MODULE 1

CHAPTER 2: ANALYSIS OF WASTE HEAT AND COLD TECHNOLOGIES

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Abbreviations

ASHP: Air Source Heat Pump
AHT: Absorption Heat Transformer
CHP: Combined Heat and Power
COP: Coefficient Of Performance
DH: District Heating
DHC: District Heating and Cooling
ECO: Economizer
EU: European Union
HE: Heat Exchanger
HP: Heat Pump
HPHE: Heat Pipe Heat Exchanger
HTHP: High Temperature Heat Pump
HTF: Heat Transfer Fluid
HU: Heat Upgrade
LHTES: Latent Heat Thermal Energy Storage
ORC: Organic Rankine Cycle
PCM: Phase Change Material
PHE: Plate Heat Exchanger
R&D: Research and Development
RES: Renewable Energy Sources
sCO2: Supercritical CO2
STES: Sensible Thermal Energy Storage
STHE: Shell and Tube Heat Exchanger
TES: Thermal Energy Storage
VHTHP: Very High Temperature Heat Pump
WF: Working Fluid
WH/C, WH/WC: Waste Heat/Cold
WHTC: Waste Heat to Cold
WHTH: Waste Heat to Heat
WHR: Waste Heat Recovery
WHP: Waste to Power
WSHP: Water Source Heat Pump

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1 Introduction

The availability in the market of suitable recovery technologies of waste heat and cold for the identified source is the third component needed to implement a good waste heat and cold recovery project, as described in Chapter 1 and Figure 1.

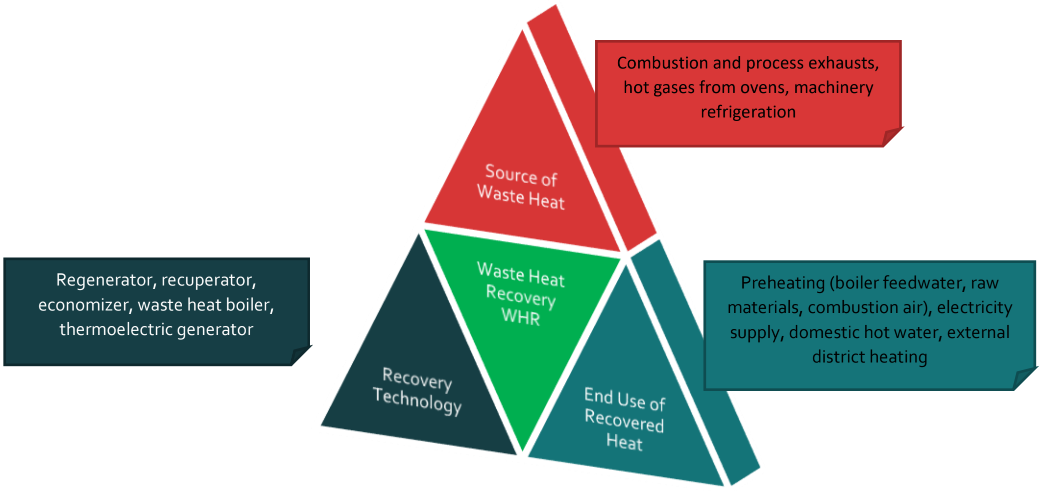

Figure 1: Essential components for Waste Heat Recovery (WHR)[1]

The equipment used for waste heat recovery must take into account parameters such as pressure and temperature operation ranges, waste heat source size (i.e. kW, MW) and waste heat intermittency (i.e. batch process or continuous process). Additional aspects, such as the waste heat carrier (i.e. gas, liquid or solid) and the purity and corrosiveness and of the waste heat streams are interesting to be considered. The existence of impure and/or corrosive products or materials that could lead to phenomena such as fouling, chemical degradation and gradual wear&tear of the heat exchanger surfaces, pipes and auxiliary components (e.g. pumps). The presence of extreme values in any of the above parameters will probably mean the mandatory use of special design and materials and therefore higher implementation costs. In the market, there are different technologies available depending on the type and power of the waste heat source, the temperature ranges and the final use of the energy. Figure 2 shows the main technologies for using waste heat for several ranges of temperature and thermal power.

The document is structured into five main sections, each one dedicated to a macro category of WH/C recovery technology, as they are classified in Figure 3:

1. **Waste Heat-to-Heat (WHTH)**: Passive WH/C recovery technologies designated to transfer heat from a source to a sink.
2. **Thermal Energy Storage (TES)**: Passive technologies designated to store thermal energy for subsequent use in time, bridging mismatch between thermal energy availability and thermal energy demand.
3. **Waste Heat-to-Cold (WHTC)**: active technologies which transform original WH stream to produce cooling.
4. **Waste Heat-to-Power (WHTP)**: active technologies which transform a WH stream to an electrical power output driving an energy conversion process
5. **Heat Upgrade (HU) technologies**: active technology which alters the conditions at which WH is available but do not transform it into a different form of energy

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Within the section of each macro-category, the individual technologies are reviewed with a focus on operating principle, performance and typical applications, prioritizing consolidated technologies available in the market.

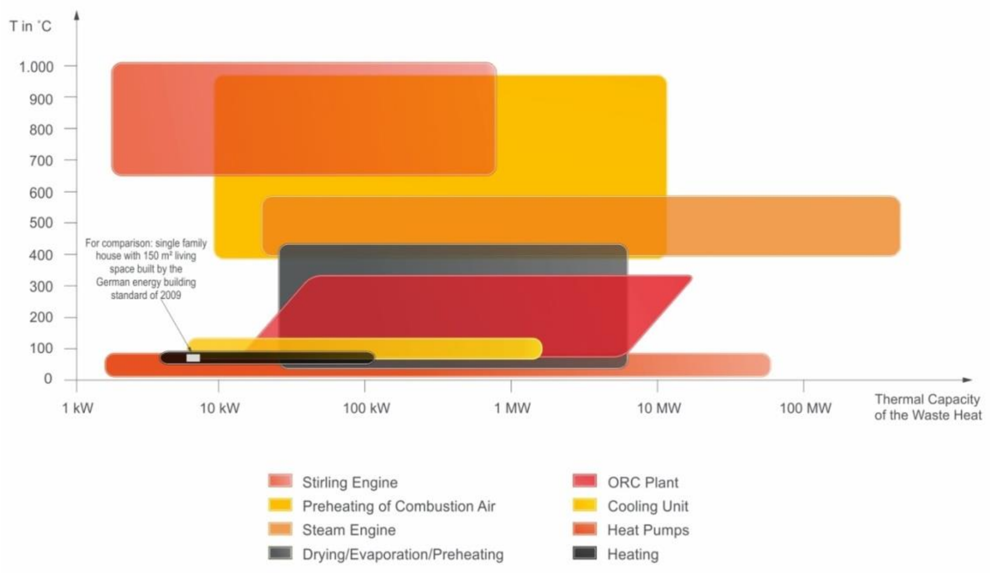

Figure 2: Categorization of waste heat utilization technologies. Source: Sächsische Energieagentur GmbH

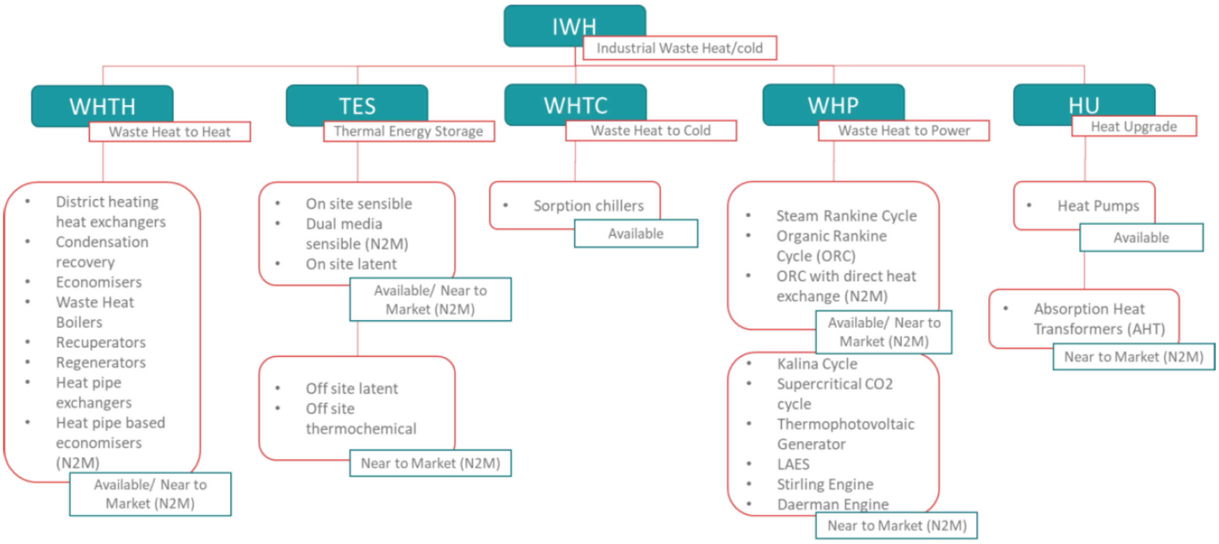

Figure 3: Classification of the technologies for recovery of industrial waste heat and waste cold [2]

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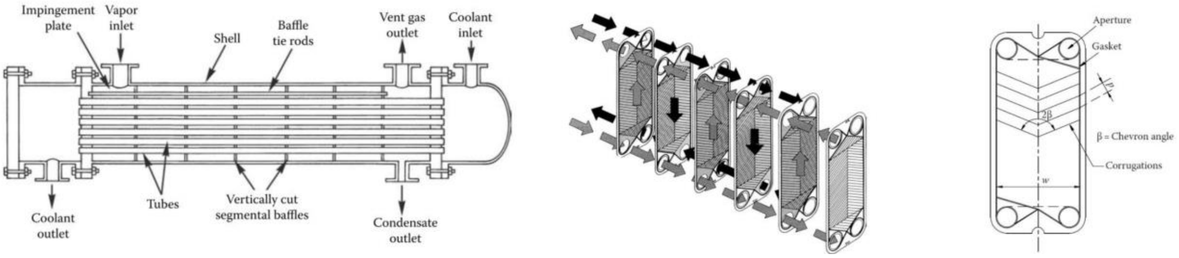
2 Waste Heat to Heat (WHTH) technologies

District Heating Heat Exchangers (DH HE)

According to [3], the fundamental idea of district heating is to use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a heat distribution network. The enabling technology to recover the waste heat from industrial processes and transfer it to the district heating network (DHN) is the District Heating Heat Exchanger (DH HE). The Shell and Tube heat exchanger (STHE) and Plate Heat Exchanger (PHE) are the most common.

STHEs are built of round tubes mounted in a cylindrical shell with the tubes parallel to the shell. One fluid flows inside the tubes, while the other fluid flows across and along the axis of the exchanger. STHEs provide relatively large ratios of heat transfer area to volume and weight and they can be easily cleaned. They offer great flexibility to meet almost any service requirement. STHEs can be designed for high pressures relative to the environment and high-pressure differences between the fluid streams [4].

PHEs are built of thin plates forming flow channels. The fluid streams are separated by flat plates[4]. They are particularly well suited to liquid–liquid duties, whereas they are not recommended for gas-to-gas applications [5]. The typical industrial applications cover thermal duties in the range hundreds of kWs to a few MWs and water pressures up to 60 bar [6].



a) *Shell and tube heat exchanger*

b) *Diagram of gasketed PHE*

Figure 4: Diagram of different types of HE [4], [5]

Economizers (ECO)

Economizers (ECO) are devices typically used to recover the waste heat from the flue gas at the outlet of industrial steam boilers at temperatures around 200-250°C to preheat the feed water entering the boiler up to 100-150°C. For every 6°C rise in feed water temperature through an economizer, there is 1% saving of fuel in the boiler [5]. The typical industrial applications cover thermal duties in the range of hundreds kWs to a few MWs and water pressures up to 60 bar [6].

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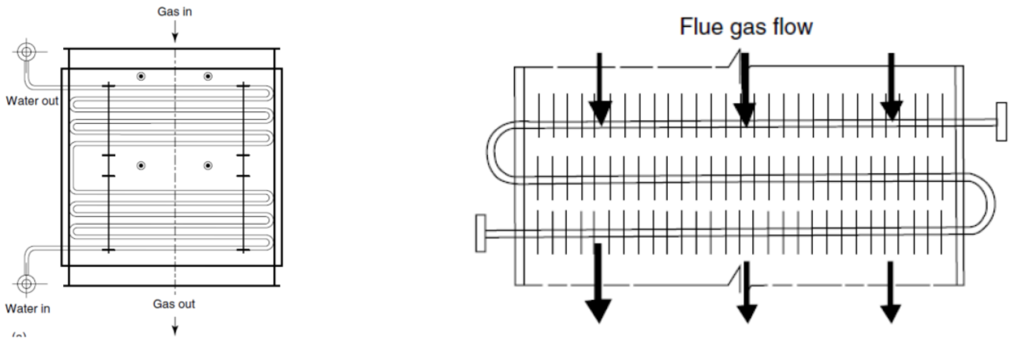

a) *Bare tubes ECO*

b) *Finned tubes ECO*

Figure 5: Diagram of different types of ECOs [7]

Heat pipe heat exchangers (HPHEs)

A significant portion of industrial processes generates WH in the form of gas streams (exhausts) under challenging operating conditions such as large mass flow rates, high temperatures or high content of some substances which may cause fouling or wearing in the equipment [8].

Heat pipe heat exchanges (HPHEs) are a class of HEs designed to meet harsh operating conditions, enabling WH recovery in industrial processes where the use of traditional HEs would be technically and/or economic not viable. The main difference between the conventional HEs and HPHEs is that the two streams exchange heat *only* via a series of components called "heat pipes", which are oriented transversally to the flow direction of the two streams. Each individual heat pipe is a passive thermal device. It consists of a sealed shell, a wick structure and a certain amount of working fluid that transfers heat from the hot side to the cold side through continuous vaporization and condensation [9].

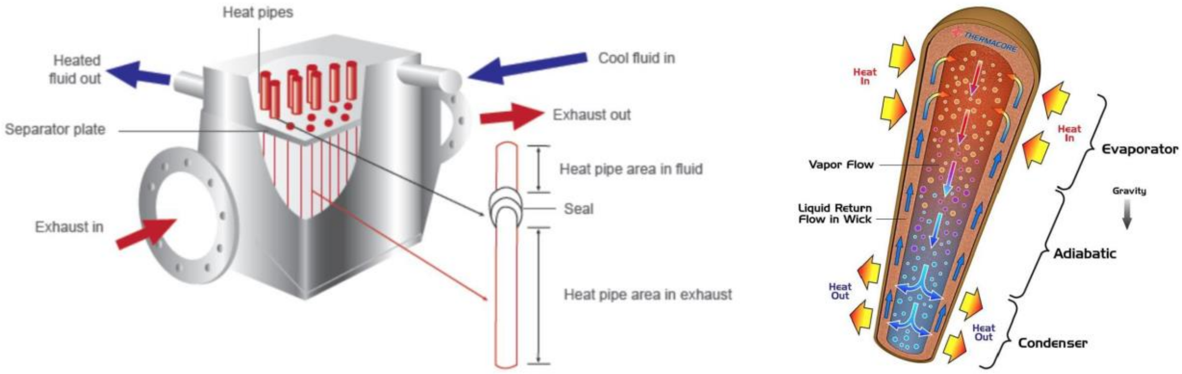

Figure 6: Heat pipe heat exchanger configuration [8] and structure of a individual heat pipe [10]

3 Thermal Energy Storage technologies (TES)

Sensible thermal energy storage (STES)

Sensible thermal energy storage (STES) is the most deployed TES technology, widely commercialized and used at scale for a broad range of temperatures. All the STES are based on the same operating principles: raising or lowering the temperature of a suitable storage medium (liquid or solid) to capture heat from a process (charging) or release it to a process (discharging) [11]. STES is also suitable for cold thermal energy, where cold is stored by lowering the temperature of the storage medium, and vice versa for release of cold.

Water is the most widely, cost-effective storage medium and it is commonly used up to about 120°C [12], [13]. Diathermic oils and molten salts are adopted as thermal storage media for temperature up to 250°C (oils) [14] and around 300-400°C (molten salts)[15], respectively.

Latent heat thermal energy storage (LHTES)

Latent heat thermal energy storage (LHTES) technology exploits the process of melting and solidification (i.e., phase change) of the storage media in order to store heat or cold. The storage media employed in LHTES are commonly referred as phase change material (PCM) [16], [17] [18]. During the energy storage process, heat transfer occurs between the PCM and suitable heat transfer fluid (HTF). During the charging process heat is supplied by the HTF to the PCM, causing the latter to melt; thermal energy is therefore stored in the form of latent heat of fusion. Conversely, during the discharge process heat is transferred from the PCM to the HTF. This causes the PCM to solidify, thus releasing the corresponding latent heat of fusion. The energy released by the PCM is then carried by the HTF and made available to the end-user.

In LHTES technology most of the energy is stored around the melting point of the PCM and in the form of latent heat (Figure 7). PCM selection it is therefore crucial since it largely dictates the operating temperature of the LHTES system and the energy stored per unity of volume (or mass), that is the energy storage density. In the context of WH/C, storage of waste heat streams requires therefore to match PCM melting temperature with the temperature at which the streams are available.

Broadly speaking, low temperature (<250°C) range PCMs are mostly constituted by organic materials such as paraffins and fatty acids, molten salts populate the class of medium/high temperature PCMs (<450°C) and, finally, metallic materials are currently explored as high temperature PCMs although their commercial application remains prohibitive due to technological and safety issues [19], [20], [21].

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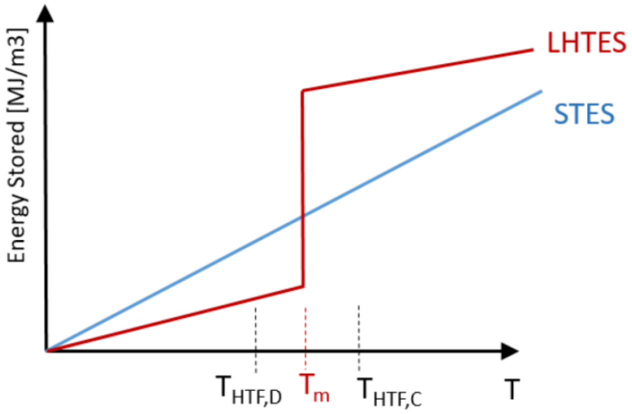
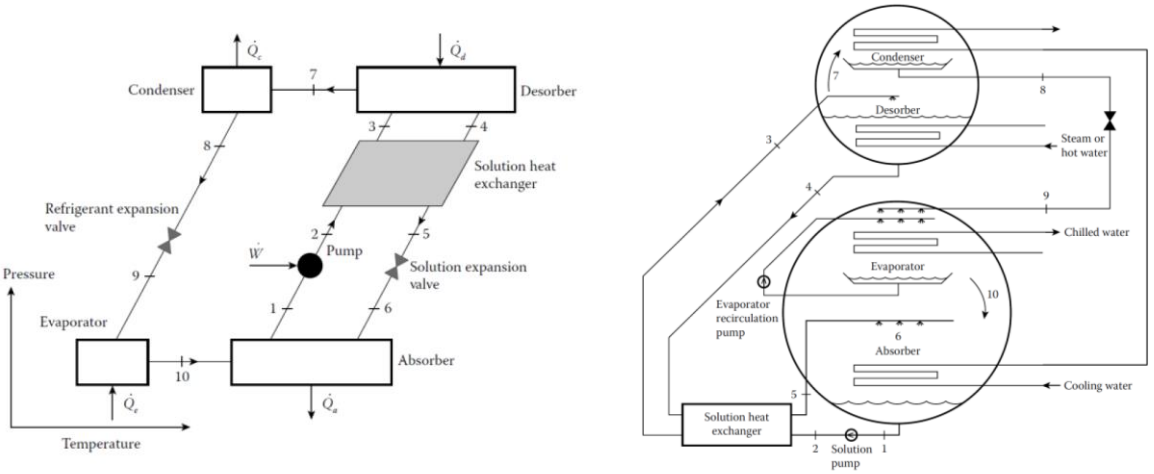


Figure 7: Thermal energy stored versus temperature increase: difference between latent TES (LHTES, red line) and sensible TES (STES, blue line) [1]

4 Waste Heat to Cold technologies (WHTC)

This section aims to present the cold production equipment from waste heat, thus achieving its recovery and valorisation. After a technological review for the production of cold from heat flows, the methods found were clustered in three main categories: sorbent systems, mechanical systems and specific systems. The focus of this Section is on sorbent cooling systems since absorption cooling based on the gas-on-liquid absorption is widely used for cold production.

Sorbents are materials that have the ability to attract and hold other gases or liquids. Sorption chillers can be defined as those equipment that through a sorption process (gas-on-liquid absorption or gas-on-solid adsorption) are able to establish two levels of pressure through which the refrigerant can condense and evaporate and therefore produce the required cooling effect. Figure 8 presents the cycle schematic and hardware schematic of a water/lithium bromide absorption chiller, which is the most widespread technology for air conditioning applications. The absorption chiller uses WH at low/medium temperatures, typically in the range 65-200°C, at the desorber (Q_d) and produces the cooling effect (Q_e) in the evaporator. The low grade heat streams released in the condenser (Q_c) and absorber (Q_a) are commonly rejected to the environment.



a) b)

Figure 8: Single-effect water/lithium bromide absorption chiller: a) Cycle schematic; b) Hardware schematic [22]

Single effect chillers require lower activation temperatures than double and triple effect chillers. However, double and triple effect chillers have higher values of performance (i.e., higher COP). Additionally some double effect chillers can be used in a dual way. When there is available hot water with waste heat origin (or solar thermal), the machines work as single effect chillers with lower performance but free cost in terms of fuel supply. When the hot water is not available, the machine is equipped with a natural gas direct fired burner that activates the second effect. Therefore, the machines operate with higher performance but with higher economic cost due to the natural gas consumption. Commercially available absorption cooling systems using lithium bromide-water or ammonia-water working pairs present a thermal COP in the range 0.7-1.4.

Absorption chiller emissions depend on the heat producer. If the chiller is integrated with CHP facilities, there are no incremental emissions from the absorption chiller. If the absorption chiller is a standalone unit that is direct fired, emissions will depend on the fuel used to produce thermal energy to drive the system and the specific combustion technology used for direct firing.

5 Waste Heat to Power technologies (WHTP)

Organic Rankine Cycles (ORCs)

In its simplest implementation the ORC layout is identical to a conventional Steam Rankine Cycle and comprises pump, evaporator, expander and condenser, as illustrated in Figure 9. The working fluid with low boiling point is pumped to the evaporator, where it is heated and vaporized by the exhaust heat. The generated high pressure vapour flows into the expander and its heat energy is converted to work. Simultaneously, the expander drives the generator and electric energy is generated. Then, the exhaust vapour exits the expander and is led to the condenser where it is condensed by the cooling water. The condensed working fluid is pumped back to the evaporator and a new cycle begins.

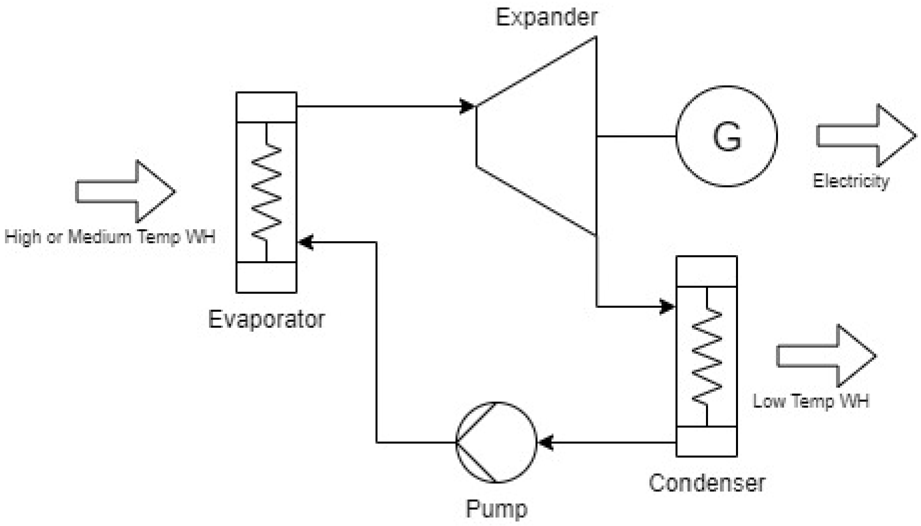


Figure 9: Schematic diagram of the ORC. Source: Own elaboration

ORC technology uses organic substances as working fluids which typically have a lower boiling point and critical temperature than that of water [23]. The low boiling point of ORC Working Fluids (WF) enables the conversion of low/mid-grade WH in the range 80-300°C into power.

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Thermal efficiency of ORCs varies in the range 5-25%. Such low values as well as the spread across a relatively large range should not come at a surprise. Indeed, ORC technology convert WH available in a wide temperature range between 80-500°C, and it is inherently less efficient than other power cycles which operate at higher temperatures. The application range of capacities and temperatures of the heat source that is conveniently covered by ORCs is usually called "mainstream ORC systems" and it is shown in Figure 10.

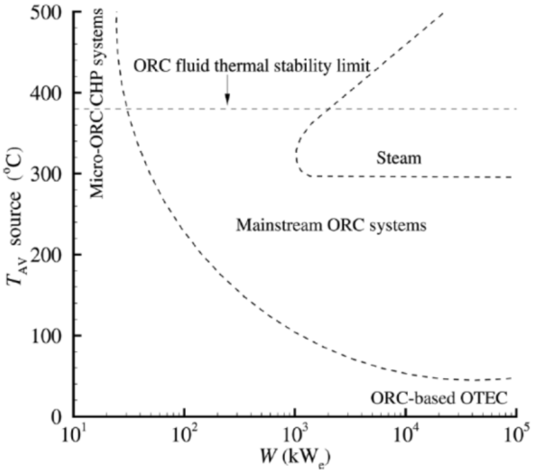

Figure 10: Current and future fields of application of ORC versus SRC in terms of average temperature of the energy source and power capacity of the system [24]

ORCs can be driven by multiple kinds of heat sources and, focusing on WHR, ORCs find application mostly in recovery of thermal energy from stationary internal combustion engines and gas turbines or from a variety of industrial processes. WH recovery from energy intensive processes by ORCs has been demonstrated at MW-scale while small scale ORCs (<100-200kW) remain under research development. The WHR ORC systems, represented in the middle power range of Figure 11, have estimated module costs around 2780 €/kW and averaging project costs of 3414 €/kW.

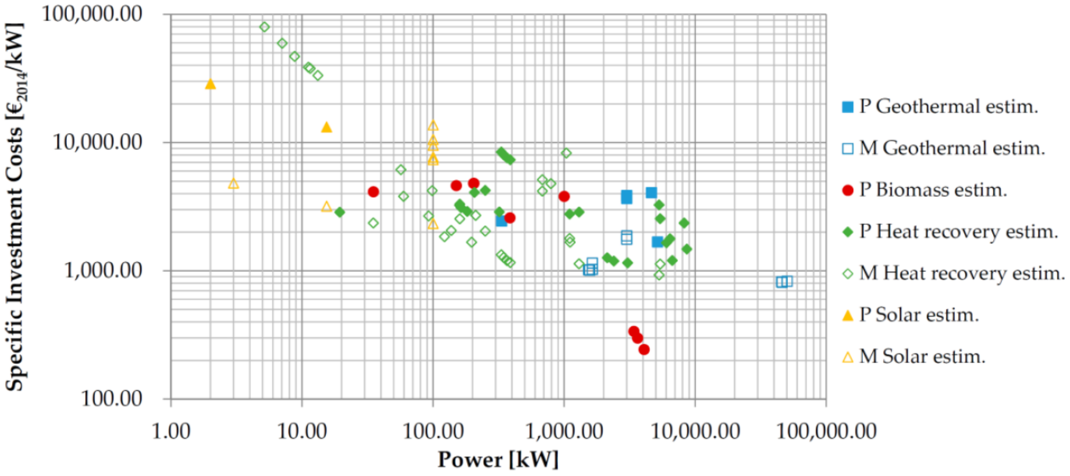

Figure 11: Estimated costs of ORC Projects (P) and Modules (M) in the literature. The WHR applications are reported using green marks [25]

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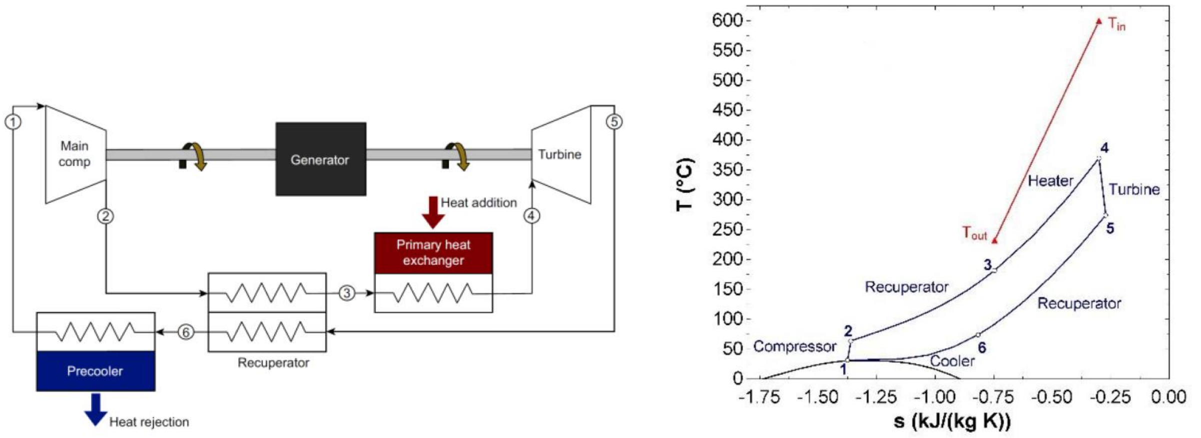
Supercritical CO2 power cycles (sCO2)

The sCO2 power cycle is a closed Brayton cycle operating with CO2 as working fluid. CO2 is compressed, heated up to the maximum cycle temperature, expanded in the turbine and cooled down to the lowest cycle temperature. The compressor inlet state is close to the CO2 critical point (73.8 bar; 30.98°C). In this region the real gas effects are significant and a marked reduction in compression work can be achieved. The flowsheet of the simple sCO2 cycle and the thermodynamic processes in the temperature-entropy (T-s) diagram are shown in

Figure 12. The CO2 leaving the compressor is first heated by regenerative heat transfer in the recuperator and then heated up to the turbine inlet temperature by the external waste heat source. Heat energy is introduced through a waste (primary) HE installed into the exhaust stack of a gas turbine or a furnace or the flue gas exhaust of an industrial process with 200°C to greater than 650°C operating temperature range [26]. While the lower temperature applications (200-350°C) are basically a variation of the ORC where CO_2 is used as WF, the higher temperature applications (350-650°C) are of particular interest as they represent an alternative to the Steam Rankine Cycles.



a)

b)

Figure 12: sCO2 power cycle: Process flow diagram [27]; b) T-s diagram of the sCO2 cycle and cooling profile of the WH source [13]

The sCO2 heat engine is a platform technology scalable from 250 kW_e to greater than 50 MW_e and is suitable with a wide range of heat sources for energy recovery with efficiencies up to 30%. Compared to ORC and SRC systems, sCO2 can achieve higher efficiencies over a wide temperature range of heat sources with compact components resulting in a smaller system footprint, lower capital and operating costs [26].

The high fluid density of supercritical CO2 enables extremely compact and highly efficient turbomachinery designs with simpler, single casing bodies. Its density makes the dimensions and weight of these compact HEs also much lower compared to a conventional STHE for the same heat duty (Figure 13). Carbon dioxide captures heat from a sensible heat source more effectively compared to water/steam, so a higher fluid temperature and thermal efficiency can be achieved for the same heat source.

On the other hand, operation near critical point is difficult and challenging due to the rapid changes in thermophysical properties of the CO2 near this point and the potential for entering the two-phase dome (gas-liquid) and having both liquid and gas in the flow. Linked to that, a significant drop of performance is to be expected in the warm season.

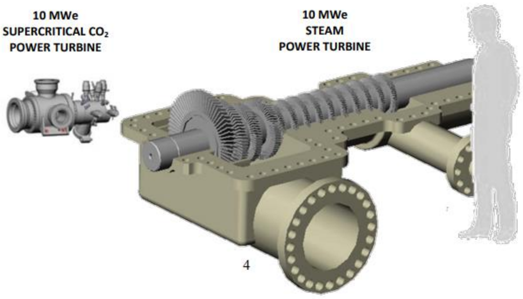


Figure 13: Echogen's 10 MWe sCO2 power turbine compared to a 10 MWe steam turbine [26]

Due to the low cycle pressure ratio and relatively high turbine outlet temperature, the sCO2 system must recuperate a large amount of heat to increase the thermal efficiency. The common HE types are not suitable as recuperators for sCO2 due to their pressure and temperature limitations.

Quite complex sCO2 architectures are required to enable an effective heat extraction from the WH source. These include a higher number of components (e.g., two turbines, two recuperators, two or three heaters) compared to the simple recuperated layout, as well as one or more flow splits. This increase the complexity and cost of the sCO2 systems for WHR.

Focusing on the WHR application, the sCO2 power cycle can provide a higher efficiency compared to the ORC for heat source temperatures higher than 350°C. Moreover, it is preferred to steam when the power output is lower than 20-30 MWe. The applications of this cycle are characterized by heat source temperatures in the range 300-600°C

Only one manufacturer worldwide provides sCO2 cycles for WHR applications. The installation cost is between 1800-1900 €/kW$_e$. The specific investment cost is up to 40% less compared to the more conventional steam bottoming cycle. The lower installed cost is the result of the simplicity of the sCO2 system, its smaller footprint, and reduced auxiliary system requirements.

6 Heat Upgrade technologies (HU)

The focus of this section is on how low grade WH sources can improve the performance or drive these heat upgrade technologies that can provide useful heat not only for the residential/commercial sectors but also for the industrial sector.

Heat Pumps (HP)

A Heat Pump (HP) is an energy device whose primary aim is to upgrade heat from a heat source to a heat sink at higher temperature. This is done in general at the expense of consuming some extra high-quality energy, for example electricity. The working principle of HPs is therefore very similar and for various instances identical to refrigeration or air conditioning systems, with the crucial difference that the amount of upgraded heat is the desired effect in HP systems. HPs can collect heat from a variety of sources, such as air, water and ground to deliver heating for residential and commercial buildings [28]. In the context of WH recovery, HPs are employed to valorise low-grade WH and upgrade it to higher temperatures, and thus making it more utilizable, for example as process heat.

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Figure 14 illustrates the principle of HPs utilization for the purpose of WH recovery and valorisation. Crucial parameters are the heat source temperature T_L (WH temperature) and the heat sink temperature T_H (usable heat temperature) across which the HP is capable to operate across. Such temperatures largely dictate the type of HP which can be utilized and the type of application.

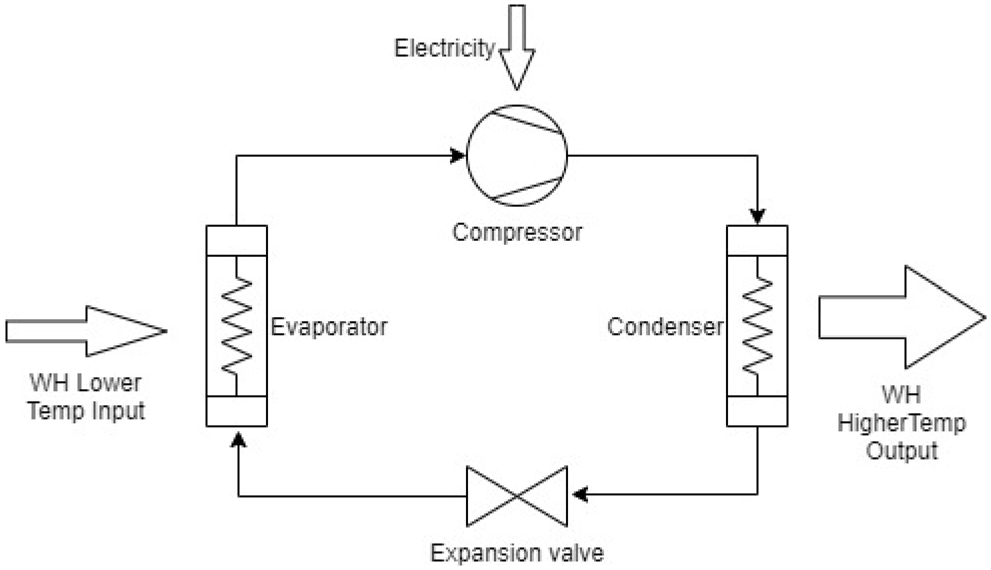

Figure 14: Heat pump utilization in the context of waste heat recovery. Source: Own elaboration

Air source heat pumps

Air source heat pumps (ASHPs) employ the outdoor air as heat source, thus drawing heat from the environment. It can be observed that ASHPs can upgrade low-grade heat around 20-40°C. However, the temperature of heat source greatly impacts on ASHPs performance. It can be noted that the COP reported for ASHPs may vary significantly, from about 1 to above 4, mostly due to the variation of outdoor temperature.

The availability of a low grade WH streams in place of ambient air could markedly improve the COP of the ASHP. In particular, the WH generated in the data centres can be profitably used by AHSP providing space heating for adjacent buildings (Figure 15) reaching a COP of 5 in some cases [29].

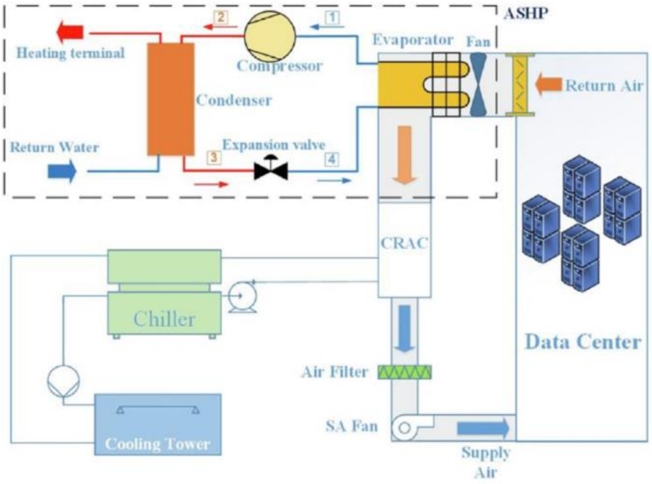

Figure 15: Coupling of an ASHP with the cooling system of a data centre [29]

Water source heat pumps

Water source heat pumps (WSHPs) take advantage of heat sources in form of liquid, in most instances water, rather than outdoor air as in the case of ASHPs. The use of water-based sources has a dual benefit: the temperature of the source is relatively more stable (i.e., smaller fluctuations) and less affected by outdoor conditions (e.g., summer versus winter). Furthermore, yearly averaged temperature of water sources tend to be higher than those of air sources. As a result, WSHPs reach higher COPs than ASHPs, often exceeding value of 4-5 [28], [30]. As a drawback, installation of WSHPs is somehow constrained as it clearly necessitates the presence of the water-based heat source.

In the context of WHR and valorisation, the utilization of sewage or wastewater streams as heat sources for WSHPs is of interest. Sewage, wastewater and more generally low-temperature water streams are common carriers of low-grade WH from industrial processes, often difficult to be recovered since typically available in the range 10-30°C [30], [31], [32], [33].

High temperature and very high temperature heat pumps

Air and water source heat pumps utilize heat sources up to ~35°C and upgrade heat to maximum temperature around 70-80°C. Consequently, they are mostly used for valorisation of low grade WH, or in the context of space and water heating. This makes ASHPs and WSHPs unsuitable for upgrade and valorisation of WH to temperatures above 80°C, which are commonly required in industrial sectors such as Pulp & Paper, Food & Beverages, and Textile [34]. In such contexts, high temperature heat pumps (HTHPs) and very high temperature heat pumps (VHTHPs) are of particular interest for industrial applications and upgrade of WH from industrial processes. HTHPs commonly refers to HPs capable to reach a maximum temperature of ~100°C at the condenser of the machine, while the concept of VHTHPs push the operational envelop up to ~160°C (Figure 16).

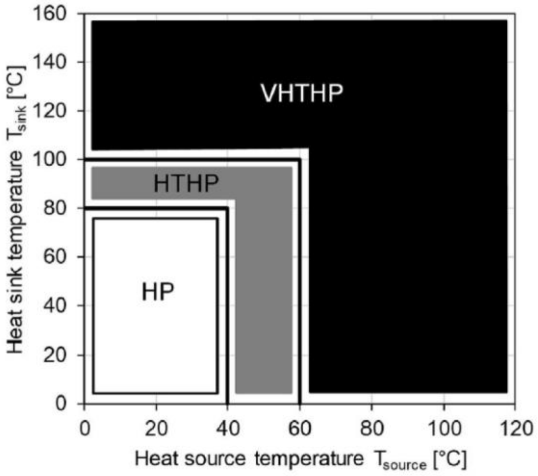

Figure 16: Development of temperature levels for compression heat pumps. HP: conventional heat pump; HTHP: high temperature heat pump; VHTHP: very high temperature heat pump [34].

From technological stand point HTHPs are an established technology and with an established supply chain. Quite manufacturers offer HPs which are able to upgrade heat to at least 90°C with products ranging from 20 kW to >1 MW in heating capacity (i.e., amount of WH upgraded).

VHTHPs for heat upgrade above 120°C currently remain subject of R&D projects and only a handful of commercially viable products are available. However, the considerable number of ongoing R&D

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projects and a quick evolution in the research field provides evidence that VHTHPs with heat sink temperatures of up to 160°C will reach market maturity in the coming years.

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Absorption Heat Transformers

Absorption heat transformer (AHTs) is a near-to-market technology which uses WH at low/medium temperature typically in the range 60-95°C and transforms it into two separate thermal energy streams: high temperature heat and low temperature heat. Thus, AHTs valorise WH by upgrading part of it to higher temperature, hence making it more utilizable, but also producing a secondary low temperature thermal energy stream which might be used for cooling purposes.

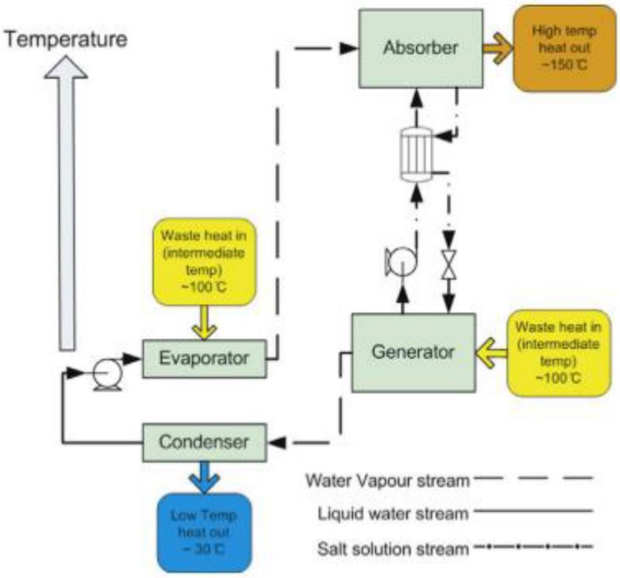

Figure 17: Layout of a single stage AHT [35]

The layout and key components of a single stage heat transformer are presented in Figure 17. A WH source is used to supply heat to the Generator, in which sorbate (more volatile component) is separated from the absorbent. A typical pair utilized in AHTs is LiBr-H_2O solution [36]. The sorbate is then condensed, releasing the corresponding latent heat producing a cooling effect (i.e., low temperature heat source). The sorbate (liquid at the outlet of the condenser) is evaporated (evaporator) and directed to the Absorber where it recombines with the liquid absorbent. The recombination process is exothermic, releasing the heat of absorption. This provides higher-grade heat at the Absorber. A temperature lift in the range of 30-60°C is typically achieved [36]. The cycle is closed by the diluted absorbent flowing back to the Generator. The COP of these machines is less than 0.5.

AHT technology has been demonstrated and fully integrated with the industrial process in a small number of cases. AHT has been reported to deliver significant energy savings, although economic viability still needs to be fully documented, which is in the range of 190-500 €/kW. Commercial uptake has therefore been lagging and it appears that no commercial products are currently available on the market. Furthermore, it has been reported that AHT are still not utilized in industry because "they are still an unknown entity" [35]. On the other side, AHTs are usually robust (low maintenance) and are thermally driven system, with minimal electrical input.

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