam purity, such as specific conductance measurement or sodium tracer techniques [3].

2.1.2 Steam distribution

Steam distribution systems start from the outlet of the boiler. There is a principal steam distribution line at higher pressure, and normally, the pressure is reduced near the processes, depending on the specific needs in each case. Distributing steam at higher pressures has the advantage of needing lower diameter tubes for the distribution, with lower heat losses associated. The initial cost of the installation will be lower (smaller pipes, less costly insulation). On the other hand, more fuel will be consumed for heating. The steam pressure is normally fixed based on the maximum temperatures needed in the processes.

Typical equipment in steam distribution networks includes filters, separators and purging systems. The steam distribution pipes have insulation to avoid or minimize heat losses. To size the steam pipes, typical velocities in saturated steam networks are 25 to 30 m/s.

Steam headers distribute the steam to different points of the plant, and then the pressure can be reduced as needed. The high-pressure steam needs pressure-reducing stations near the processes, where it reduces pressure in a valve. A water separator with a condensate purge is used before the reduction valve, and normally, a security valve is installed downstream of the reduction valve.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

When steam is used in the processes, it condenses into water. In direct steam consumption processes, steam is mixed with the products, and thus, condensed water cannot be recovered. However, in indirect steam consumption processes, heat is transferred to the processes by heat exchange surfaces, and the condensate can be recovered in condensate return lines, returning to the feed water tank. This way, the energy contained in the condensates can be used, saving energy in heating the feed water to the boiler.

The steam delivers heat to the processes, but heat is also lost during its distribution over the steam network, and when in contact with colder surfaces (such as in start-ups), the steam condenses into water. The presence of water in the steam distribution lines is detrimental in different ways. The heat transfer is poorer when the steam is not dry [4]. Also, the presence of water can cause erosion in some parts of the system.

Thus, the condensed water must be removed from the lower parts of the pipes to ensure good heat transfer. The ideal situation is to have dry steam. Steam purge systems remove the water and are conducted to the condensate return lines.

In the same way, when the steam transfers its heat to the processes to be heated, it condenses into water. At the outlet of the steam-consuming processes, purge systems are necessary to separate steam and water. This way, all the water goes to the condensate lines.

Different types of purge systems include [4]:

- Thermostatic purge systems are activated by the temperature difference between steam and condensate.
- Mechanical purge systems are activated by the difference in density between steam and condensate.
- Thermodynamic purge systems are activated by the velocity difference between steam and condensate.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

2.1.3 Steam consumption in the processes

Steam can be consumed directly (mixing with the product) or indirectly (via heat transfer surfaces).

Direct steam use

The steam is mixed directly with the product to be heated, transferring its latent heat plus a part of the sensible heat of water. The mass of the product to be heated is increased by the amount of steam consumed in the heating process. This operation is usually made in heating vats and tanks with direct steam injection. Steam can be introduced into the tanks by sparge pipes or by steam injectors.

Some production processes that can make use of direct steam consumption include:

- Textile industry: Steam is utilized in dyeing, bleaching, and fabric finishing, where direct steam injection ensures efficient and uniform heat transfer to achieve desired coloration and treatment effects.
- Pharmaceutical industry: Direct steam consumption is common in sterilization processes of equipment, vials, and other pharmaceutical products to maintain stringent quality standards and prevent contamination.
- Chemical industry: Steam is employed for heating and controlling temperature in various chemical reactions, such as polymerization, distillation, and synthesis processes.
- Canning and food processing: Direct steam is used to sterilize cans, jars, and food containers before filling to ensure product safety and extend shelf life.
- Distilleries and breweries: Steam is crucial for the heating and boiling stages in alcohol production, including mashing, fermentation, and distillation processes.
- Power generation: Steam turbines play a vital role in converting the thermal energy of steam into mechanical power, which drives generators to produce electricity.
- Sterilization of milk and other food products: Direct steam injection is employed in processes such as ultra-high temperature (UHT) pasteurization to ensure proper sterilization and preservation of food products.
- Cooking of food products: Steam plays a crucial role in cooking various food items, ranging from vegetables to baked goods.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

- Anaerobic digestion: Steam is utilized to facilitate the breakdown of organic materials during anaerobic digestion processes, enabling efficient biogas production.
- Rubber vulcanization in autoclave: Steam is essential for the vulcanization process of rubber, improving its strength, elasticity, and durability.
- Heating of tanks in different processes: Steam is employed to heat tanks containing water or other products, ensuring optimal temperatures for specific manufacturing or treatment processes.
- Direct steam injection in the paper industry: Steam is utilized in different stages of paper production, including paper drying, pulp processing, and moisture control.
- Malt mashing in breweries: Steam is used in the mashing process of malted grains during beer production, aiding in enzymatic activity and starch conversion.

Indirect steam use

The heat contained in the steam is transferred to the process indirectly using heat-exchanging surfaces in different types of heat exchangers. When the saturated steam contacts the surface of the heat exchanger, which is colder, it condenses, releasing the latent heat and transferring it to the product to be heated. This way, a great amount of energy is transferred in a short period. The condensed water leaves the heat exchangers and flows to the condensate return line. Normally, the heat transfer is controlled by the temperature of the product to be heated.

Steam can be indirectly consumed in the different types of heat exchangers or equipment:

- Heat exchangers

  Heat can be transferred from steam to heat liquid or gaseous products through different heat exchangers, such as shell and tube heat exchangers, plate heat exchangers or plate and shell heat exchangers. Heat exchangers can also use steam in reboilers to evaporate water or other products.
- Coils

  For instance, coils placed inside tanks need to be heated. Steam passes inside the tubes of the coil, heating the fluid inside the tank.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

- Jacketed heated vessels
  These are vessels with an external jacket covering the vessel, through which the steam flows, transferring heat to the product inside the vessel. They are normally used for cooking purposes.
- Air heating finned coils
  These heat exchangers are built-in coils with externally finned tubes to increase the heat transfer area on the air side. Air is circulated externally using a fan and heated by the steam condensing inside the tubes.

Some production processes that can make use of indirect steam consumption include:

- Chemical industry: Indirect steam use is prevalent in processes that require precise temperature control, such as heat-sensitive reactions, solvent recovery, and crystallization processes.
- Refineries: Steam is utilized in heat exchangers for preheating crude oil and other feedstocks and steam-assisted processes in refining operations.
- Brewery and distillery industry: In producing beer and spirits, indirect steam consumption is used for wort boiling, mash heating, and fermentation vessel temperature control. Steam passes through heat exchangers to heat the brewing and distilling fluids indirectly.
- Paper and pulp industry: Indirect steam consumption is prevalent in various stages of paper production, such as drying, paper machine heating, and evaporation processes.
- Plastic manufacturing: Indirect steam consumption is employed in plastic extrusion and molding processes. Steam passes through heat exchangers to heat the plastic material indirectly, facilitating melting, shaping, and curing.

2.1.4 Energy efficiency in steam generation and distribution systems

Designing, operating, and maintaining steam generation and distribution systems with maximum efficiency is important. Multiple ways of improving energy efficiency in steam generation and distribution systems exist. Some examples of efficient steam and heat recovery measures are described below.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Water preheating by the economizer

An economizer is a heat exchanger which recovers heat from the exhaust gases. This way, the feedwater to the boiler is heated, leading to energy savings. The economizer is installed in the exhaust gases duct or chimney, where the exhaust gases circulate outside a bundle of finned tubes, and the water flows inside the tubes (see Figure 3).

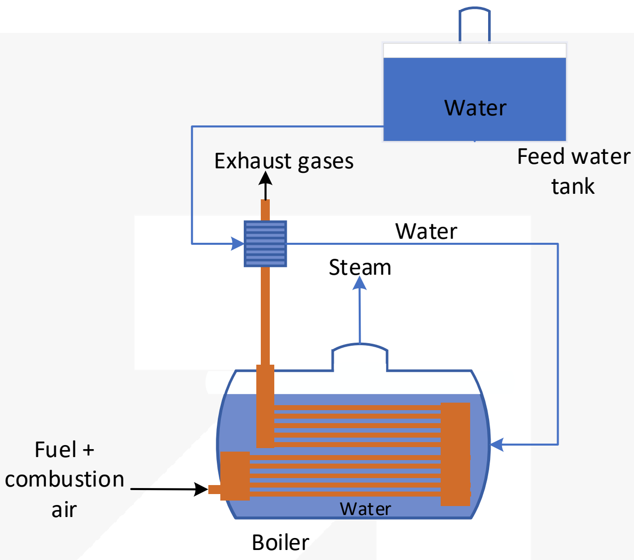


Figure 3 Scheme of an economizer for feedwater preheating condensate return

Returning the condensate to the feedwater tank will yield important energy savings whenever possible. It will also result in savings in treating feed water to the boiler and the direct cost of water. Nowadays, most steam systems include condensate return lines, an effective strategy for improving overall energy efficiency, lowering operational costs, and minimizing environmental impact in steam generation processes.

Combustion air pre-heating

Combustion air pre-heating is a vital technique in steam generation systems to enhance energy efficiency. By pre-heating the combustion air before it enters the burner, the system takes advantage of waste heat and reduces the energy required for fuel combustion. This process

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

typically involves passing the incoming combustion air through a heat exchanger, where it is heated using the waste heat from the flue gases. As a result, the temperature of the combustion air increases, leading to improved fuel combustion and reduced fuel consumption.

Condensate heat recovery through flash steam

The condensate has less energy than steam but is still enough to recover heat. The condensate can be used to generate flash steam. When the condensate lowers its pressure, part of it evaporates again, and this steam can be used in low-pressure steam lines or directly in the processes. The generation of revaporised steam from the condensate takes place in a flash tank, a tank with an inlet of water at a certain pressure, in which the pressure is reduced, and the flashing occurs. Inside the tank, steam and water are at equilibrium. The generated water and steam go out of the flash tank, and steam can be injected into a low-pressure line or used for tasks such as sterilization, pasteurization, and cleaning in food processing, pharmaceutical manufacturing, and chemical processing. Also, low-pressure steam can be used for humidity control in textile manufacturing or for providing thermal energy in drying operations. The higher the difference between the inlet pressure of condensate to the flash tank and the outlet steam pressure, the higher the percentage of steam produced. For instance, saturated condensate at 8 barg, reducing its pressure to 2 barg, can generate 8,4 % of steam.

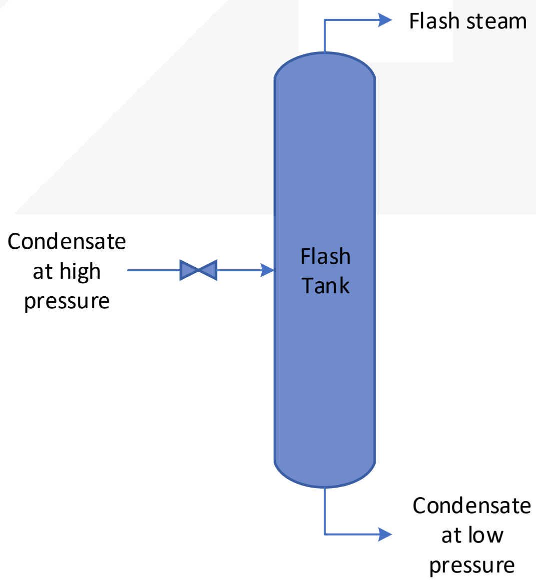


Figure 4 Scheme of flash steam generation

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Heat recovery through thermocompressors

A thermocompressor can be used to boost the pressure of the steam generated, for instance, in a flash tank, to a higher pressure for its use in the processes. The thermocompressor needs high-pressure steam, or motive steam, mixed with low-pressure steam, or suction steam. The result is a medium-pressure steam. Figure 5 shows a simplified scheme of a thermocompressor.

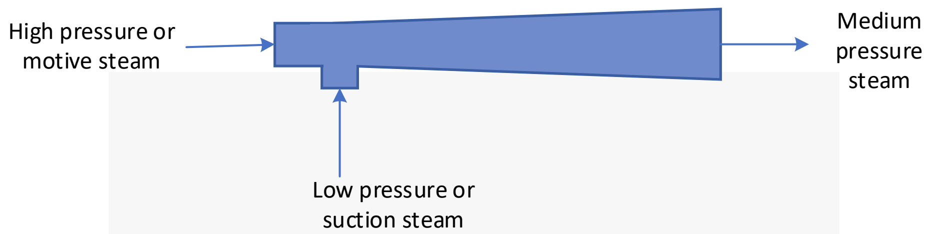


Figure 5. Scheme of thermocompressor

Heat recovery through mechanical vapor recompression

Mechanical vapor recompression (MVR) is another method to enhance the energy efficiency of a vapor distribution system. By recompressing low-pressure vapor using mechanical means, such as a compressor, MVR enables the recovery of waste heat and the utilization of energy that would otherwise be condensed and lost. This technique conserves steam by recycling and raising the temperature and pressure of the vapor, reducing the need for fresh steam generation. Furthermore, MVR improves process efficiency by optimizing heat transfer and minimizing condensate losses. Implementing MVR in a vapor distribution system leads to substantial energy savings, reduced fuel consumption, and a lower environmental impact.

Heat recovery from the boiler blowdown

A heat recovery system can be installed after the blowdown of water from the boiler, which is hot, providing an opportunity to recover heat. Heat can be recovered in different ways, such as:

- Direct heat recovery by a heat exchanger, heating the make-up water.
- Flash the saturated water into steam with a flash tank. The generated flash steam can be used to heat the feedwater tank.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Steam Pressure Optimization

Optimizing steam pressure levels to match the requirements of various processes and avoiding operating at unnecessarily high pressures that increase energy consumption is another way of increasing the system's efficiency. One should implement pressure-reducing valves or pressure modulation controls to maintain optimal pressure levels throughout the system.

2.2 Use of steam and needs in relevant sectors

2.2.1 Paper industry

Around 13 % of the production costs of paper production are energy costs, which makes the paper industry an energy-intensive industry [5]. Paper can be produced based on wood or recovered paper. The most energy-intensive process steps are pulp production and the further processing of this semi-finished product to the paper web.

Steam is widely used in the pulp and paper industry. Some plants do not include power generation and only have steam-producing boilers. Some paper plants include combined heat and power generation installations (CHP). In those cases, high-pressure steam is produced in a boiler (different types of fuels can be used) and medium and low-pressure steam is extracted from the turbine and used mainly in the following processes:

- Process heating (water, wood fibers, pulp, air and chemicals)
- Heating cooking liquor in chemical pulping
- Evaporation of water from kraft and sulfite pulping liquors
- Evaporation of water from the paper (drying)

According to Windholz et al. [6], the potential for steam-generating heat pumps in the paper industry over various European countries accounts for around 6.1 GWth, corresponding to about half of the installed heating capacity in the paper industry.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Steam demands in pulp and paper mills are usually met by low-pressure and medium-pressure steam. Below, the use of steam in the different pulp and paper production processes is described.

Pulping process

The pulping process is made to free the fibers in wood from the lignin and to suspend them into a water slurry that forms the pulp for paper making. There are different ways of pulping, mainly chemical (Kraft or sulfite pulping) and mechanical pulping from wood, and recycled fibers pulping from recovered paper or cardboard.

In chemical pulping, steam is used first to soften the wood chips, then to cook them with different chemicals to get the pulp, usually between 130 to 150 °C.

Chemical recovery

Chemical recovery allows the separation of chemicals from the liquor obtained in the pulping phase to be used for the subsequent pulping process. The first step is the concentration or evaporation of water from the liquor, made by indirect heating with steam, usually in multiple-effect evaporators. Medium-pressure steam is normally used in the evaporators.

Bleaching

The pulp bleaching is applied for white paper production by adding chlorine dioxide, hydrogen peroxide, and/or sodium hydroxide. The pulp is heated with steam before entering the bleaching tower, and the use of steam is affected by the bleaching temperature, which also affects the brightness of the pulp.

Pulp drying

In non-integrated pulp mills, the pulp is dried to reach around 10% water content. This is a highly energy-intensive process, requiring the use of steam.

Papermaking

In the papermaking process, the pulp is prepared and fed into the papermaking machine, which has a wet-end where the paper web is formed and a dry-end where the paper is pressed and dried. Part of the water is removed mechanically by pressing the paper, and the other part is

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

removed using steam-heated rollers. This thermal drying process is the most energy-intensive step in the papermaking process.

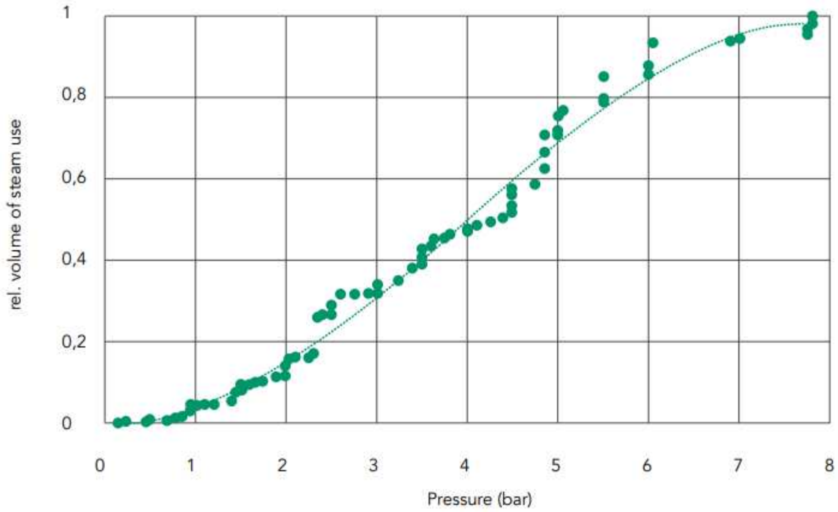


Figure 6. Range of pressures in paper machines [7]

The pressure and temperature of the steam used depend on the steam and condensate system used by the paper mill. Typical steam pressures range from 0 to 8 barg (see Figure 6). In most paper mills, steam pressures are different in each drying section, with low pressures in the first sections and higher pressures in the last drying sections. Pressure levels also fluctuate by a maximum of 20% depending on paper grades and grammages.

Contact drying with steam-heated cylinders is the predominant drying method in paper and paperboard machines. Almost all paper machines around the globe manufacturing paper and paperboard use conventional steam-heated cylinders or multi-cylinder drying configurations. Besides conductive heat transfer between the hot cylinder surface and the wet web, the role of air that is either the drying medium or surrounds the drying atmosphere is very significant. Paper drying is associated with both heat and mass transfer. The heat energy released when steam condenses is transmitted through the dryer shell to the wet paper, constituting the heat transfer aspect of drying. Steam pressure and temperature are the factors that most influence the paper drying operation.

The rolls used are internally heated with steam. Maintaining a uniform temperature across the surface of the roll is essential for making quality products. Since steam is a gas, it fills the entire roll

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

volume and evenly distributes heat as it condenses, which is beneficial for the process. Because the saturated steam has a constant temperature at a given pressure, the operators can set the exact temperature of the steam inside the roll by controlling the pressure.

2.2.2 Oil & gas industry

Refining crude oil and gas has numerous processes in which steam is used. Petroleum refineries use steam mainly for the following processes: stripping, fractionation, power generation, mechanical drive, quenching, dilution, process heating, and vacuum drawing. In refineries, the following steam networks can be found:

- High-pressure steam network (> 30 bar, 350 to 500 °C). This steam is normally used for producing electricity in steam turbines, from which medium-pressure steam can also be extracted.
- Medium-pressure steam network (7 to 20 bar, 200 to 350 °C). This steam is normally used for stripping, atomization, vacuum generation, and process heating.
- Low-pressure steam network (3.5 to 5 bar, 150 to 200 °C). This is normally used in stripping, tracing, and process heating.

There are countless steam-consuming points in a crude oil refinery. Below, some examples of steam use in some of the principal processes which can be found in refineries are described.

Atmospheric crude oil distillation

The primary crude oil distillation unit (CDU) makes the fractionation or separation of crude oil into different fractions according to their boiling range possible. The crude oil is heated before entering the distillation column, separating the lighter fractions in the upper part of the column and the heavier fractions in the lower part. The fractionation towers have reboilers to improve the separation. These reboilers are heated by steam or other process hot streams. Steam is also injected from the bottom of the tower to strip any remaining gas from the liquid coming down the tower.

Vacuum distillation

The heavy fraction from the bottom of the atmospheric distillation unit goes to a vacuum distillation tower to separate the hydrocarbons from the heavy components. Lower pressures allow further separation at lower temperatures, avoiding hydrocarbon cracking and excessive coke formation.

Vacuum distillation towers also include reboilers; some are fed by steam. Steam is also introduced in the tower's lower part, in the strippers, and used in steam ejectors to maintain the vacuum.

Hydrocracking

In this process, the heavy oil products from the vacuum distillation units react in the presence of hydrogen and catalysts. Hydrogenation and cracking reactions occur to produce different products. Steam is used in these processes as a mass transfer medium to ease the removal of lighter products and quenching the reaction.

Hydrotreating

The hydrotreatment removes contaminants or unwanted products, such as sulfur, ammonia, etc., and improves the quality of the fractions by converting olefins into paraffins. This prevents adverse effects on catalysts in other parts of the refinery, such as catalytic reforming or hydrocracking units. The hydrotreatment is carried out with hydrogen and catalysts. Steam is used for stripping and improving the separation of hydrocarbons.

Alkylation

In this process, light products from the cracking operations are converted into alkylates, blending components for gasoline and jet fuels. The processes include catalysts for the reactions. Steam is used mainly for stripping products from the alkylate.

2.2.3 Chemical industry

In the chemical industry, steam is generally used to transfer heat in an economical, reliable, and safe way from one unit process to another.

More than 70% of the chemical industry's primary energy is heat, not electricity. Heat means, in almost all cases, steam. In 2020, the European chemical industry accounted for approximately

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

425 TWh steam demand [8], equivalent to 53 GW full continuously or, expressed in tons of steam, 80 thousand tonnes per hour[1].

Although they use similar unit processes (e.g., distillation), the product differentiation in the chemical industry is enormous compared to oil & gas. Figure 7 gives an overview of the big product branches in the chemical industry. In general, the complete chemical industry is based on four resource building blocks: naphtha, ethane, propane, and methane, as shown in the lower part of the flowchart shown in the figure.

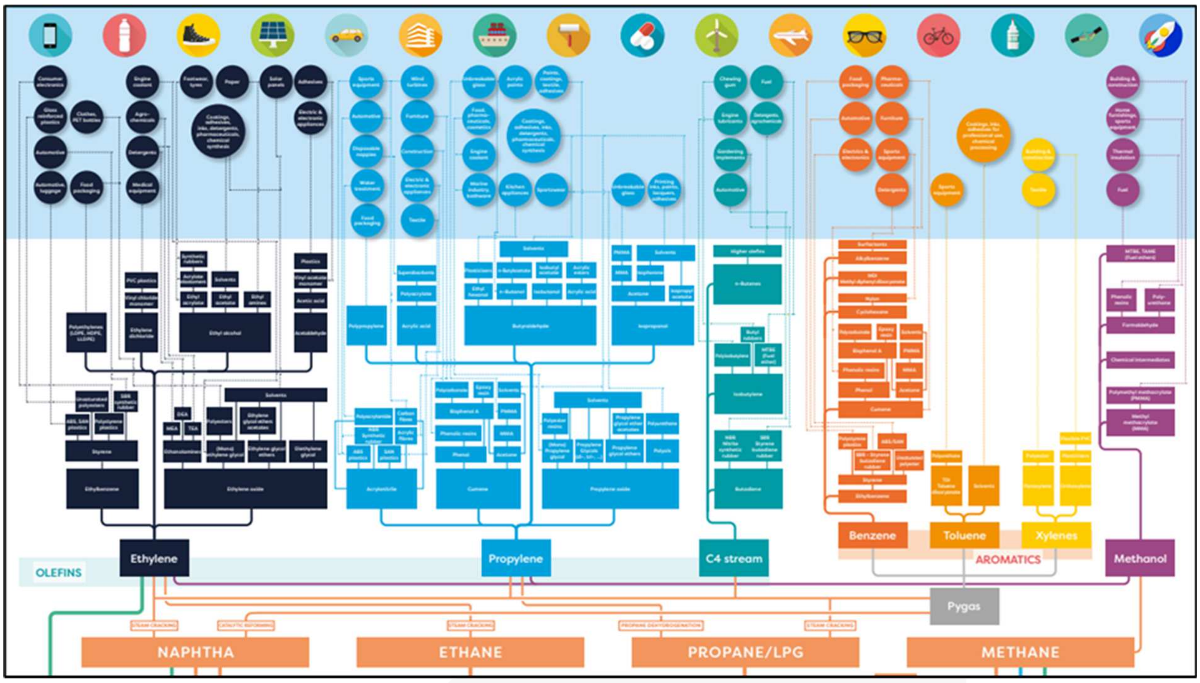


Figure 7. Overview of chemicals produced in the chemical industry. Each line represents a conversion technology. An individual conversion technology is often composed of a set of unit processes [9].

Each building block is generated in a biorefinery, conventional refinery or gas processing unit. From these building blocks, three main branches can be deduced: olefins, aromatics, and methanol. The fertilizer business is closely related to the methanol branch. Other downstream chemicals are, in most cases, derived from one of these three main branches. Each block in Figure 7 represents a

[1] Conversion TWh to GW basis 8'000 hours per year operations. Conversion GW to t/h based on boiler feed water at 100 °C and steam at 20 bar.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

chemical product, whereas each line represents a conversion technology. One conversion technology typically comprises different unit processes, e.g., a distillation column.

Each conversion step can only take place if the thermodynamics can be guided in the right direction, and doing so often requires heating in the form of steam. This relates to another important aspect of Figure 7: the lower the conversion process drawn on the figure, the higher the energy intensity and the bigger the production volumes on a global scale. Thus, in the example given, the conversion of naphtha to ethylene via steam cracking is much more energy intensive (3.5 to 7.0 MWh/ton ethylene) [10] and bigger in production volume (EU: 20 million tonnes in 2020) [11] than the conversion of benzene to phenol (1.9 MWh/ton phenol and 2.7 million tonnes in 2020) [12].

This illustrates the key importance of energy, specifically steam, for the different conversion steps in the chemical industry. Steam consumption in those conversion steps can typically be divided into (a) direct use and (b) indirect use.

Apart from superheated steam expansion over a turbine to produce kinetic energy, direct use of steam occurs in unit operations where steam can not only deliver thermal energy but also contribute hydrogen and oxygen atoms to the chemical reaction taking place. One such key example is the production of hydrogen and/or syngas in a steam methane reformer. If the syngas yield needs to be maximized (e.g., for methanol production), the following energy-intensive reaction takes place:

$$H_2O(v) + CH_4(g) \rightarrow CO(g) + 3H_2(g)$$

Whereas if the conversion of natural gas to hydrogen is maximized, the so-called water-gas shift reaction is additionally pursued, also requiring steam:

$$CO(g) + H_2O(v) \rightarrow CO_2(g) + H_2(g)$$

Examples of indirect steam use can be found in unit processes very similar to those in the oil & gas industry (see Section 2.2.2 Oil & gas industry), such as providing heat to distillation column reboilers. Separating molecules based on their boiling point via distillation is considered the most energy-consuming unit process in the chemical industry, accounting for 40% of total energy consumption [13].

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Aside from steam use in the chemical industry, there is also steam production. In most cases, steam is generated by the combustion of (fossil) fuel in either CHP plants or conventional steam boilers. However, production facilities with significant exothermic reactions can valorize their excess heat by turning boiler feed water into steam at a sufficiently high pressure so it can be reused as the heating medium. Examples of steam-generating exothermic processes are steam crackers and polymerization and oxidation reactions.

In a steam cracker, the high-temperature olefin-rich gas is quenched by direct steam production at a pressure as high as possible. The steam can be used to drive the gas compressors in the same cracker (thus saving the need for external electricity) or exported to neighboring operations.

Polymerization reactions of, e.g., ethylene to produce polyethylene are exothermic and require cooling, which can partially be done by steam generation when the reaction occurs at elevated temperature. Oxidation reactions, on the other hand, can be energetically optimized by recovering their exothermic heat into steam. An example in the chemical industry is the oxidation of p-xylene to produce terephthalic acid, a key precursor to produce polyester.

To conclude, as diverse as the industrial production of chemicals is, as diverse is the use of steam in this sector. The previous descriptions provide a brief first insight into this complex industry.

2.2.4 Food & beverage industry

According to Windholz et al. [6], the potential for steam-generating heat pumps in some specific subsectors of the Food Industry (dairies, breweries, and meat processing) over various European countries accounts for around 2.2 GW_{th}, which corresponds to almost half of the installed heating capacity in those specific sectors.

The Food and Beverage industry widely uses steam in different processes at different temperature levels. Some examples of steam use in the sector are described below.

Pasteurization

Pasteurizing in food & drink production is often one of the key processes to ensure food safety, avoiding microorganisms' growth. Different kinds of pasteurizers exist, depending on the needs of the product. Some examples include:

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

- Indirect sterilization of milk: The milk is heated with water or steam at a certain temperature for a certain duration; this water can be indirectly heated with steam. The combination of temperature and duration of the process determines the destruction of microorganisms and the duration of the milk. The temperatures can vary from around 70 °C for lower temperature heat treatments to around 140 °C for higher temperature heat treatments.
- Direct sterilization of milk: Direct steam is injected into the milk for UHT, heating until around 140 °C. After mixing, the milk is separated from the extra water and cooled down.
- Can or bottle tunnel pasteurizers: Bottled products like sodas are pasteurized by passing through a tunnel and spraying water at different temperature levels. Usually, the maximum temperature level is around 70 to 80 °C. The hot water can be heated using steam. The beer production process requires this step after fermentation. Temperature levels are around 60 °C. The steam can be relevant for mass production to warm up the liquid, which is already bottled, killing the remaining living microbes. Breweries use it to stabilize their product before final packaging.

CIP (Cleaning-in-place) units

CIP units are used in many food & beverage plants. These are cleaning systems in which different products are prepared and circulated over the production plant for cleaning the different pipelines, heat exchangers, tanks and other elements in contact with the food or drink products. Normally, after a certain batch or batches of products are produced, the cleaning takes place by passing the different cleaning agents through the equipment:

- Rinsing hot water,
- Chemicals like alkaline, neutral or acid detergents,
- Cold water after the cleaning.

Steam can be used to heat the water and chemical elements of the CIP. Water and cleaning solutions usually need a temperature of around 75 °C.

Cooking

Cooking of different food products can be made with jacketed vessels. The vessels contain the product to be cooked and an external jacket through which steam or hot water passes. Using

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

steam makes it possible to control the temperature inside the vessels better, as the steam condensing occurs at a constant temperature.

Cooking of food products is done in different types of ovens, which can be indirectly or directly fed with steam. Also, direct steam injection is used in some food processing steps to adjust the water content of the product.

Steam ovens are the best solution for slow cooking processes where a gradual temperature increase is relevant for the final quality of the product. The heat from the steam is also used to warm up process machines to keep ingredients at their working temperature.

This technology is widely applied in the so-called "sous vide" (vacuum-sealed) cooking. An example is the ham cooking, which requires around 60 to 70 °C. The ovens are gradually warmed up from 30 to 45 °C and then to 60 °C. The cooking process requires constant steam injection since it lasts for around a day.

Peeling

In certain food processing, such as fruit and vegetables, steam is used for peeling the skin in a continuous process (continuous steam peeler) or batch process (flash steam peeling), usually at pressures between 9 and 15 bar.

Refining of vegetable oils

Heat is mainly used in the acid or dry degumming process. In the first case, steam is used combined with phosphoric or citric acid. The temperature range can vary from 70 to 80 °C depending on the specific oil and the acid used. Dry degumming is an option for palm or coconut oils with low amounts of phospholipids. The temperature reaches 120 to 140 °C, with pressure levels around 2 to 5 barg, Additional use of steam can be seen in the vacuum machines needed to manage processes wasted like the bleaching earths.

Drying

Different drying processes are used in the food industry. For example, sugar beet pulp drying can be achieved using high-pressure superheated steam, usually in a pressurized steam fluidized bed dryer. The sugar industry uses steam in both the extraction and crystallization steps of the

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

production: the pressure level is usually around 2 to 3 barg. In the extraction process, low-pressure steam is used to strip out sugar from beets. Purification of sugar juice is another field where steam is generally applied to a vacuum boiling machine: the aim is to reach a level of 50 to 60 % concentration; the temperature level is around 110 to 120 °C.

Evaporation

Evaporation or removal of water content of liquid or solid products is often carried out using steam. Some examples are sugar processing (evaporation from sugar juice to get the solid sugar), fruit juice concentration, dairy products (evaporation and concentration for milk powder or whey protein production), starch processing, etc.

In multistage evaporation systems, the vapor extracted from the product in the first stage is used to heat the product in the next evaporation stage. The second and successive steps work at lower pressure to evaporate the water at a lower temperature. Three to five evaporation steps are common in these kinds of processes. Increasing energy efficiency in this process is to compress the vapor between each stage by thermal or mechanical vapor recompression (see Section 2.1.4 Energy efficiency in steam generation and distribution systems).

2.2.5 Carbon capture and storage (CCS)

The (energy-intensive) industry faces a tremendous challenge to decarbonize and reach climate neutrality within the next decades. To achieve this target, a hierarchic approach is needed on the emissions related to the use of fossil fuels:

1. Prevention: e.g., prioritizing product types and manufacturing techniques with the lowest associated carbon footprint.
2. Reduction: e.g., improve the energy efficiency of a production process by heat recovery technology such as heat pumps.
3. Substitution: e.g., electrification via switching from fossil-fired steam boilers to electrical-driven e-boilers with electricity coming from a renewable source.
4. Mitigation/Neutralization: e.g., avoiding point-source CO_2 emissions of flue gases by implementing Carbon Capture and Storage/Utilization technology (CCS/U).

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Each stakeholder is developing and executing its strategic decarbonization strategy, influenced by external factors such as energy market conditions, global and local regulations, and the maturity level of available technical solutions. Within this perspective, CCS/U is increasingly receiving interest due to changing market conditions (e.g., increasing carbon taxation) and technological development status advancements (scale, reliability, operational performance). These trends improve the financial returns and the cost of deployment (CAPEX) and operating the plant (OPEX).

A CCS/U process chain includes (1) the capturing of CO_2 produced within an industrial plant, (2) compressing it for transportation, and (3) eventually storing it (a) in a remote underground location or (b) utilizing it as a feedstock material into another production process (e.g., methanol from CO_2 and H_2). Focusing on the CO_2 capturing step, a set of different physicochemical processes are found suitable to separate CO_2 from an industrial flue gas stream [14]:

1. Physical/chemical adsorption
2. Gas-solid reactions
3. Cryogenic separation
4. Membrane separation
5. Physical/chemical absorption

Due to the widely differing characteristics of flue streams within the industry, it is not possible to rule out one technology against the other. Matching the flue gas source with the best separation technology depends on the required selectivity, capacity, and diluteness within the gas stream (related to CO_2 partial pressure).

In general, CO_2 absorption into a chemical solvent is identified as one of the most relevant types due to its high absorption capacity at low CO_2 concentrations (low CO_2 partial pressure), making it widely applicable to post-combustion CO2 sources. Over the past decades, significant technological developments have been made in several chemical solvents, especially amine-based, reaching TRL9 and being implemented and operated at increasing scales over the last decade [15]. An important factor to consider is that CO_2 separation by chemical absorption relies on a significant amount of work input, typically in the form of low-pressure steam. The energy consumed for chemically capturing and separating the CO_2 (GJ/ton CO_2) is considered one of the main differentiators between technology providers. One of the main innovation drivers for

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

technology licensors has been (and will be) to decrease this energy intensity of the CO_2 capturing step as it significantly impacts the operational cost of the overall CCS plant.

The typical process diagram of a CO_2 separation unit via chemical absorption can be found in Figure 8. It is built out of two main columns, the first to absorb the CO2 and the second to release pure CO2 and regenerate the chemical solvent for reuse.

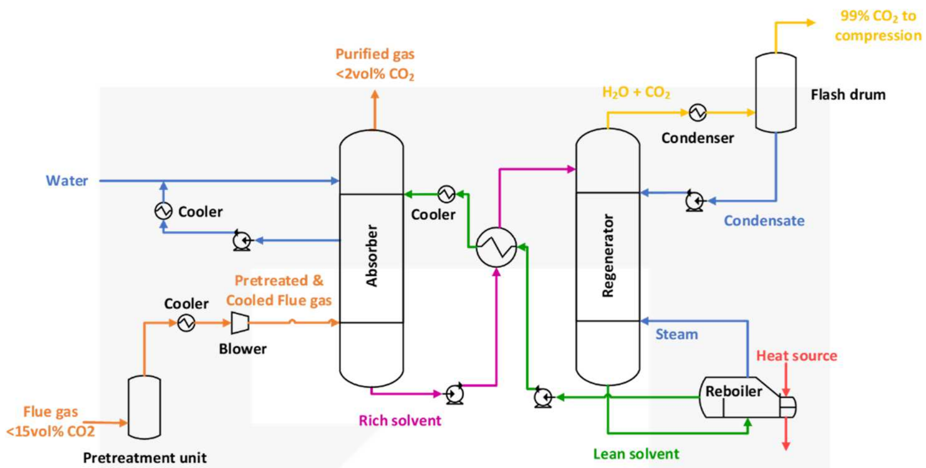


Figure 8. Process diagram of Carbon Capture process via chemical absorption.

The CO_2 gas stream, for example, the exhaust of a gas burner, is pretreated (SO_x, NO_x and PM removal) and blown towards the absorption column. Here, it is brought into contact with the lean solvent, forming an intermediate compound via chemical bonding and the formation of a salt. As the absorption step is the most effective at lower temperatures, the flue gas and the lean solvent are cooled before entering the column. In addition, cooling is foreseen via intercooling a side stream of the amine solution and quenching with cold water on top of the column. The latter also helps avoid solvent loss with the treated flue gas leaving the column on top.

On the bottom, a CO_2-rich solvent stream is pumped towards the regeneration side after being preheated with a lean-rich amine heat exchanger. Inside the regeneration column, the solvent is regenerated to its initial state by rising low-pressure steam, increasing its temperature to release the chemically bonded CO_2. This internal steam is generated in the reboiler, the main heat consumer within the capturing unit. On top, the water-saturated CO_2 flow is being cooled down, dehumidifying the gas stream and producing an almost pure stream of CO_2 ready for compression and transportation. The regenerated solvent is pumped back into the absorber and cooled in the solvent-solvent heat exchanger.

The exact energy intensity of the regeneration step within is different for each proprietary technology and dependent on a set of factors:

1. The flue gas composition: most importantly, the CO_2 concentration/partial pressure.
2. The solvent characteristics:
   - The CO_2 carrying capacity (higher = lower energy intensity) determines the solvent circulation rate.
   - The absorption enthalpy (higher = higher energy intensity) determines the energy needed to break the chemical bond in the regenerator.
   - The water concentration (higher = higher intensity), downwards limited by viscosity and corrosion behavior.
3. The degree of energy integration: optimization of the overall mass and energy balance of the process and making maximum use of the available waste heat to cover the net required process heat. Within the process, waste heat is available at different locations:
   - The flue gas cooler
   - The regenerator overhead condenser
   - The lean solvent cooler

There is a long list of proprietary chemical solvents, mainly dominated by amine-based variants. The first-generation amine solvent is 30wt % MEA (MonoEthanolAmine) in water with a typical regeneration energy of a minimum of 3.6 GJ/ton CO_2. Further advancements within the commercially available amine solvents group reduce the energy intensity to a minimum of 2.1 GJ/ton CO_2. A 1 Mtpa operational CO2 capturing plant at the lowest available energy intensity implies a continuous reboiler low-pressure steam consumption of over 100 tons/hr [16, 17]. The required steam pressure and temperature for the regenerator depend on the proprietary technology and the solvent used, but these typically range from 2 to 6 barg [16, 17].

Therefore, it is clear that the chemical absorption carbon capture technology is an energy-intensive process that requires vast amounts of (low-pressure) steam to drive its regeneration step. At the same time, large amounts of waste heat are available within the process. This brings opportunities for heat recovery technologies (e.g., heat pumps) to decrease the reboiler net

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

energy consumption by upgrading the available waste heat. For the most efficient integration of these technologies, it will be important to be involved at an early engineering stage during the design of the CCS plants. Being involved in the design phase allows optimizing the mechanical integration of the heat recovery technology, minimizing the complexity of capturing the waste heat. In addition, the process engineering of the CCS unit can be optimized to reduce the temperature jump needed from the heat source to the heat sink to implement heat recovery technologies at the maximum possible efficiency.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

3. STEAM GENERATION BY HEAT UPGRADE TECHNOLOGIES

3.1 State of the art

3.1.1 Steam generation by HTHP

Steam-generating heat pumps (SGHP) have been gathering increasing interest in the last few years. High-temperature heat pump technology is continuously evolving and improving, and one of the goals for technology providers is to tackle the industry needs in this scope and generate steam with their equipment. Thus, several research activities have been developed around this in recent years. Most of the research studies found in the literature include thermodynamic simulations. A few experimental studies are showing SGHP with different configurations, as well as some commercial units. A detailed list of references for research, testing and demonstration activities on SGHP can be found in the work of Bless et.al. [18]. Moreover, in that paper, different cycle configurations for the steam generation with HTHPs were analyzed, including the classical subcritical closed-cycle HTHP, the transcritical cycle and the reversed Brayton cycle, when focusing on closed cycles. Also, a closed cycle + MVR combination and an open loop cycle compressing steam are analyzed. At the moment, classical closed-cycle HTHP is the cycle with the most potential for wide commercial industrial applications for steam generation with heat upgrade technology employing compressors.

In summary, global research on SGHPs has intensified in recent years, with prototypes having heating capacities in the range of a few hundred kW, meaning that the studied technologies use volumetric compressors (piston and screw). Up to date, there is no application of SGHP using centrifugal compressors. Pilot plants commonly generate steam temperatures around 130 ± 20 °C, utilizing multi-stage configurations with HTHP, Internal heat exchanger (IHX), flash tank, or MVR. The average COP is approximately 3.2 at a temperature lift of 60 K using 70 °C waste heat.

Overall, until now, R245fa has predominantly been employed as a refrigerant in SGHPs due to its favorable temperature range in subcritical processes. A high critical point is crucial for effective

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

two-phase heat exchange at the steam generation temperature. However, because of its elevated GWP (858), attention has been shifted towards natural refrigerants such as hydrocarbon n-butane (R600) or water (R718). Additionally, there is a growing interest in exploring new synthetic hydrofluoroolefins (HFO) with significantly lower GWPs, such as R1233zd(E), R1224yd(Z), and R1336mzz(Z).

Apart from the previous research references (Bless et al. [18]), a recent example of research development of SGHPs has been carried out in the European project Bamboo. EDF developed a SGHP combined with a flash tank, producing steam up to 165 °C [19]. Another example of research activity in this field is the AHEAD project, in which a HTHP from SPH will be combined with a compressor to provide steam at 184 °C in a pharmaceutical plant in Austria [20].

Focusing on commercial equipment, Annex 58 of the IEA Heat Pumping Technologies Technology Collaboration Programme (HPT – TCP) shows SGHPs as one of the promising applications in industrial heat pumping technologies (see Section 3.2.2 of Task 1 Report [21]. The main SGHP technology providers and developers are [22]:

- Enerin
- SPH (Push2heat project member)
- Olvondo
- Mayekawa
- Turboden
- Enertime (Push2heat project member)
- Heaten
- Siemens Energy
- Kobelco

Some SGHPs use synthetic refrigerants, and others use natural refrigerants, mainly butane. In terms of how they produce steam, some machines do it indirectly by generating steam externally (via a flash tank in connection with pressurized water obtained in the HTHP, see Section 3.2.2 Indirect steam generation). Others do it directly in the HTHP through special heat exchangers (see Section 3.2.1 Direct steam generation). Most of the machines can produce steam until 165 to 175 °C. The manufacturers claiming to reach higher temperatures in steam are Turboden and Olvondo (until 200 °C) and Enerin (until 250 °C). Different TRL levels apply to these commercial technologies.

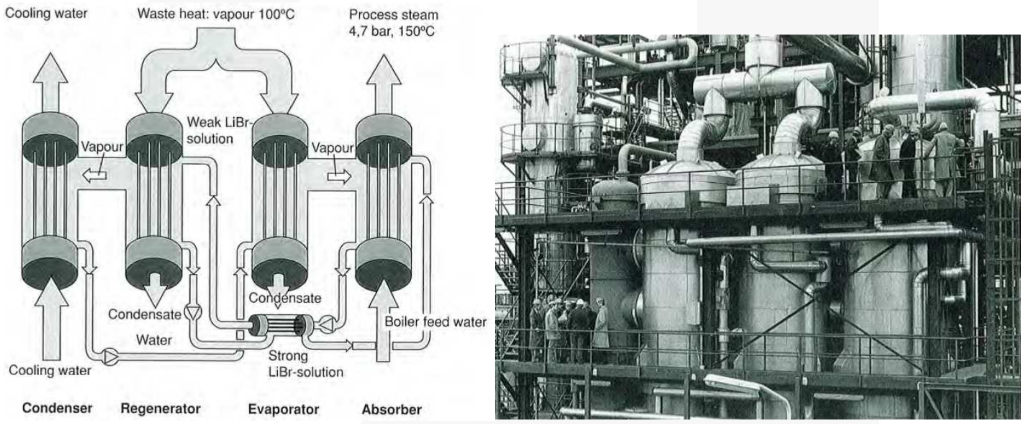
Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Two real case examples of SGHPs can be found in Annex 58. One includes Kobelco HTHP, which produces 120 °C steam indirectly (flash tank) in a bioethanol distillation process in Japan [23]. The other example includes HTHPs by Olvondo, which produce 183 °C steam indirectly (shell and plate heat exchanger) and are installed in a pharmaceutical plant in Sweden [24].

3.1.2 Steam generation by AHT

Some examples of steam generation in industrial processes by Absorption Heat Transformer (AHT) technology exist in the literature. An old example can be found in the IEA Heat Pump Centre Newsletter of 1990 [25]: an AHT integrated into a chemical plant (Delamine BV) in the Netherlands (operation started in 1985). The AHT uses 13,7 MW waste heat from an ethylene amine production plant in the form of saturated steam at 100 °C. 11 tons/h of saturated steam are produced in the absorber at 145 °C and 4,6 bar.



(19) (b)

Figure 9. Steam producing AHT in Delamine chemical plant in the Netherlands. (a) Scheme of AHT. (b) AHT installed in the plant. [25]

Another example of steam-generating AHT is the one installed in the Hoogovens steel plant [26]. The AHT makes use of waste heat at 90 °C (from the cooling water from a reheating furnace in the hot strip mill) and produces 6,5 tons/h steam at 2.7 bara. The steam is used in a cold-reducing mill/hot dip efficiency process.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

New experimental developments also show concepts of steam-generating AHTs by a combination of AHT and flash tank at laboratory level (14 kW) [27] and medium scale (200 kW) [28]. The two previous references correspond to double-lift AHTs driven by hot water at 80 °C and producing steam at 170 °C.

Figure 10 shows the operation scheme of the AHT (small scale in [27]), where it can be observed how the production of steam is done. The AHT provides hot water to a flash tank, where the pressure is reduced, and part of the water is vaporized, producing steam. The outlet water is pumped back to the absorber of the AHT, mixing with the feedwater necessary to complete the total flow rate of the circulating water through the absorber.

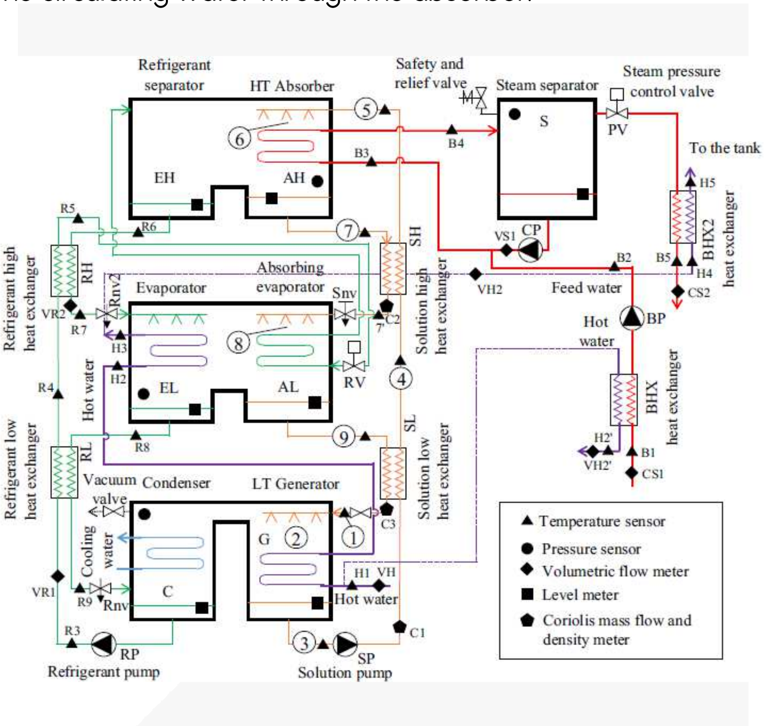


Figure 10. Double-lift AHT system flow diagram [27].

3.1.3 Steam generation by THT

Steam generation using the thermochemical heat transformer (THT) is a way to produce steam by extracting waste heat exergy and concentrating it in carbon-neutral steam. The steam produced is made available at higher temperatures than the waste heat itself.

The system is based on a reversible chemical reaction using phosphoric acid. The dimer formation of phosphoric acid is an endothermic reaction. This reaction is not spontaneous under ambient

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

conditions, so the necessary conditions are created in the endothermic reactor (cold reactor) for this endothermic reaction to progress spontaneously. By forming dimers, the energy in the waste heat is extracted and stored under covalent binding energy for a small amount of time.

In the exothermic reactor (known as the hot reactor), the dimers are converted back to monomers, releasing their covalent bond energy. Through smart heat integration, the heat is released at the desired steam temperature. The working fluid, phosphoric acid, is neither consumed nor degraded and can be utilized for long periods.

It should be highlighted that the only rotating equipment are pumps. All other equipment is static. This impacts one of the key differentiators of the THT technology: its very low electricity consumption. Roughly half of the amount of captured waste heat is cooled away to the environment to create the driving force for the thermal lift of the other half. Because of the economies of scale, THT is well suited to recover large amounts of waste heat (MW scale) and turn it into CO_2-neutral steam. CO_2 emissions are thus reduced while improving the energy efficiency. The third defendable differentiator is the high-temperature jump, which can be created using this technology (see Figure below). Depending on the waste heat quality, a thermal compression of 50 to 100 °C is achievable. Atmospheric steam can thus be converted to medium-pressure steam. This technology utilizes thermal rather than mechanical compression to cope more efficiently with process fluctuations. Mechanical compressors have an optimal operating point; deviating from this design point makes compressors less efficient, while a HUT's efficiency is not impacted by this.

The Qpinch technology represents state-of-the-art steam generation by the THT and can reach temperatures of up to 210°C. The current Qpinch plants apply indirect steam generation using a flash tank, but other configurations are also possible. The commercial units are integrated into chemical production plants and transform waste heat between 90 °C and 140 °C to process heat between 140 °C and 185 °C. They have a capacity between 1 MW and 2 MW. The commercial operating window and respective temperature jumps are indicated in Figure 11. Depending on the temperature lift the commercial plants are designed for a thermal efficiency between 40% and 50%.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

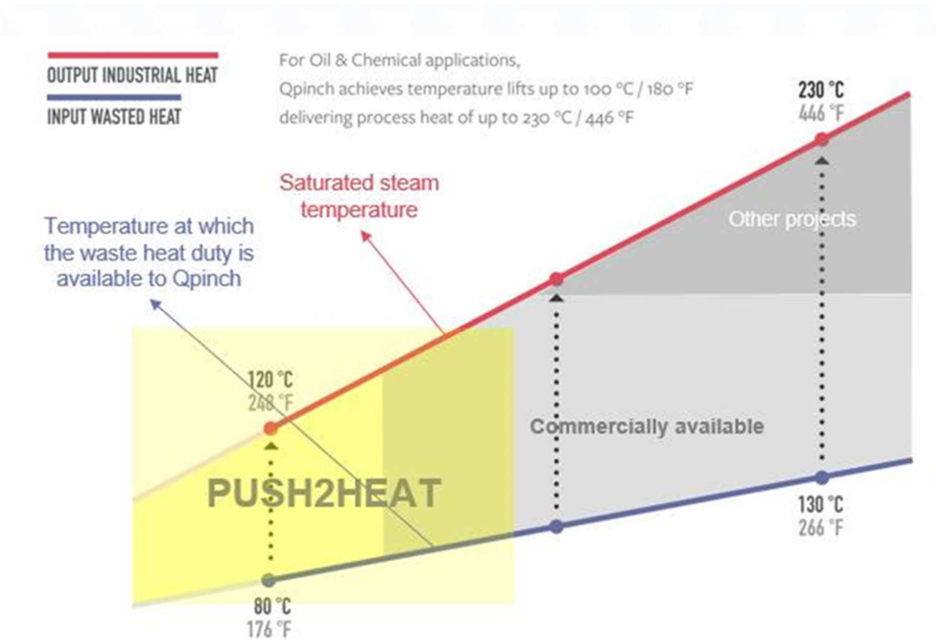


Figure 11. Commercial operational conditions for steam generation with the THT of Qpinch.

3.2 Methods for steam generation with HUTs

In Figure 12, different possibilities of steam generation using HUTs are shown. Firstly, steam can be generated directly or indirectly in the HUTs. Direct steam generation in the HUTs means that the condenser of compression heat pumps or the absorber of absorption heat pumps is generating the steam. Indirect steam generation can be tackled by a flash tank, in which part of the pressurized water is evaporated or in a heat exchanger, where the pressurized water heats and vaporizes incoming water. Another step can include the generated steam recompression, which can be done by thermocompression or mechanical vapor recompression.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

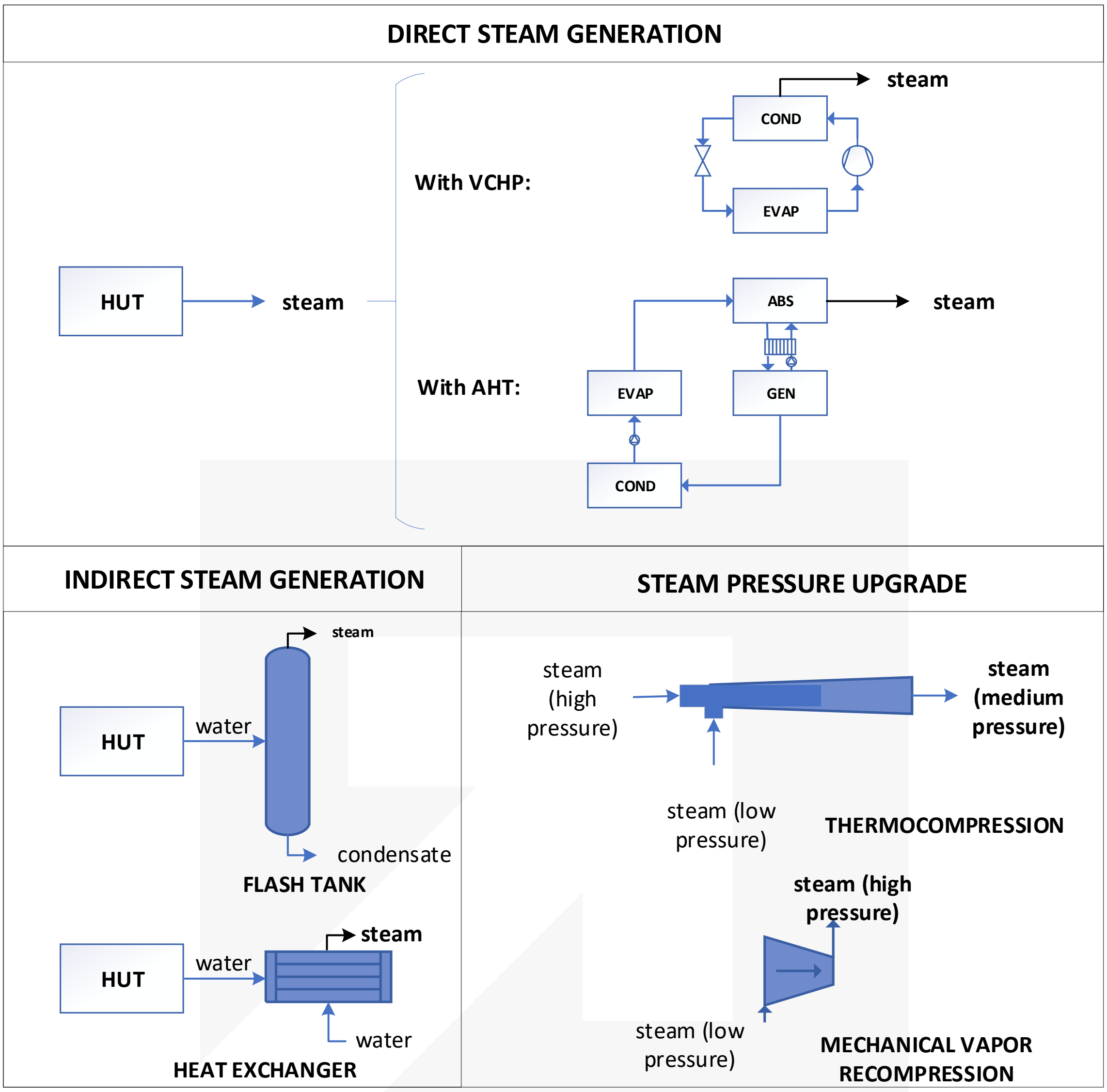


Figure 12. Steam generation by HUTs.

3.2.1 Direct steam generation

Direct steam generation is the most efficient way to generate steam with a heat pump because of the lowest achievable pinch point between the condensing temperature of the heat pump and the evaporation temperature of the steam. Direct steam generation denotes the steam production directly in the condenser of the heat pump. To do this, a heat exchanger is needed, which can handle condensation of refrigerant on the hot side and evaporation of water on the cold side. In principle, every type of heat exchanger can do this, but there are other important criteria. A steam-producing unit in an industrial environment must be robust. That means that

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

pressure fluctuations in a normal steam grid are normal and can lead to steam blow or water hammer in the heat exchanger. An increasing steam pressure can lead to a sudden condensing of saturated steam at the water surface in the heat exchanger. This sudden condensing leads to local pressure peaks, which can damage the heat exchanger. Most plate heat exchanger manufacturers recommend not using plate heat exchangers in such an application. Shell and tube heat exchangers can be used to be very robust against possible pressure peaks. A drawback of this kind of heat exchanger is its bigger footprint and refrigeration volume. A very good mixture between a plate heat exchanger and a tube and shell heat exchanger is plate and shell heat exchangers. Figure 13 shows a plate and shell heat exchanger with additional water volume for more stable steam production. The heat exchanger consists of a shell, used as a steam boiler, and fully welded, very robust plates, used as a condenser for the refrigerant. The heat exchanger has the refrigerant in and outlet normally at the side, the feedwater connection at the bottom and the steam outlet at the top. Typical manufacturers for this type of heat exchanger are, for example, Vahterus, Gesmex, or API Schmidt Bretten.

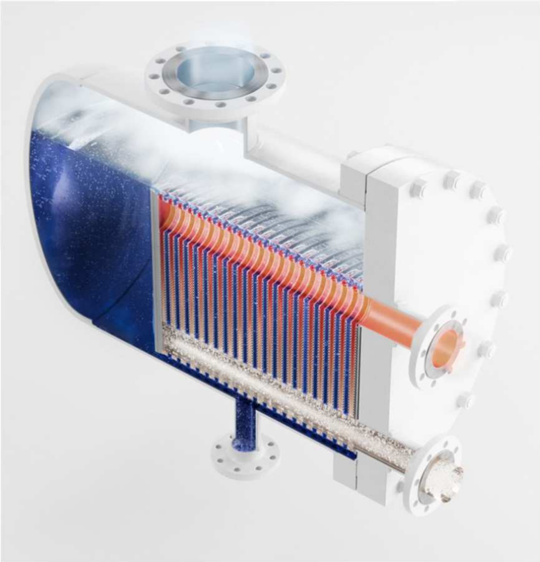


Figure 13: plate and shell heat exchanger (Vahterus, [29])

To control the steam production, control of the water level in the heat exchanger is necessary. This can be done by controlling the feedwater pump or a regulation valve. For optimal performance, the water level should always cover the entire surface of the plates. A droplet separator can be integrated to ensure a dry steam at the outlet if necessary.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

3.2.2 Indirect steam generation

Figure 14 shows a scheme for indirect steam generation using a flash tank. Heat comes from the HUT in the form of overpressurized water at T_1 and P_1. The condensate pressure is decreased over a control valve or a restriction orifice depending on whether several steam pressures are targeted or only one. Next, in the flash tank, the condensate is expanded to saturation pressure P_2 and temperature T_2 of the steam header. The energy needed to produce the steam (T_2, $P_{2(V)}$) comes from the transition of T_1 to T_2. The condensate phase in the flash tank (T_2, $P_{2(L)}$) is overpressurized via pump energy (T_3, P_1) and circulated back to the HUT, which lifts the temperature again (T_1, P_1). Finally, the flash tank is supplied with make-up water, also called boiler feed water (BFW). Its temperature T_0 is lower than T_2, and the pressure P_0 is higher than P_2 to avoid backflow. This process is also shown on the T-s and P-h diagrams in Figure 14.

Indirect steam generation allows buffering steam demand. A sudden increase in steam demand results in a decrease in pressure. The flash tank can buffer this demand by making steam available at a slightly lower pressure. It acts as an extra reserve of steam. In case of a disturbance, it can potentially provide steam long enough to overcome it, contributing to the continuous operation of a production plant. Moreover, cooling by the liquid phase without phase transition allows more uniform and consistent cooling at the HUT, resulting in more stable operation.

Another option for indirect steam generation is to use a water-steam heat exchanger instead of a flash vessel. The pressurized water generated in the HUT will evaporate water coming into the heat exchanger, generating steam. For instance, Høeg et al. [30] presented a HTHP based on the Stirling cycle in which steam up to 7 barg is generated indirectly from pressurized hot water in a shell & tube heat exchanger. The hot side (hot water circuit) flows through the plates, and the cold side (water and steam) flows between the outer shell and the plates.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

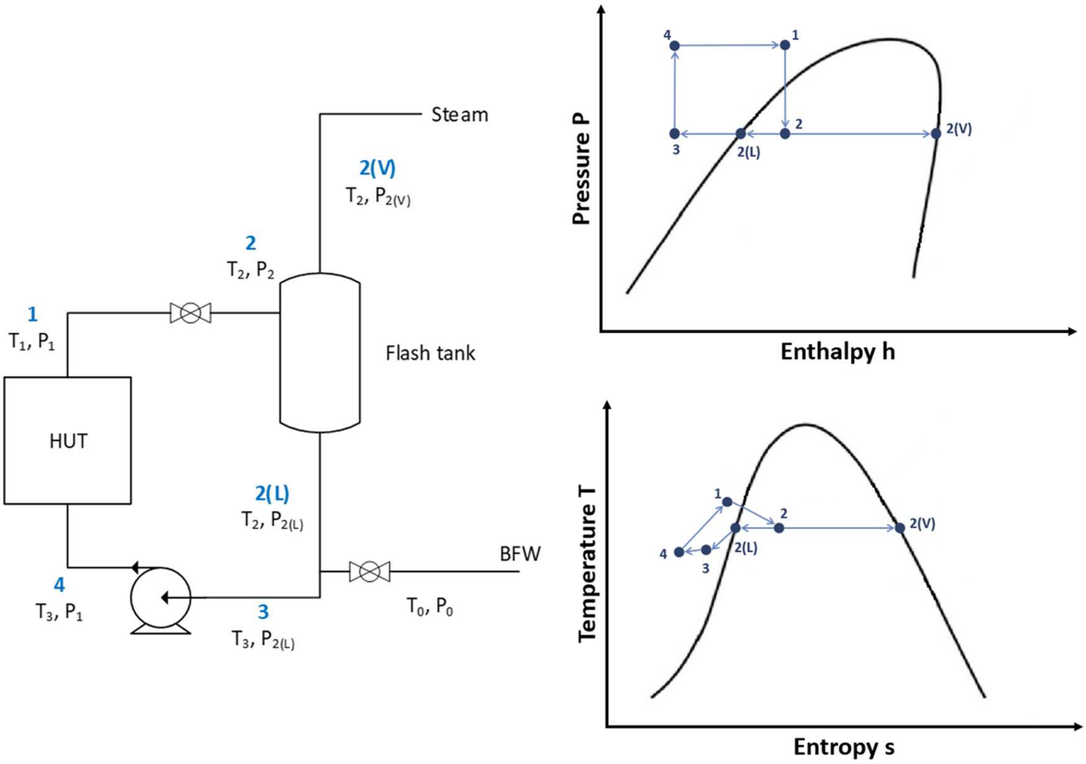


Figure 14. Schematic representation of indirect steam generation by flash tank including P-h and T-s diagram.

3.2.3 Steam pressure upgrade

After direct or indirect steam generation by HUTs, the steam can still be recompressed to a higher pressure if needed. This can be tackled either by thermal compression or by mechanical compression. The choice between a mechanical compressor and a thermocompressor depends on factors such as the specific application, required pressure ratios, and efficiency considerations. One should consider various advantages and drawbacks for each. Those options are explained below.

Thermocompressors

Thermocompressors are ejectors which can boost low-pressure steam to a higher pressure by mixing it with higher-pressure steam. Figure 5 shows the schematic representation of a thermocompressor. The high-pressure steam, or motive steam, enters the nozzle of the thermocompressor and leaves it at high velocity. This way, the low-pressure steam, or suction

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

steam, is entrained into the mixing chamber, where the mixing fluid is accelerated. In the diffuser, the velocity of the fluid is gradually decreased, so in the end, the fluid's pressure is higher than the suction steam pressure.

Compression and entrainment ratios are parameters when analyzing thermocompressors sizing and operational points.

The compression ratio (CR) is between the discharge and suction pressure (absolute pressure). Depending on the compression ratio, the thermocompressor is working in sonic conditions (CR > 1.8) or in subsonic conditions (CR < 1.8). Different methods for controlling the thermocompressor are used for sonic and subsonic operation. In sonic conditions, the high pressure steam flow rate is fixed, and in subsonic conditions, it can vary. Many installations work in subsonic mode, varying the suction flow varies with the motive steam flow at a given discharge pressure [31].

The entrainment ratio (ER) refers to the ratio between the motive steam mass flow rate and the suction steam flow rate. For the same compression ratio, the higher the motive steam pressure, the lower the entrainment ratio. Therefore, less motive steam is needed at higher pressures to compress the same amount of steam. Typically, the entrainment ratio lies between 1.5 and 3 to ensure a good operation of the thermocompressor [31], with 4 as an upper limit for the ER.

Several manufacturers and providers of thermocompressors exist, for instance, Armstrong, TLV, Spirax Sarco, Koerting, Kadant, Baelz, etc. Thermocompressors are usually implemented in industrial processes where low-pressure steam can be recovered. A typical application combines a flash tank to recover energy from condensates and the turbocompressor to boost the pressure level to useful conditions for the process. This combination can also be used in a HUT to provide medium-pressure steam using low-pressure steam generated in a flash tank.

Advantages

1. Simple Design: Steam ejectors have a simpler design with no moving parts, resulting in lower maintenance requirements and potentially longer operational life.
2. Suitability for Low-Pressure Applications: Steam ejectors can efficiently handle low-pressure steam, making them suitable for certain applications where vapor compressors may struggle.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Drawbacks

1. Lower Efficiency: Steam ejectors typically have lower efficiencies than vapor compressors, especially in higher-pressure applications.
2. Less Control: Ejectors might offer less precise control over the compression process than vapor compressors, limiting their adaptability to varying conditions.
3. Limited Capacity: Steam ejectors might have limitations in capacity, making them less suitable for large-scale applications. There should be a necessity for the additional mass of vapor used to upgrade the low-pressure vapor produced by the heat pump.

Mechanical vapor recompression

Different types of vapor mechanical compressors are tailored to specific operational requirements. Common types include reciprocating compressors, rotary compressors, and centrifugal compressors. Reciprocating compressors, characterized by piston-cylinder arrangements, offer precise control and are adept at handling varying loads. Rotary compressors, with their continuous rotary motion, excel in compact designs and lower maintenance requirements. Centrifugal compressors, leveraging centrifugal force, are prized for their high capacities and efficiency in large-scale applications.

In a compressor design, efficiency is paramount, which hinges on isentropic and volumetric efficiency. Isentropic efficiency refers to the ratio of the isentropic work (minimum possible work without energy losses) and the real work on the compressor (taking into account energy losses due to friction, heat transfer, etc.)., while volumetric efficiency pertains to its capacity to intake and compress a given volume of vapor. Striking a balance between these factors ensures optimal energy utilization, reducing overall operational costs and environmental impact. Another important parameter for compressor design is the maximum pressure ratio, a key performance metric that delineates the compressor's capability to elevate the vapor pressure. Different compressors exhibit varying pressure ratios, influencing the overall efficiency of the heat pump system. Careful consideration of this parameter is imperative to ensure the compressor operates within its designated range, optimizing performance and longevity.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Advantages

1. Higher Efficiency: Vapor compressors often exhibit higher isentropic efficiencies compared to steam ejectors. This means they can compress vapor with less energy loss.
2. Variable Speed Operation: Many vapor compressors allow variable speed operation, enabling better control and adaptability to varying loads.
3. Compact Design: Depending on the type, vapor compressors can be designed to be more compact, making them suitable for diverse applications, including smaller heat pump systems.
4. No additional mass of vapor needs to come into play, and the exact flow rate of low-pressure steam produced by the heat pump will be upgraded.

Drawbacks

1. Mechanical Complexity: Vapor compressors involve mechanical components such as pistons, rotors, or impellers, which can introduce complexity and maintenance requirements.
2. Limited for Low-Pressure Applications: Some vapor compressors may face challenges efficiently handling very low-pressure steam.

3.3 Challenges of HUTs providing steam to industrial processes

3.3.1 Challenges of SGHPs

Although HUTs have become a mature technology in past decades, they are not applied as widely as they could be. Research efforts are required to improve energy performance and reduce costs. Advanced cycle layouts, such as multi-stage, cascade, and vapor ejection systems, can be utilized to enhance systems COP, which, however, complicates the system design and potentially increases their costs.

Very often, the steam demand in industrial processes fluctuates very strongly. This can cause problems in the steam-producing devices due to much lower water content compared to standard industrial steam boilers. In this case, an additional steam storage device could be needed to compensate for the high demand fluctuations. Depending on the heat pump technology, the SGHP can adapt the power output to slowly fluctuating processes. Piston compressor-based systems can normally control the thermal power output quite fast by controlling the compressor speed without losing the ability to provide the needed pressure ratio in the refrigerant cycle. Other technologies are often slightly more limited in their possibilities to adapt to such fluctuations in demand. So, it is very important to choose the heat pump technology according to the needs of the process.

3.3.2 Challenges of the integration of HUTs in the industry

The integration of heat pumps in the industry presents several challenges to overcome. Still, a good understanding of the end user's process and identifying the possible waste heat available on-site that can serve the maximum potential of upgrading heat to satisfy the industry's needs are the main challenges of integrating HUTs. Advancement in HUT performance will ease the process of potential case identification and HUT integration. Some features that need to be considered in overcoming the mentioned challenges are listed below:

- High upfront costs: Heat pumps are generally more expensive to install than conventional heating systems, making them less appealing to companies trying to minimize their capital expenditures.
- Limited operating temperature range: Heat pumps are most effective at low to medium temperatures, making them unsuitable for industrial processes that mostly require high-temperature heat. This can limit their use in metallurgy, glass, and ceramics industries.
- Electrical power supply: Compression heat pumps require significant electrical power, which can be challenging in areas with limited or unreliable power supply. This can increase the operational costs of the heat pump and may require additional investments in electrical infrastructure. This is not the case with thermally driven heat pumps (AHT and THT), which have a very low electrical consumption compared to compression heat pumps. Anyway, in decarbonization scenarios with the electrification of a high share of the

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

industrial heat in a process (or full electrification scenarios), HPs consume less electrical energy than purely electrical boilers to obtain the same heat. Therefore, whenever waste heat is available in the processes, it is one of the best options to consider for electrification of heat and for making use of the waste heat.

- Maintenance and servicing: Heat pumps require regular maintenance to ensure optimal performance, and servicing can be complex and expensive. This can be a challenge for industries that operate around the clock and cannot afford lengthy downtime.
- Integration with existing systems: Integrating heat pumps with an existing system can be complex as one should meet some specifications to be acceptable for the process of companies such as ramp-up time, temperature and pressure levels, and control system compatibility, and these may require additional investments in infrastructure and control systems. In the case of SGHPs, the injection of steam directly into the processes might be more difficult to ensure stable conditions than, for instance, the injection of the generated steam in one of the plant's low or medium-pressure lines.
- Environmental considerations: Heat pumps are generally considered more environmentally friendly than conventional heating systems but still require significant energy. This energy source can significantly impact their environmental performance, and companies must carefully consider the carbon footprint of their heat pump systems.
- Energy performance and durability: The COP of heat pumps should overcome the market electricity-to-gas price ratio to be acceptable by the industry with a realistic investment payback time and should have a lifetime that can bring enough added value to the companies.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

4 PROCESS INTEGRATION OF HUTs

In any industrial energy efficiency project, the first stage should be a thorough analysis of the process to understand the subprocesses involved and how the energy is produced and consumed, to quantify the thermal (heating & cooling) and electrical demands as well as their variability over time, and to identify and quantify possible waste heat sources that could be used for recovery or upgrade.

The integration of HUTs such as those developed in the PUSH2HEAT project also needs comprehensive knowledge of the processes to be integrated optimally into the industry. On the one hand, the use of such a HUT requires a suitable waste heat source. On the other hand, some processes are not fully optimized and are heated up by higher temperature sources than needed (for instance, high-pressure steam when a lower temperature source could be enough). In those cases, an initial process optimization could lead to improvements in decreasing energy demand and pose a benefit for the HUTs integration by a lower temperature lift needed in certain cases and a higher reachable COP value.

Also, it is important to consider the match between waste heat source and heating demand, which can be relatively constant and coincident in time or variable and not match completely over time. This depends on the type of process, and the variabilities and mismatches can be tackled by energy storage systems, which have proven to be very useful in maximizing waste heat utilization and upgrading in certain cases.

The methodology of Pinch Analysis is a comprehensive approach to process analysis for optimizing heat exchange, reducing heating and cooling duties, and identifying possible heat upgrading techniques for the processes. It was developed in the seventies and has been applied to many industrial processes since then. Detailed information about Pinch analysis and its application can be found in the literature (as an example, take the references [32, 33]).

The method analyzes stream data (heat flows and temperatures) and targets the minimum energy consumption by generating composite curves (temperature-enthalpy graphs) for heating sources and sinks. The Grand Composite Curve is another useful tool for targeting different utility temperature levels and can provide a valuable approach to the best way to integrate HUTs. The

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

gold rule for HUTs integration into the processes is that they must be integrated across the Pinch temperature. This is represented in Figure 15 for a compression heat pump.

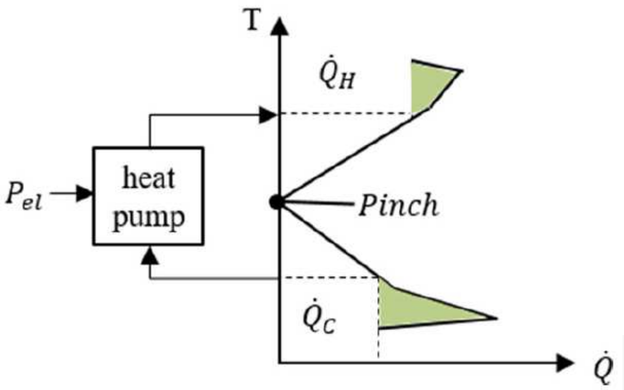


Figure 15. Heat pump integration represented in the Grand Composite Curve of a process. From [34].

Figure 16 shows the inappropriate integration of compression heat pumps below or above the pinch point. Also, it is important to note that one should always try to optimize the process to find the best conditions for HUT integration.

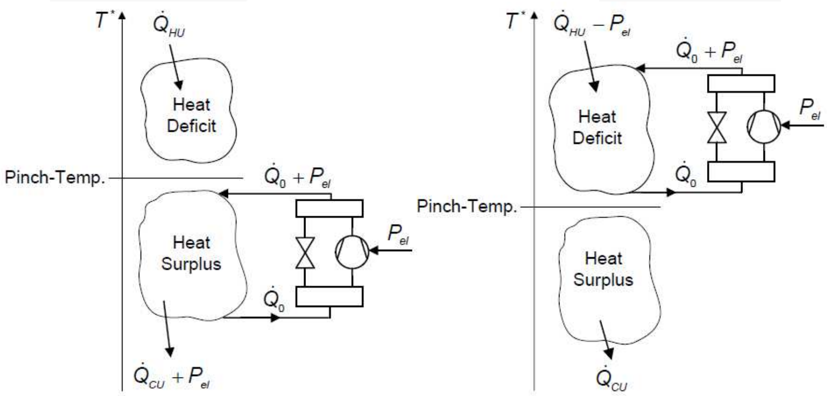


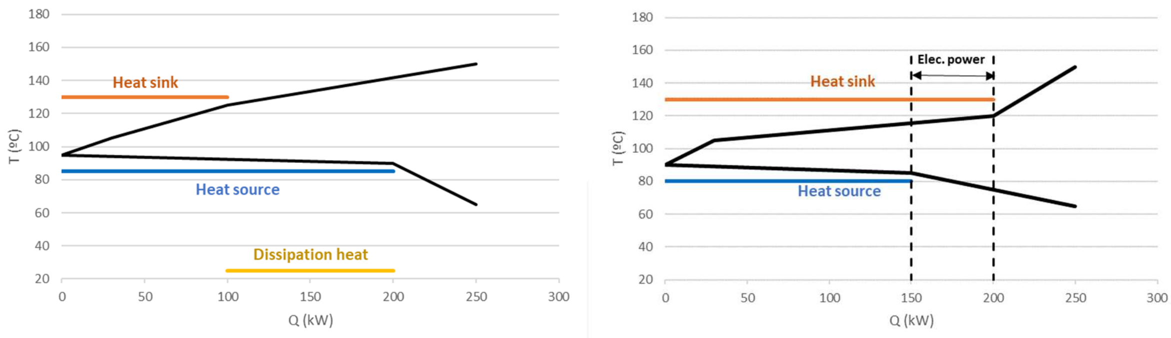
Figure 16. Inappropriate heat pump integration, below (left) or above (right) the pinch temperature. From [35]

Depending on the form and temperature levels of the Grand Composite Curve, the most suitable type of HUT (thermally or electrically driven heat pumps) to be integrated can be determined. Also, economic factors need to be taken into consideration, as well as the relation between fossil fuels and electricity costs.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Theoretical examples of the integration of heat transformer (a) and compression heat pump (b) are shown in Figure 17. Around half of the energy recovered in heat transformers is upgraded across the pinch. Therefore, they can be integrated into processes where the waste heat loads are much higher than the revalued streams. On the contrary, compression heat pumps transfer a higher amount of heat across the pinch due to the extra electric power as an input for the cycle.



(a) (b)

Figure 17. Theoretical examples of integration of HUTs in processes. (a) Heat transformer (b) Compression heat pump.

The integration of heat transformer and mechanical heat pump can also be graphically represented in the hold and cold composite curves, as shown by Bakhtiari et. al. [36]. Figure 18 shows an example of this representation for both technologies.

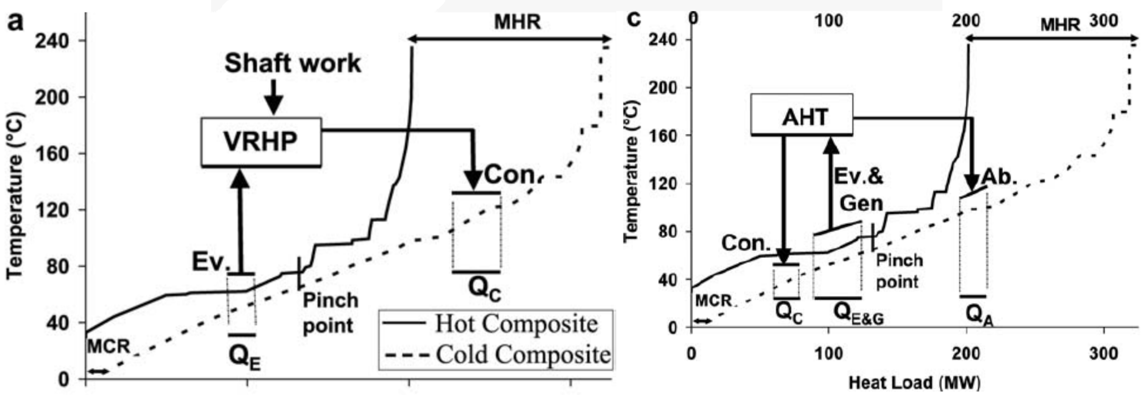


Figure 18. (a) Vapour Recompression Heat Pump (VRHP) and (b) Absorption Heat Transformer (AHT) integration represented in hot and cold composite curves [36].

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

According to Wang et al. [37], the procedure for heat pumps integration into process systems can be summarized by the following steps:

(1) Perform Pinch Analysis of a given industry process.
(2) Select proper process streams recovered by diverse types of heat pumps.
(3) Select corresponding heat sinks.
(4) Determine the operating parameters for different heat pumps (in their study they include vapor compression heat pump, absorption heat pump, and absorption heat transformer).
(5) Calculate and compare different heat pumps based on different criteria.
(6) Heat exchanger network (HEN) reconfigurations (if required).

Pinch analysis can also be applied to batch or time-dependent processes. The methodology can serve to identify possible heat exchange between streams, but also rescheduling of processes or heat storage integration. The integration of HUTs into certain industrial processes shows the need of using thermal storage, independently of the method use for its integration analysis.

Pinch analysis is probably the most widely known method for process integration. As described before, it can be used for proper selection and integration of HUTs into industrial processes.

In the report of Task 3 of IEA Heat Pump Program Annex 48 [38], an analysis of available tools for industrial heat pump integration was made. Figure 19 shows an overview of the most relevant tools identified and how they can be categorized attending to their functionalities. Three categories are shown which can summarize those tools' approaches: Pinch analysis, Heat pump, design, and Utility integration.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

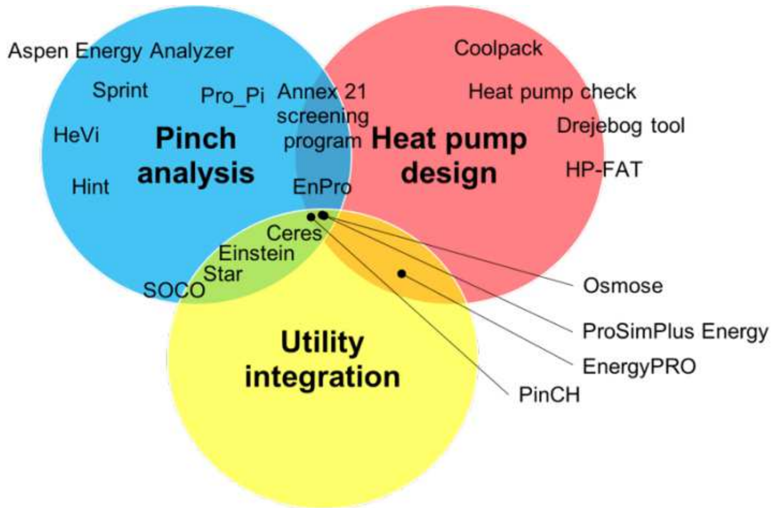


Figure 19. Relevant tools for industrial heat pump integration [38]

The practical guidelines developed in that report of Task 3 of Annex 48 for the integration of heat pumps include the following phases:

1) Initial data acquisition
2) Preparation & decision
3) Company visit
4) Analysis of status-quo
5) Pinch analysis (heat recovery)
6) Utility integration & heat pump design
7) Identify point of integration
8) Decision
9) Detailed planning

There are several papers in the literature where heat pump integration is discussed and case studies described; generally related to compression heat pumps, although some examples also apply to heat transformers. Below, some of those examples involving case studies are briefly described and referenced. Some of the examples refer to heat pumps with temperature levels lower than the ones developed in Push2heat, but the general principles of their integration and the methodologies which have been used for the purpose are applicable to Push2heat technologies. It is just a matter of the temperature levels occurring in the processes, whenever a sufficient COP level is achieved for economic feasibility, and the possibilities of integration.

Funded by
the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Olsen et.al. [35] show an example of integration of a compression heat pump in the food industry (candy production process), where six different operating cases were identified and analysed, taking as a reference for design the longest (with most operating hours) operating case. Heat recovery measures together with the heat pump integration result in a payback time of 3.7 years.

Bakhtiari et. al. [36] analised the integration of absorption heat pump (AHP) and absorption heat transformer technology in a pulp and paper factory. The study shows the hot and cold streams, and different possible AHP and AHT integration concepts, including an economic analysis. Two of the cases based on AHT (AHP type II) were selected as the most promising ones for that industrial site. The difference between AHP and AHT cycles is described in [39].

Wang et al. [37] analysed the potential integration of different types of HUTs (mechanical heat pumps, absorption heat pumps, and absorption heat transformers), introducing a novel criterion for the optimal selection of the HUT, the coefficient of performance in exergy per total annual cost. With this approach, a case study is conducted on a dairy process. Based on the results, the AHT was selected as the most suitable HUT in this specific case, with very similar values of coefficient of performance in exergy per total annual cost.

Schlosser et. al. [40] analyzed the integration of heat pumps into different industrial processes, by the evaluation of typical Grand Composite Curves of industrial processes in the food, paper, electroplating, metalworking, and chemical industries.

Ahrens et. al. [41] presented an integrated heat pump and thermal storage system in a dairy in Norway, with different types of heat pumps using natural refrigerants. With this configuration, waste heat recovery rate of over 95% was calculated, being able to compensate peak demands and reaching a system COP of 4.1.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

REFERENCES

[1] EN 12953-10:2005. Shell boilers – Part 10: Requirements for feedwater and boiler water quality.

[2] EN 12952-10:2005. Water-tube boilers and auxiliary installations – Part 10: Requirements for safety devices against excessive pressure.

[3] Handbook of Industrial Water Treatment | Veolia (Handbook of Industrial Water Treatment | Veolia (watertechnologies.com))

[4] Learn about steam – Spirax Sarco (Learn about steam | Spirax Sarco)

[5] Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board (2015). Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)

[6] Bernd Windholz, Johannes Riedla, Sophie Knöttnera, Paula Schmidbergera, Franz Helmingera, Annemarie Schneebergera, Clément Gachotb, Florence de Carlanb, Yannick Beucherb. Steam generating heat pumps – Measuring results and market potential. 14th IEA Heat Pump Conference (2023)

[7] Trough pumps to pulp: greening the paper industry's heat. A joint paper by the European Heat Pump Association (EHPA) and the Confederation of the European Paper Industries (Cepi) (2023)

[8] https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/energy-consumption/#:~:text=The%20electrical%20energy%E2%80%9D%20consumption%20accounted,from%2021.5%25%20in%201990)

[9] https://www.petrochemistry.eu/about-petrochemistry/flowchart/?_gl=1*ci9zt5*_up*MQ..*_ga*MTU4MzUzODI1MC4xNjg2NjY1Mjcz*_ga_WQPSN2ZBNV*MTY4NjY2NTI3Mi4xLjAuMTY4NjY2NTI3Mi4wLjAuMA

[10] Gulf Publishing Company (2010), Hydrocarbon Processing's Petrochemical Processes 2010.

[11] https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/european-market-overview/

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

[12] https://www.icis.com/subscriber/icb/2021/08/06/10671235/chemical-profile-europe-phenol/#_=_

[13] Kiss, A. & Smith, R. (2020), Rethinking energy use in distillation processes for a more sustainable chemical industry, Energy vol. 203, 2020.

[14] Bazzanella, A., & Krämer, D. (Eds.). (2017). Technologien für Nachhaltigkeit und Klimaschutz-chemische Prozesse und stoffliche Nutzung von CO2: Ergebnisse der BMBF-Fördermaßnahme. DECHEMA Gesellschaft für Chemische Technik und Biotechnologie eV.

[15] Kearns, D., Liu, H., & Consoli, C. (2021). Technology readiness and costs of CCS. Global CCS institute, (3).

[16] Bhadola, A., Patel, V., Potdar, S., & Mallick, S. (2020). Technology Scouting—Carbon Capture: From Today's to Novel Technologies. Concawe Group.

[17] Brickett L. (2015). DOE/NETL Carbon Capture Program - Carbon Dioxide Capture Handbook

[18] F. Bless, C. Arpagaus and S. Bertsch, "Theoretical investigation of high-temperature heat pump cycles for steam generation," 13th IEA Heat Pump Conference, p. 357–369, 2021.

[19] Webinar: Industrial Heat Pumps and Steam-Generation. Capabilities and Challenges of Heat Pumps in Industrial Processes. BAMBOO-webinar_high-temperature-heat-pumps-1.pdf (bambooproject.eu)

[20] AHEAD - Advanced Heat Pump Demonstrator. AHEAD - Advanced Heat Pump Demonstrator | NEFI

[21] Annex 58 – High Temperature Heat Pumps. Task 1 – Technologies. Task Report. August 2023. Report no. HPT-AN58-2. Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP).

[22] Annex 58 - High Temperature Heat Pumps. Task 1 - Technologies. Task 1 - Technologies - Annex 58 (heatpumpingtechnologies.org)

[23] Steam supply heat pump for distillation process at Hokkaido Bioethanol - casehokkaido-bioethanol.pdf (heatpumpingtechnologies.org)

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

[24] High Temperature Heat Pump for Steam Production at AstraZeneca - caseastrazenecaolvondo.pdf (heatpumpingtechnologies.org)

[25] IEA Heat Pump Centre Newsletter. Vol. 8, No. 4, December 1990.

[26] USE OF A HEAT TRANSFORMER BETWEEN TWO DIFFERENT AND INDEPENDENT PROCESSES IN A STEEL PLANT | | Project | Fact sheet | ENG | CORDIS | European Commission (europa.eu)

[27] Arnas Lubis, Niccolo Giannetti, Seiichi Yamaguchi, Kiyoshi Saito, Naoyuki Inoue. Experimental performance of a double-lift absorption heat transformer for manufacturing-process steam generation. Energy Conversion and Management 148 (2017) 267–278.

[28] Kiyoshi Saito, Naoyuki Inoue,Yasuaki Nakagawa,Yukihiro Fukusumi,Hiroyuki Yamada &Tomoyoshi Irie. Experimental and numerical performance evaluation of double-lift absorption heat transformer. Science and Technology for the Built Environment. Volume 21, 2015 - Issue 3: 2014 International Sorption Heat Pump Conference.

[29] Vahterus web-page. www.vahterus.com

[30] Arne Høeg, Kristian Løver, Trond-Atle Asphjell, Norbert Lümmen. Performance of a new ultra-high temperature industrial heat pump. 14th IEA Heat Pump Conference (2023).

[31] No. 44 - Steam Thermocompressor Systems (invenoeng.com)

[32] Linnhoff March. Introduction to Pinch Technology (1998).

[33] Ian C. Kemp. Pinch Analysis and Process Integration. A User Guide on Process Integration for the Efficient Use of Energy (2007).

[34] F. Schlosser, M. Jesper, J. Vogelsang, T.G. Walmsley, C. Arpagaus, J. Hesselbach. Large-scale heat pumps: Applications, performance, economic feasibility and industrial integration. Renewable and Sustainable Energy Reviews 133 (2020) 110219

[35] D. Olsen, Y. Abdelouadoud, P. Liem, S. Hoffmann, B. Wellig. Integration of Heat Pumps in Industrial Processes with Pinch Analysis. 12th IEA Heat Pump Conference (2017)

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

[36] Bahador Bakhtiari, Louis Fradette, Robert Legros and Jean Paris. Retrofit of Absorption Heat Pumps into Manufacturing Processes: Implementation Guidelines. The Canadian Journal of Chemical Engineering. Volume 88, October 2010.

[37] Mengying Wang, Chun Deng, Yufei Wang, Xiao Feng, Xingying Lan. Process Integration and Selection of Heat Pumps in Industrial Processes. Chemical Engineering Transactions. Vol. 70 (2018).

[38] IEA Heat Pump Program Annex 48 – Task 3: Application of existing models (2020)

[39] Felix Ziegler. Recent developments and future prospects of sorption heat pump systems. International Journal of Thermal Sciences Volume 38, Issue 3, March 1999, Pages 191-208.

[40] Florian Schlosser, Cordin Arpagaus, Timothy Gordon Walmsley. Heat Pump Integration by Pinch Analysis for Industrial Applications: A Review. Chemical Engineering Transactions. Vol. 76 (2019), https://doi.org/10.3303/CET1976002.

[41] Marcel Ulrich Ahrens, Sverre Stefanussen Foslie, Ole Marius Moen, Michael Bantle, Trygve Magne Eikevik. Integrated high temperature heat pumps and thermal storage tanks for combined heating and cooling in the industry. Applied Thermal Engineering 189 (2021) 116731.