A MINI-REVIEW OF INDUSTRIAL WASTE SOURCES, EFFICIENCY ENHANCEMENT TECHNIQUES, AND HEAT UPGRADE SOLUTIONS WITH AN EMPHASIS ON THERMOCHEMICAL PROCESSES

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ABSTRACT

Industries consume huge amounts of energy to cover their needs and produce significant amounts of waste heat at various temperature levels and in different forms. The proper exploitation of these waste heat streams to produce useful outputs (e.g., higher temperature heat, electricity, etc.) would increase the overall efficiency and sustainability of industries. The objective of the present mini-review article is to briefly discuss the main available waste heat sources in industries (e.g., flue gases, hot radiative surfaces, etc.) and the possible ways for exploiting them. Different industries, including Aluminum, Cement, Ceramic, Chemical, Food & Beverages, Glass, Iron & Steel, Paper/Pulp, and Wood, are covered. Energy efficiency improvement techniques such as heat recovery, air preheating, thermal storage, condensing economizers, organic Rankine cycles, heat pipes, etc. are investigated. An emphasis is also given to heat upgrade techniques for producing heat at higher temperatures than the waste heat to be re-used again in the industry. Thermochemical heat upgrading is studied in more detail because of its promising attributes. The conclusions of this work highlight the most efficient methods for waste heat recovery and upgrading in the industry as well as the future directions in this area.

1 INTRODUCTION

The industrial sector is responsible for 26% of the European Union's (EU) final energy demand and for 48% of the final CO_2 emissions (“Database - Eurostat”, 2023). Thermal energy consists of 70% of the consumed energy in industrial processes (e.g., furnaces, dryers, boilers, etc.), while 1/3 of the thermal energy is wasted in the form of e.g. flue gases, radiative thermal losses, etc. in various temperature levels (Agathokleous *et al.*, 2019). Specifically, the yearly waste heat potential is estimated at 300-350 TWh in the EU (Agathokleous *et al.*, 2019) representing a significant amount of thermal energy and highlighting the potential for its possible exploitation.

Numerous industries can be ideal candidates for waste heat recovery (WHR). The recovered heat can be used for electricity production via a proper thermodynamic cycle (e.g., Organic Rankine Cycle – ORC) (Loni *et al.*, 2021) or in other processes within the same industry, such as heating and/or cooling (Zhang *et al.*, 2017). Another option is the heat upgrade of the available waste heat stream for re-utilization in high-temperature processes. Aluminum, Cement, Ceramic, Chemical, Dairy, Food & Beverages, Glass, Iron & Steel, Paper / Pulp, Textile, and Wood are some of the industries with the most extensive waste heat stream availabilities. Among them, some of them are more energy-intensive and others are less. For example, the cement industry is a very energy-intensive industry with an energy demand level almost 10-fold of that in the wood industry, and 40-fold of the industries on the production of iron-based materials (Korczak *et al.*, 2022). Another interesting industry to investigate in this sense is the aluminum industry as the demand for aluminum is estimated to increase by 200-300% by 2050,

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compared to 2013 (Haraldsson and Johansson, 2018). Statistics show that 70% of the greenhouse gas emissions of the industrial sector are produced by the iron & steel, chemical, and non-metallic minerals industries ("SpringerLink", 2023).

The objective of the present mini-review is to identify the waste heat sources in basic industries and to determine the most competitive exploitation techniques of the waste heat streams, giving thermochemical heat upgrading methods a spotlight. Moreover, the paper discusses some enhancement techniques that can be performed within the industrial sector to increase energy efficiency. The conclusions of the present work can be used as guidelines for further steps in the industry to achieve higher levels of sustainability.

2 ENERGY EFFICIENCY IMPROVEMENT TECHNIQUES

The energy efficiency improvement in the EU industries is a critical issue for achieving sustainability. In this direction, various ideas have been suggested and applied in the industrial sector. Except for WHR, which is the major efficiency enhancement method, there are additional techniques that can be applied. The following bullets briefly summarize the ways that industries can achieve sustainability:

- Heat recovery technologies can be applied for thermal energy re-utilization or power production by the use of a power cycle. Typically, these kinds of systems recover the heat contained in a hot air or gas stream and provide heat input to another device (e.g., heat exchanger, storage unit, power cycle). The most common power cycle is the organic Rankine cycle (ORC), while the installation of thermoelectric power generation units has been suggested (Barati *et al.*, 2011).
- Use of advanced power cycles that can optimally exploit the waste heat streams. Trilateral cycles are units that present optimal compatibility between the waste heat stream and the cycle's heat input, minimizing the exergy destruction losses. They can be applied in applications with temperatures in the range of 70-200^{o}C, offering significant potential to increase the heat recovery exploitation efficiency compared to typical ORC (Agathokleous *et al.*, 2019).
- Heat upgrade by using thermochemical cycles that can increase the temperature of the waste heat streams and re-utilize them in other industrial processes (Michel *et al.*, 2023).
- Improvement of the capacity utilization of the industries (Maghrabi *et al.*, 2023) which is about 85% in the last decades ("European Chemical Industry - cefic.org", 2023).
- Preheating the combustion air with various techniques (e.g. from exhaust gases) to reduce the fuel consumption in the combustion chamber or the furnace (Agathokleous *et al.*, 2019).
- Application of condensing economizers which can exploit latent and sensible heat from the flue gasses and increase the boiler efficiency significantly (e.g. over 90% or more) (Agathokleous *et al.*, 2019).
- The use of flat heat pipes is a promising idea for absorbing radiation thermal energy and they are a more effective solution compared to the common cylindrical heat pipes *(Agathokleous et al.*, 2019).
- The use of latent storage with phase change materials (Chowdhury *et al.*, 2018) is a promising choice in order to avoid superheating during thermal storage and also to increase the thermal energy storage density in [kWh/m^3].
- The application of heat pumps (Chowdhury *et al.*, 2018), and especially of high-temperature heat pumps (Gomez-Hernandez *et al.*, 2023), for upgrading the waste heat streams and enabling suitable re-utilization in the industrial processes. Especially in the cases where the electricity that drives the heat pumps comes from renewables (e.g., photovoltaics), this idea presents high sustainability.
- Refrigeration/cooling is produced by using sorption machines (e.g., absorption or adsorption chillers (Chowdhury *et al.*, 2018) which exploits waste heat streams in the range of 100-200^{o}C.
- The use of bioenergy (Chowdhury *et al.*, 2018) is also a choice for green heat/electricity production by the industries. Pyrolysis and gasification can be used for the proper conversion of the initial raw materials into efficient fuels.

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- Cogeneration/trigeneration is another option that can provide various useful outputs in the industry simultaneously leading to an increased overall efficiency (Kasaeian *et al*., 2020).
- Extra ideas regard carbon capture, utilization, and storage, hydrogen use as fuel or as energy storage material, as well as the application of thermochemical storage (Korczak *et al*., 2022).
- Other ideas regarding industrial sustainability are based on the recycling and reuse of industrial products (e.g. The substitution of cement with alternative materials) (Korczak *et al.*, 2022).

3 WASTE HEAT RECOVERY IN INDUSTRIES

The benefits of the WHR devices are various, and they are related to energy savings, cost reduction, CO_2 emissions reduction, etc. Specifically (Agathokleous *et al.*, 2019): a) electricity production, b) fuel consumption reduction, c) reduction of the operating cost, d) productivity increase, and e) reduction of CO_2 emissions and generally the greenhouse gas emissions. The waste heat recovery sources (WHS) are classified according to the temperature level in the following categories (Panayiotou *et al.*, 2017):

A) Low-Temperature (LT) WHS: < 100ºC
These WHS can be found in almost all industries and thus is a challenge to utilize them. Thermochemical heat upgrade techniques seem to be a great technology to exploit these WHS. An example of LT WHS is the cooling water from various compressing and condensing processes (Brückner *et al.*, 2015).

B) Medium-Temperature (MT) WHS: 100–299ºC
MT WHS can be found in all industries. In energy-intensive industries, they can be found in steam boilers and the exhaust gases of heat recovery devices. Another important process with MT WHS potential is the distilling process of the chemical industry (Brückner *et al.*, 2015).

C) High-Temperature (HT) WHS: ≥ 300ºC
Most of the time, HT WHS are the result of combustion processes or processes taking place in furnaces or kilns. These temperature ranges can be found in energy-intensive industries and are related to HT needs. For example, they can be found in the glass production, metal production, and ceramics industries. The most representative processes that can be exploited in this field are refining and melting (Brückner *et al.*, 2015).

Table 1 presents the share of each industrial sector in the overall waste heat potential. The iron and Steel industry, as well as the non-metallic minerals industry, appear to have the highest share, which is equal to 11.40% in both cases.

Table 1: Share of different industries in the waste heat potential (Panayiotou *et al.*, 2017)

Type of industry	Waste heat potential
Iron and Steel	11.40%
Chemical and Petrochemical	11.00%
Non-ferrous metal industry	9.59%
Non-metallic minerals	11.40%
Food and Tobacco	8.64%
Paper Pulp and Print	10.56%
Wood and Wood Products	6.00%
Textile and Leather	11.04%
Other	10.38%

Table 2 includes the basic material industries and the temperature levels of the thermal needs and the waste heat streams. The glass industry is an energy-intensive industry, consuming 4-17 GJ of energy per ton of glass product (Zier *et al.*, 2021). The waste heat temperature range lies between 140°C and

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1550°C for the glass melting process, where the maximum temperature is found at the melting furnace (Saha and Chakraborty, 2017). The maximum waste heat temperature is associated with the melting process in the furnace due to the high melting point of SiO_2, estimated at 1650°C (Zier *et al.*, 2021). Another energy-intensive industry is the ceramics industry, with a maximum temperature of 1000°C in the ceramic kiln (Brückner *et al.*, 2015). The maximum needed heat temperature is 1850°C to produce refractory products (Furszyfer Del Rio *et al.*, 2022). The textile industry is of great importance, with a maximum energy demand of up to 80 MJ/kg of cloth produced (Ozturk *et al.*, 2020). The maximum heat waste temperature is estimated at 190°C for the stentering process (Ozturk *et al.*, 2020) and the maximum needed heat temperature is 250°C for the drying process (Brückner *et al.*, 2015). For the wood industry, although the main waste is wood waste, some WHS come from the cooling of the machinery, for instance. The maximum required heat temperature can reach up to 500°C drying of wood particles at rotary dryers (Panayiotou *et al.*, 2017).

Additionally, in the paper and pulp industry, waste heat stream temperatures can be up to 100°C for drying processes, while the required heat temperature for this process can be up to 200°C (Obrist *et al.*, 2022). Plastics are also considered important materials, with LT heat needs for drying and preheating processes, as well as MT applications such as separation, with a maximum temperature of 220°C (Farjana *et al.*, 2018). The fabricated and pure metals industry presents a huge variety of needed temperatures and WHS. The main waste heat streams regard the refining furnaces, with temperatures up to 1650°C (Brückner *et al.*, 2015). The heat needed also varies since the degreasing process needs temperatures of approximately 20°C (Farjana *et al.*, 2018) but the hot stoves require approximately 1500°C (Panayiotou *et al.*, 2017). Mining is an energy-intensive industry, with processes such as crushing and grinding, while its products include industrial materials and coal (Luberti *et al.*, 2022). One of the highly energy-intensive industries is the iron and steel industry, which is responsible for 8% of the global energy demand (Shahabuddin *et al.*, 2023). In this industry, waste heat streams can reach temperatures up to 1800°C for the process of steelmaking (Inayat, 2023). In the bricks and blocks industry, the temperature in the furnace of a brick kiln can be up to 1000°C, where the flue gas stream leaving the chimney can provide high-quality energy with a temperature higher than 200°C (Labib *et al.*, 2019). For non-ferrous metals production, a common process is the smelting process, with maximum temperatures at 1200°C (Panayiotou *et al.*, 2017). The cement industry is an energy-intensive industry, consuming large amounts of thermal and electrical energy, as well as significant amounts of raw materials. The maximum WHS can be found in the cement sintering process (Miró *et al.*, 2016), where the temperature of the needed heat can be up to 1500°C in the clinkering process because calcium oxide undergoes a high-temperature reaction (Rahman *et al.*, 2013).

Table 2: Waste heat streams and needs for the basic material industries

Material Industry	Heat waste [°C]	Heat needs [°C]	References
Glass	140-1550	325-1650	Brückner *et al.* (2015), Panayiotou *et al.* (2017), Saha and Chakraborty (2017), Zier *et al.* (2021).
Ceramic	150-1000	300-1850	Brückner *et al.* (2015), Furszyfer Del Rio *et al.* (2022).
Textile	30-190	40-250	Brückner *et al.* (2015), Lim *et al.*, (2022), Su *et al.* (2021).
Wood-based panels	110-170	40-500	Brückner *et al.* (2015), Panayiotou *et al.* (2017).
Paper & Pulp	60-100	40-200	Farjana *et al.* (2018), Obrist *et al.* (2022).
Plastics & Rubber	90-200	50-220	Farjana *et al.* (2018), Jia *et al.* (2018), Miró *et al.* (2016).

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Fabricated and Pure Metals	700-1650	20-1500	Brückner *et al.* (2015), Farjana *et al.* (2018), Panayiotou *et al.* (2017).
Mine	20-1600	50-1600	Farjana *et al.* (2018), Jia *et al.* (2018), Luberti *et al.* (2022).
Iron & Steel	35-1800	900-1800	Brückner *et al.* (2015), Inayat (2023), Panayiotou *et al.* (2017).
Bricks & Blocks	200-800	60-1000	Farhana *et al.* (2022), Labib *et al.* (2019), Su *et al.* (2021).
Non-ferrous metals	350-1650	200-1200	Brückner *et al.* (2015), Panayiotou et al. (2017).
Cement	300-1450	900-1500	Brückner *et al.* (2015), Miró *et al.* (2016), Rahman *et al.* (2013).

Table 3 includes thermal needs and waste heat streams for the food and beverage industry, as well as for the chemical industry. The food industry is considered one of the most important industries. The food sector consumes approximately 56 PWh per year (FAO, 2017). The maximum heat needed refers to the frying process, where the maximum temperature is approximately 200°C (Panayiotou *et al.*, 2017). For the tinned food industry, the maximum temperature levels can be found during the sterilization process, and the minimum levels are found in other important processes, such as cooking and pasteurization (Jia *et al.*, 2018). For the meat industry, the maximum temperature refers to the cooking process (Jia *et al.*, 2018). Another energy-intensive food industry with high heat waste potential and needs is the dairy industry. The most important thermal processes in the dairy industry are pasteurization and sterilization, with temperatures up to 120°C (Ramirez *et al.*, 2006). Agriculture presents heat needs with temperatures of about 90°C for drying and water heating processes, whereas flour and its by-products require approximately 80°C for sterilization (Farjana *et al.*, 2018). The brewery industry needs hot water of approximately 80°C for the mixing processes (Farjana *et al.*, 2018). One of the main food industries is the sugar industry, where sugar and ethanol are produced. The temperature of the exhaust flue gasses in this industry ranges from 150 to 300°C (Uphade, 2021). The chemical industry consists of various sectors, but the most important sector is the petrochemical one. WHS can be found in various processes, such as the bottom oil of xylene at 215°C (Su *et al.*, 2021).

Lastly, **Table 4** includes the thermal needs and waste heat streams for some other industries. Specifically, the reported industries regard the waste incineration & treatment, the automobile, the machinery & equipment, the power generation industry, the production of optical fiber cable, the surface treatment industry, as well as the cooling water industry. Various temperature levels are reported for the waste heat and the thermal needs of these industries.

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Table 3: Waste heat streams and needs for food and chemical industries

Industry	Heat waste [°C]	Heat needs [°C]	References
FOOD INDUSTRIES			
Food & beverages	30-300	20-200	Farjana *et al.* (2018), Panayiotou *et al.* (2017).
Tinned food	120-140	60-120	Farjana *et al.* (2018), Jia *et al.* (2018).
Meat	40-65	60-100	Farjana *et al.* (2018), Jia *et al.* (2018).
Dairy	30-150	60-180	Farjana *et al.* (2018) Jia *et al.* (2018), Ramirez *et al.* (2006).
Agriculture	30-60	80-90	Farjana *et al.* (2018), Jia *et al.* (2018).
Flour & By-products	40-65	60-80	Farjana *et al.* (2018), Jia *et al.* (2018).
Brewery	30-224	40-80	Farjana *et al.* (2018).
Sugar	70-300	70-120	Uphade (2021).
CHEMICAL INDUSTRIES			
Chemical general	100-400	20-300	Brückner *et al.* (2015), Farjana *et al.* (2018), Jia *et al.* (2018).
Petrochemical	98-215	52-200	Su *et al.* (2021).

Table 4: Waste heat streams and needs for other industries

Industry	Heat waste [°C]	Heat needs [°C]	References
Waste incineration & treatment	650-1430	100-1450	Brückner *et al.* (2015), Panayiotou *et al.* (2017).
Automobile	25-500	50-120	Farjana *et al.* (2018), Jia *et al.* (2018), Kurle *et al.* (2016).
Machinery & Equipment	85-650	20-120	Farjana *et al.* (2018), Jia *et al.* (2018), Rattner and Garimella (2011).
Power generation	30-980	30-800	Brückner *et al.* (2015), Cruz *et al.* (2021), Panayiotou *et al.* (2017), Rattner and Garimella (2011).
Production of OFC (Optical Fiber Cable)	200-350	45-1100	Brückner *et al.* (2015), Panayiotou *et al.* (2017).
Surface treatment using organic solvents	20-220	150-800	Brückner *et al.* (2015), Panayiotou *et al.* (2017).
Cooling water	30-230	20-30	Brückner *et al.* (2015), Rattner and Garimella (2011).

https://doi.org/10.52202/077185-0177

4 HEAT UPGRADE TECHNIQUES

Low-grade waste heat streams, typically with temperatures up to 100°C, can be effectively utilized through heat upgrade technologies. These systems facilitate the transfer of heat from a low-temperature medium to a high-temperature medium, often with the assistance of an external energy source. The primary objective is to enhance the temperature of the waste heat to a level suitable for feeding into various industrial processes. The heat upgrade systems are categorized into the following types: vapor compression high-temperature heat pumps (HTHP), sorption (absorption/adsorption) heat pumps or heat transformers, hybrid heat pumps, and thermochemical heat transformers (Zhang *et al.*, 2016), (Jiang *et al.*, 2020).

The most conventional, and widely used technology in this field is the vapor compression HTHP, which upgrades the heat at the evaporator temperature, to the higher temperature level of the condenser using a vapor compressor. Typically, these units achieve heat sink temperatures up to 160ºC (Zhang *et al.*, 2016). In recent years, researchers have examined the potential to expand the operating temperature range. Indicatively, Gomez-Hernandez *et al.* (2023) studied the utilization of the mixture of 5% CO_2 /95% acetone in an HTHP, calculating a maximum sink temperature of 200ºC, with a temperature lift that was equal to 70 K. Apart from vapor compression, Häggqvist *et al.* (2023) examined the implementation of a Stirling cycle-based heat pump, which can reach heat sink temperatures at about 200ºC, and even greater.

Furthermore, there are two types of absorption heat upgrade systems, i.e. the absorption heat pumps, and the absorption heat transformers. Both of them have a similar structure and include an absorber, a generator, an evaporator, and a condenser, while the most commonly used working pair is LiBr/H_2O. More specifically, the absorption heat pump is fed with a low-temperature waste heat at the evaporator and releases heat at a medium-temperature level, at the absorber, and at the condenser. Additionally, it requires a supply of high-temperature heat load, at the generator. The coefficient of performance (COP) ranges from 1.3 to 1.4 providing heat with a temperature up to 100ºC. On the other hand, the absorption heat transformer exploits a medium-temperature heat load at the evaporator, and the generator, with one part upgraded and the other downgraded. This technology achieves a COP of about 0.5 (Zhang *et al.*, 2016) and can deliver heat at temperatures up to 165ºC (Cudok *et al.*, 2021). According to the review study of Cudok *et al.* (2021), most absorption heat transformers in the industrial sector have been installed in the chemical and food industries. These units are fed with waste heat from one process of the industrial plant, with the upgraded heat supplied to the same or another process, while the low-temperature downgraded heat is released to the ambient, in most cases.

On the other hand, an adsorption heat pump typically consists of an adsorbent material, which is packed or coated onto an adsorbent bed and can be zeolite, silica gel, or activated carbon, an evaporator, which is fed with a low-temperature heat source, an expansion valve, as well as a condenser, which releases useful heat (Dias and Costa, 2018). The COP varies from 1.40 to 1.60 using silica gel/water, or from 1.30 to 1.50 using zeolite/water, while the condensing temperature ranges typically up to 60ºC (Pinheiro *et al.*, 2020). Moreover, the adsorption heat transformers include absorbent material, and similarly to the absorption heat transformers, have three temperature levels, being fed with heat at an intermediate level, and providing heat at a higher level (Saren *et al.*, 2023).

A couple of publications in the literature have concentrated on the combination of compression and absorption technologies within integrated hybrid systems. Indicatively, Liu *et al.* (2022) investigated a high-temperature compression-absorption heat pump, where ammonia-water was used as a working pair. The heat pump produced steam at a temperature of 154ºC and a pressure of 0.53 MPa, achieving an electricity-to-heat performance coefficient of 5.29. Furthermore, in certain scenarios, the heat source for the heat pump can originate from a solar field, especially from non-concentrating collectors such as flat plate collectors, evacuated tube collectors, or photovoltaic thermal collectors capable of producing low-grade heat (Rosales-Pérez *et al.*, 2023). As suggested by Martínez-Rodríguez *et al.* (2023), integrating a vapor compression heat pump with a field of flat plate collectors results in an 85%

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reduction in the aperture area compared to using solar collectors alone for industrial heat provision. Simultaneously, there is a decrease in both environmental impact and cost.

The aforementioned absorption/adsorption-based systems involve reversible sorption reactions between a gas and a liquid. In contrast, chemical sorption reactions between a gas and a solid take place in a thermochemical heat transformer. Although this technology is less mature, it has garnered considerable attention in recent years. Researchers have investigated pairs of salts with ammonia, methanol, water, or carbon dioxide. Water vapor, in particular, stands out as a promising option due to its low cost, low toxicity, and ability to provide heat at temperatures exceeding 150ºC (Michel and Clausse, 2020). In the case of using salt hydrate, the hydration process is exothermic, and the dehydration process is endothermic. Beyond its heat-transforming capabilities, this method also serves for thermochemical energy storage, with the exothermic reaction used for discharging and the endothermic one for charging (Stengler and Linder, 2020). Notably, Stengler *et al.* (2020) examined the implementation of the $SrBr_2/H_2O$ (strontium bromide/water) working pair in a thermochemical heat transformer, achieving high specific energy density, specific thermal power, and reaction rates. The hydration reaction occurred at 180ºC, while the dehydration reaction took place at 210ºC. Other studies have focused on ammonia-based thermochemical pairs. For instance, Jiang *et al.* (2020) analyzed a resorption-compression heat transformer, where sorbents such as $MnCl_2$, $SrBr_2$, $CaCl_2$, and NH_4Cl ammoniate were examined to react with ammonia. According to the results, when the heat source temperature ranged from 40 to 90ºC, the exergy efficiency was determined from 0.8 to 0.64, while the heat output temperature varied from 124 to 194ºC. Finally, **Table 5** summarizes and presents comparatively the aforementioned heat upgrade technologies.

Table 5: Heat upgrade techniques

Heat upgrade technique	**Heat sink temperature**	**Coefficient of performance**	**References**
High-temperature heat pump	Typically up to 160ºC Recent advances up to 200ºC and even more	3.5-5.5	Zhang *et al*. (2016), Gomez-Hernandez *et al*. (2023)
Absorption heat pump	Up to 100ºC	1.3-1.4	Zhang *et al*. (2016)
Absorption heat transformer	Up to 165ºC	~0.5	Cudok *et al*. (2021), Zhang *et al*. (2016)
Adsorption heat pump	Up to 60ºC	1.3-1.6	Pinheiro *et al.* (2020)
Thermochemical heat transformer	Up to 280ºC	Up to 0.7	Stengler and Linder (2020), Li *et al*. (2023)

5 CONCLUSIONS AND DISCUSSION

Waste heat recovery is a critical way to reduce CO_2 emissions, increase energy savings, and contribute to the decarbonization of the industrial sector. There are numerous ideas for exploiting the waste heat streams and one promising approach is the heat upgrade to cover thermal needs. The most important solutions that can be used for heat upgrade are given below:

- The high-temperature heat pump produces thermal energy up to 160ºC usually by consuming electricity which can be produced by renewables (e.g. photovoltaics).
- The absorption/adsorption heat transformers exploit low-grade waste heat streams (e.g. 100ºC) and they upgrade them into heat outputs of higher temperatures (e.g. 250ºC) for utilization in the industry.
- Thermochemical heat transformers with advanced materials such as $SrBr_2/H_2O$ which exploit the hydration reaction occurred at 180ºC, while the dehydration reaction took place at 210ºC.

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- Hybrid systems can combine electrical and heat input to upgrade the thermal energy and promote the flexibility of the total configuration.

According to the present literature review, there are several industries with high potential for utilizing their waste heat. More specifically, regarding the heat upgrade idea, the most suitable industries are the following:

- The textile industry waste heat temperature is estimated at 190°C for the stentering process and the maximum required heat temperature is 250°C for the drying process.
- The paper and pulp industry has waste heat streams that can be up to 100°C for drying processes and the heat needed for the processes can be up to 200°C.
- The plastics industries present low-temperature waste heat for drying and preheating processes, while they need medium-temperature heat of around 200-220ºC.
- The food & Beverage industries are also ideal candidates for heat upgrade. For instance, the dairy industry requires heat for pasteurization and sterilization, while there are also waste heat streams for exploitation.

Therefore, there is significant potential for the application of new ideas regarding heat upgrade technologies in various industries with the goal of developing a more sustainable and greener industrial sector in the next decade.

NOMENCLATURE

Abbreviations

COP	Coefficient of Performance
EU	European Union
HT	High-Temperature
HTHP	High-Temperature Heat Pumps
LT	Low-Temperature
MT	Medium-Temperature
ORC	Organic Rankine Cycle
WHR	Waste Heat Recovery
WHS	Waste Heat Sources

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