H2020 Work Programme

D5.7 – FINAL RELEASE OF SO WHAT INDUSTRIAL SECTORS WH/C RECOVERY POTENTIAL

Lead Contractor: ELEUKON GLOBAL (ELEU)

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[1] PU = Public
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22/11/2022	1.0	Pablo Fernández Arias (ELEU)	First Draft
28/11/2022	2.0	Pablo Fernández Arias (ELEU)	Addition of chapter 5, adjustment of temperature ranges and addition of pictures and references.

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Abbreviations

BFG: Blast Furnace Gas

COG: Coke Oven Gas

EAF: Electric Arc Furnace

EU: European Union

HRSG: Heat Recovery Steam Generator

HVAC: Heating — Ventilation — Air Conditioning

LNG: Liquefied Natural Gas

ORC: Organic Rankine Cycle

PH: Potential of Hydrogen

ppm: parts per million

RTOs: Regenerative Thermal Oxidizers

TEG: Thermoelectric Generator

UBC: Used Beverage Cans

VOCs: Volatile Organic Compounds

WH/C: Waste Heat/Cold

WP: Work Package

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Executive Summary

This document represents the Deliverable 5.7, titled "Final release of SO WHAT Industrial Sectors WH/C recovery potential", which belongs to Work Package 5 (WP5: "SO WHAT tool validation in real industrial democases") of the SO WHAT Project.

The deliverable is structured into the following six main chapters:

- Chapter 1: Introduction
- Chapter 2: Waste Heat Sources in the Industrial Sector
- Chapter 3: Industrial Sectors
- Chapter 4: Barriers to Waste Heat Recovery
- Chapter 5: Recovery of Waste Cold
- Chapter 6: Conclusion

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1 Introduction

The energy consumption of the industrial sector in all its forms (electricity, fuel, steam, etc.) accounts for around 25% of the total energy consumption of the countries that make up the EU. The transport sector accounts for around 30% and the rest, around 45%, is derived from the consumption of households and other consumers.

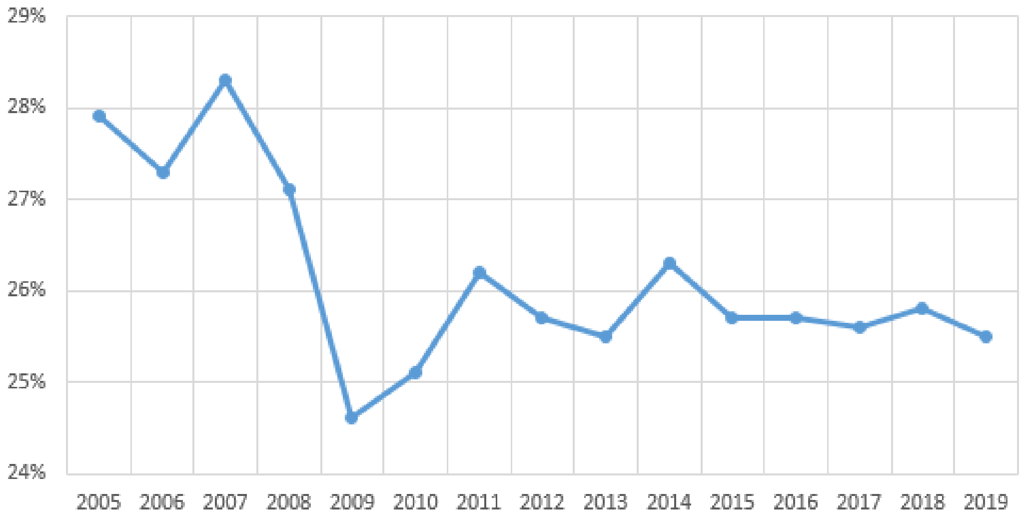

Figure 1: Percentage of energy consumption of the industrial sector 2005–2019 (European Union–27) (1)

The energy consumed by an industrial plant is usually divided into a large number of subsystems, which can be included in one of the following main categories:

- **Process energy use:** such as machine driving, process heating, process cooling and refrigeration, etc.
- **Non–process energy use:** such as HVAC, lighting, onsite transportation, etc.
- **On–site generation of power and other utilities:** such as steam, compressed air, water, etc.

More than 80% of the total power consumption of a plant usually comes from process energy use and on–site generation applications. Additionally, these two categories encompass areas where large energy losses typically occur (for example, process heating energy losses typically account for 25% to 55% of the total energy consumption). Nearly all losses from on–site generation and process power applications are lost as heat (convection, radiation, latent and sensible heat) that is transmitted to the environment. Recovering this waste heat and using it as a source of energy for industrial subsystems is one of the best methods to reduce energy consumption in industrial plants.

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2 Waste Heat Sources in the Industrial Sector

The waste heat sources from the industrial sector vary in terms of temperature, composition, and content, which may include particulates, steams, or condensable materials, but are part of one of the following waste heat forms.

Exhaust Gases or Vapours

Exhaust gases or vapours can be classified into the following subcategories:

- **High temperature combustion products or flue gases (clean):** Due to they are considered clean gases (they do not contain pollutants or particles), widely used heat recovery equipment can be implemented to produce high–temperature steam, air, or water for other processes or for heating buildings. The most representative examples are directly and indirectly fired heating processes that are widely used at industrial level.
- **High temperature combustion products or flue gases with contaminants:** It is common for these sources to contain condensable particles and vapours, creating fouling problems on heat transfer surfaces due to the condensation of vapours on liquids or solids. The most representative examples are the exhaust gases from coal boilers, kilns, melting furnaces and dryers.
- **Heated air or flue gases containing high (>14%) O_2 without large amount of moisture and particulates:** This waste heat source is not as restrictive in terms of condensation temperature, and can be cooled to a lower temperature without the negative consequences of corrosion, due to the absence of acid–forming gases (such as CO_2). The most representative examples are the exhaust gases from gas turbines and air coolers used in refrigeration or chiller systems.
- **Process gases or by–product gases and vapours that contain fuels:** These fuels are in gaseous or vapour form and require a previous treatment before being released into the atmosphere. The most representative examples are the exhaust gases from coating ovens.
- **Process or make–up air mixed with combustion products, large amounts of water steam or moisture:** Normally these sources contain small amounts of particulates but no condensable organic vapours. The most representative examples are the exhaust air from paper machines, food dryers and ceramic dryers.
- **Steam discharged as vented steam or steam leaks:** The most representative examples are steam generation boilers.

Heated Water or Liquids

Heated water or liquids can be classified into the following subcategories:

- **Clean heated water discharged from indirect cooling systems:** This waste heat source does not contain any solid or gaseous pollutants. The most representative examples are steam condensers and the cooling of products or processes.
- **Hot water that contains presence of large amount of separable solids:** It is important to note that these sources do not contain liquids or organic vapours, so that solids can be easily filtered without the need for further water treatment. The most representative examples are

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the cooling or quenching water used to cool hot parts in the metallurgical industry, the cement industry or the paper industry.

- **Hot water or liquids containing dissolved precipitable solids or dissolved gases:** This water (or liquids) require a previous treatment before being used or discharged as effluent. The most common dissolved gases are SO_2 and CO_2. The most representative examples are the wash water and the scrubber water from chemical processes or from the paper, food or textile industries.

Heated Products or By–Products

Heated products or by–products can be classified into the following subcategories:

- **Hot solids that are cooled after processing:** There are two main cooling methods for these products, by natural or forced air cooling, or by water or a mixture of air and water. The most representative examples are hot slabs, hot coke, slag, fly ash, paper and heat–treated parts.
- **Hot liquids and vapours that are cooled after thermal processing:** The most representative examples are heated fluids in the chemical, petroleum refining, paper and food industries.

High–Temperature Surfaces

High–temperature surfaces can be classified into the following subcategories:

- **Furnace or heater walls:** The waste heat in the form of convection and radiation from these sources is very high.
- **Extended surfaces or parts used in furnaces or heaters:** The waste heat from these sources is not as high as in the case of furnace or heater walls, but must also be taken into account.

Table 1 summarizes the different types of waste heat sources, according to the industrial sector in which they are generated and their temperature range, using the following colour coding:

- >1,000ºC
- 500 — 1,000ºC
- 400 — 500ºC
- 300 — 400ºC
- 200 — 300ºC
- 100 — 200ºC
- <100ºC

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Table 1: Temperatures (coded by colour) of waste heat sources for each Industrial Sector (REFERENCE)

WASTE HEAT SOURCE	Aluminium	Steel	Chemical	Pet. Refining	Glass	Cement	Paper	Food	Coatings	* Steam Generation
Exhaust Gases or Vapours										
High temperature combustion products or flue gases (clean).										
High temperature combustion products or flue gases with contaminants.										
Heated air or flue gases containing high (>14%) O2 without large amount of moisture and particulates.										
Process gases or by–product gases and vapours that contain fuels.										
Process or make–up air mixed with combustion products, large amounts of water steam or moisture.										
Steam discharged as vented steam or steam leaks.										
Heated Water or Liquids										
Clean heated water discharged from indirect cooling systems.										
Hot water that contains presence of large amount of separable solids.										
Hot water or liquids containing dissolved precipitable solids or dissolved gases.										
Heated Products or By–Products										
Hot solids that are air cooled after processing.										
Hot solids that are cooled after processing using water or air–water mixture.										
Hot liquids and vapours that are cooled after thermal processing.										
High–Temperature Surfaces										
Furnace or heater walls.										
Extended surfaces or parts used in furnaces or heaters.										

** Steam generation has been included despite not being considered an industrial sector by itself, since it is integrated into many of them.*

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3 Industrial Sectors

This deliverable analyses the potential for waste heat recovery in the main industrial sectors, which are listed below:

- Aluminium — Primary Production
- Aluminium — Recycling and Secondary Melting
- Steel — Integrated Steel Mill
- Steel — Mini Mill and EAF Mill
- Chemical and Petroleum Refining
- Glass — Fiberglass Manufacturing
- Cement — Dry Process and Shaft Furnaces
- Paper — Pulp Mill
- Food Processing – Snack Manufacturing
- Coatings — Vinyl Coating Mill

To carry out this analysis, the following factors have been taken into account within each sector:

- Sources and availability of waste heat.
- Possible applications for waste heat inside and outside the plant (internal or external end use).
- Barriers to waste heat recovery.

3.1 Aluminium — Primary Production

This chapter analyses the recovery potential of the sources of waste heat in the following areas of the aluminium primary production process:

- Refining (calciners).
- Smelting (electrolysis).
- Anode baking.
- Melting.

3.1.1 Refining

<u>Calciners</u>

In the aluminium production process, a high percentage of the total energy consumed is used in the calcination process. The exhaust from the calcination process contains a significant amount of waste heat, with the handicap that this gas contains polluting particles such as alumina at a relatively low temperature (180–200ºC), together with a considerable percentage of moisture (around 50% water by volume). These exhaust gas conditions cause severe fouling of any type of heat exchanger, posing a challenge for waste heat recovery.

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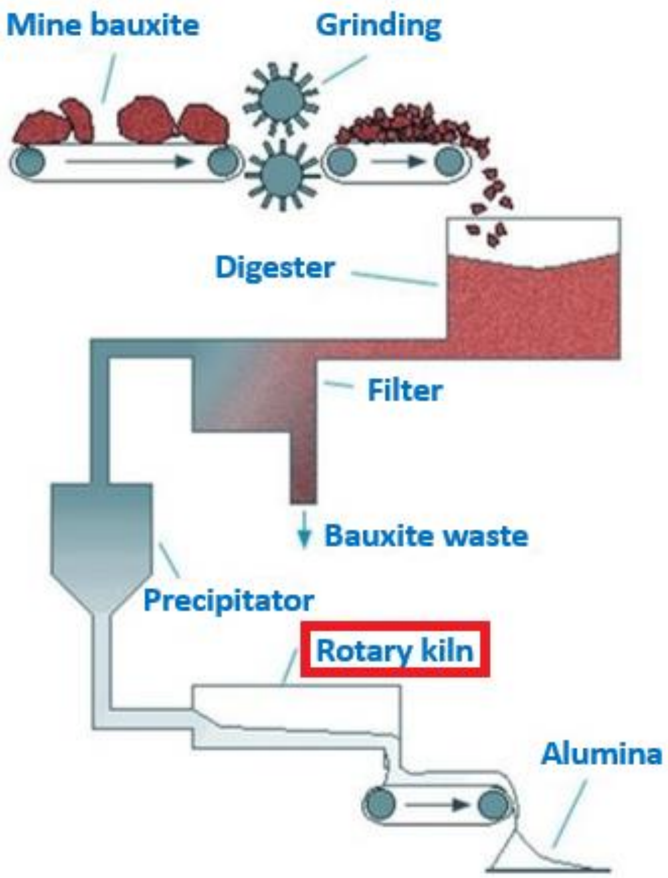

Figure 2: Alumina production process (calcination process highlighted within a red rectangle) (2)

Another source of waste heat would be the hot alumina discharged at a very high temperature, which reduces the problem of the presence of particles. There is the possibility of recover the heat from the hot alumina for the production of hot water for use in other internal plant processes. Another possibility would be to take advantage of this hot water through a Kalina cycle for the production of electricity, thus building a cogeneration facility.

There is also the possibility of recover heat from the coke calciner afterburner waste gas streams (1,050–1,100ºC) for steam production, which in turn could be used for electricity production.

3.1.2 Smelting

<u>Electrolysis</u>

There is great potential for heat recovery in the electrolysis area. There is an energy loss in the exhaust gases of around 15%, while a heat loss in the pot (aluminium smelting cells or reactors commonly known as "pots") walls of 15–20% occurs. The heat flow in the pot walls is 10–15 kW/m^2, with a temperature of 300–550ºC. These conditions make it possible to place thermoelectric devices on the walls of the pot, which are normally covered with a steel shell. The accessibility for placing the thermoelectric devices varies depending on the type of pot.

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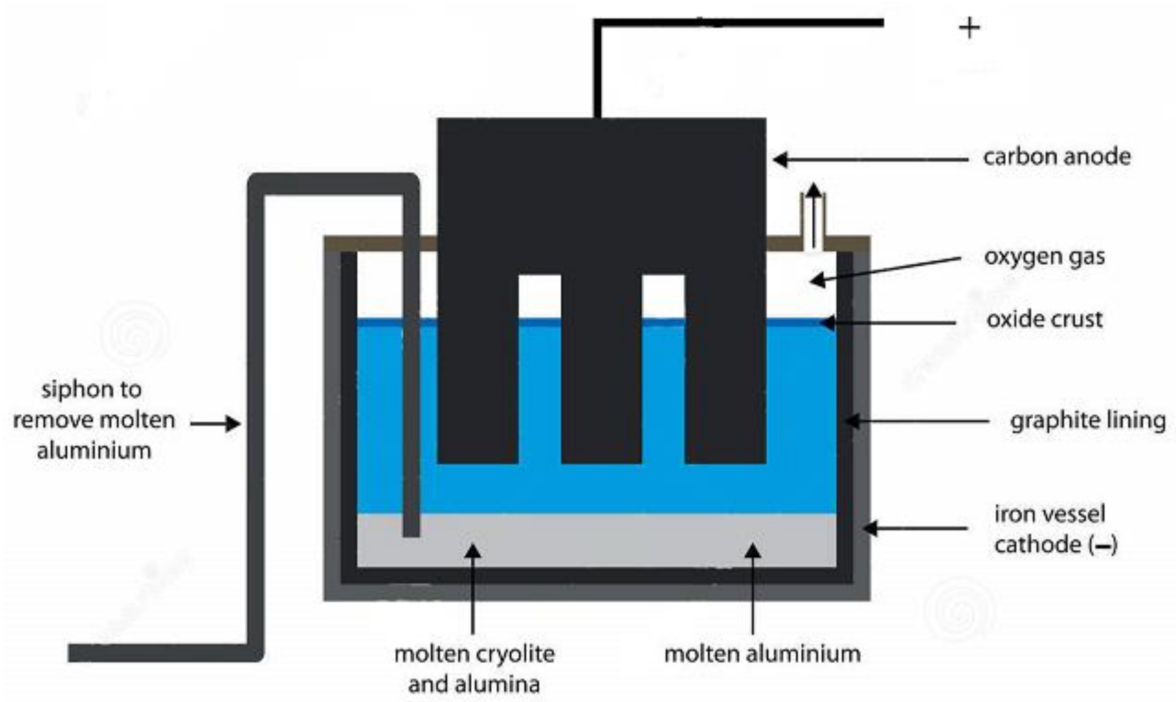

Figure 3: Aluminium electrolysis process (3)

The pots work with a crust of a few centimetres of thickness. A heat sink is needed to maintain the crust; however, too much cooling can result in a ledge that is too thick, reducing the pot's capacity. In order for the crust thickness to remain stable, a heat sink is needed (too much cooling causes an increase in crust thickness, which reduces the capacity of the pot). Studies are being carried out for waste heat recovery, so that a thermal balance is maintained in the pot. This, in addition to the inherent benefits of waste heat recovery, can hold some additional benefits such as more stable operation and an improved working environment.

The exhaust gases from the pot before the scrubbers are at 100–130°C, while after the scrubbers they do not exceed 100ºC. An opportunity of waste heat recovery would be possible before the scrubbers (due to problems of fouling and accumulation of particles) through a gas–water heat exchanger in order to obtain hot water. There is also the possibility of using a heat exchanger in the exhaust gas stream to recover waste heat from the pots.

3.1.3 Anode Baking

Anode baking processes generate hot exhaust gases from fuel combustion that represent a substantial source of waste heat. The exhaust gases have a high content of volatiles and tar vapours, which pose a handicap in the waste heat recovery due to tar encrustation. Exhaust gas temperatures are 200–400°C, containing large amounts of excess air, due to a lean mixture combustion.

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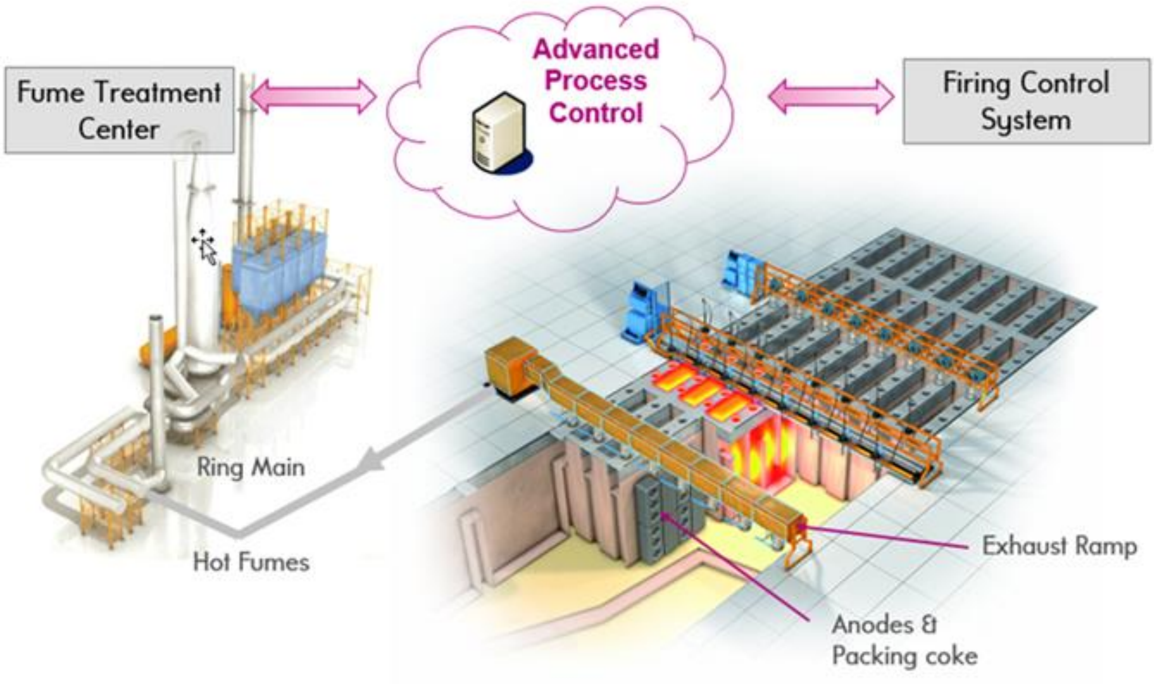

Figure 4: Anode baking process (4)

3.1.4 Melting

Regarding the primary cast area, holding furnaces use a cold charge to increase production or cool superheated metal. The furnaces work in batches or discontinuously, which implies variable temperature and flue gas flows. Most furnaces are gas powered, although there are some plants that use electric furnaces. Exhaust gases may contain small amounts of hydrogen fluoride (typically less than 1 ppm, but in some cases as high as 5–10 ppm), which limits the use of conventional heat exchangers. Heat losses through walls and openings have been greatly reduced over the years due to improvements in furnace designs. Due to all of the above, waste heat recovery in the primary cast area can be considered a low–impact and high–complexity category.

Regarding the secondary cast area, melting furnaces discharge a large amount of heat as high–temperature exhaust gases (generally higher than 870°C) and which may contain particles, organic vapours and flux material vapours. The separation of these contaminants at higher temperatures is a handicap for waste heat recovery. A solution would be to treat the gases with absorbents to neutralize the contaminants, which would eliminate the need to cool the gases, generating cleaner gases that could be used for waste heat recovery through conventional heat recovery devices.

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Figure 5: Melting and Holding aluminium furnace from Hindalco Industries Ltd., Aditya Aluminum, Lapanga project, Orissa (SECO/WARWICK Corp. USA) (5)

3.2 Aluminium – Recycling and Secondary Melting

In the Figure 6 it is shown a simplified flow diagram of the aluminium industry (primary melting, secondary melting and scrap recycling).

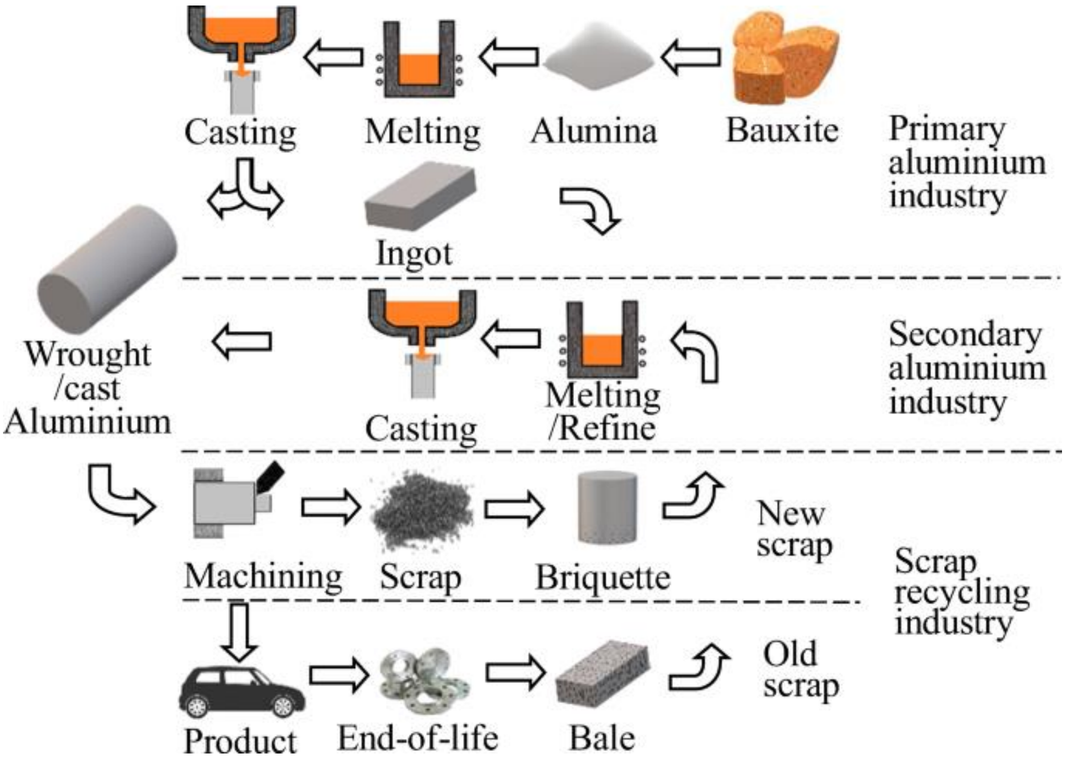

Figure 6: Flow diagram of aluminium industry (primary melting, secondary melting and scrap recycling) (6)

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The main sources of waste heat from the secondary aluminium melting process are listed below:

- **Waste heat from reverb furnaces, gas generators and crucible heaters:** Waste heat is generated in the clean exhaust gases from reverb furnaces (1,100ºC), gas generators and crucible heaters (800ºC), which contain combustion products of natural gas and thus, no significant pollutants. The main option for the recovery of waste heat would be the preheating of the combustion air through the use of recuperative or regenerative devices. Another option would be the use of low temperature energy generation cycles, such as an organic system based on the Rankine cycle.
- **Waste heat from rotary kilns:** The gases generated in rotary kilns contain a large number of pollutants, their temperature is not too high and their flow rate is cyclical (and often unpredictable). There is no industry accepted method for waste heat recovery from these gases.
- **Waste heat from pickling systems:** These systems remove volatile materials from aluminium from UBC (Used Beverage Cans) and preheat it to about 480°C before discharging it from a rotary kiln. Preheated but partially cooled UBC aluminium is charged to a reverb furnace. Delacquering systems use a gas generator that incinerates volatiles from the paint coating on UBC aluminium. The exhaust gases from the unit are discharged at around 340°C and are relatively clean, so there are good conditions for waste heat recovery.
- **Waste Heat from crucible heaters:** These types of devices are relatively small units used to preheat crucibles before pouring hot aluminium metal from rotary or reverb furnaces. The burners are relatively small and light intermittently. The gases are discharged at around 790°C, which is a considerable value of temperature to be taken into account in reference to waste heat recovery.

3.3 Steel – Integrated Steel Mill

This chapter analyses the recovery potential of the sources of waste heat in the following areas of an integrated steel mill:

- Blast furnaces, the iron–making process, and power generation at the site.
- Coke ovens and coke oven gas processing equipment.
- Reheating and heat treating furnaces at the rolling and finishing area.

3.3.1 Blast Furnaces, Iron Making, and Power Generation

<u>Blast Furnaces</u>

In order to increase the production of a blast furnace, a blast of hot air with oxygen enrichment is usually used (coal injection and natural gas injection have been used in some plants). Compressed air is preheated to 1,066–1,122°C with an added oxygen percentage of 5–10%. Waste heat discharged from the blast furnace is in the form of sensible and chemical heat from Blast Furnace Gas (BFG), which is used as fuel in various processes within the plant. As the BFG is discharged from the top of the blast furnace it must be cleaned with a scrubber and then dehumidified as it contains contaminants such as sulphur, particulates and other compounds.

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Figure 7: Blast furnace steelmaking process (7)

The main sources of waste heat from blast furnaces are listed below:

- **Waste heat from BFG:** The hot BFG contains an amount of sensible heat to be taken into account, but at the same time, contains condensable materials and particles that pose a handicap for waste heat recovery devices.
- **Waste heat from flared BFG (when is not in use):** There is a potential of waste heat recovery, since otherwise the heat is lost directly to the environment.

Blast Furnace Stoves

Blast furnace stoves are direct–fired regenerators used to preheat the blast air used in the blast furnace. Coke oven gas (COG) and BFG are used as fuel to feed the blast furnace stoves, together with an injection of natural gas, with the aim of achieving the required temperature in the blast furnace stoves, and hence the preheated air.

The main sources of waste heat from blast furnace stoves would be their exhaust gases. These gases are at approximately 320°C and are relatively clean, being free of particles or other contaminants, so there is great potential of waste heat recovery.

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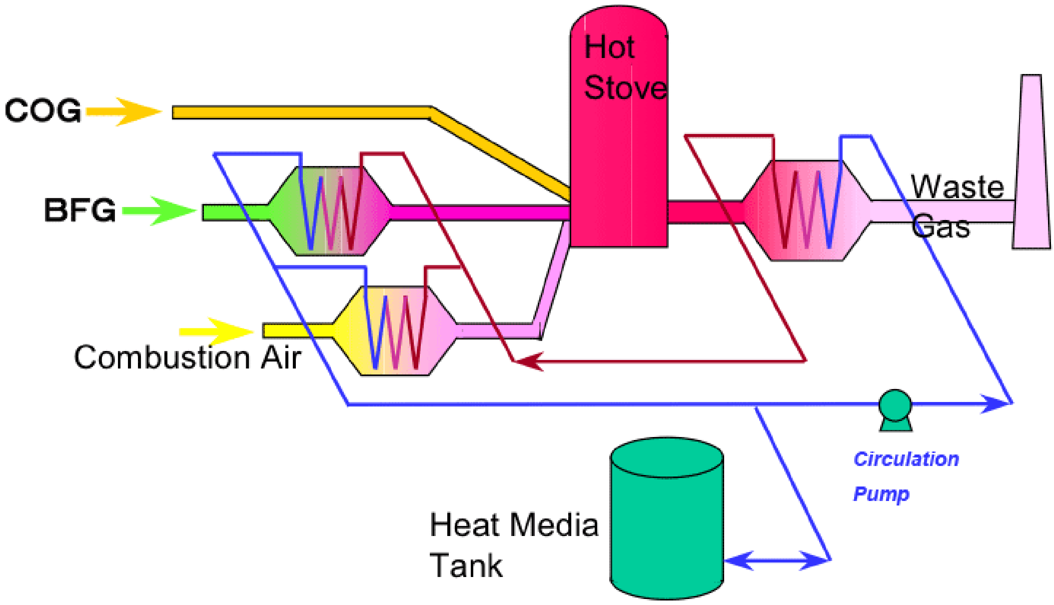

Figure 8: Waste heat recovery system from blast furnace stoves (8)

Power Plant (Boilers)

BFG and COG are typically used as fuel in integrated steel plants to feed boilers. The temperature of the exhaust gases from the boilers vary depending on the age of the facility, being in the range of 340–450°C, with an O2 content that vary between 3% and 7.5%. The exhaust gases have potential of waste heat recovery, since they are free of pollutants and therefore, no treatment is required.

The main beneficiaries of the waste heat recovery from boiler are listed below:

- BFG and COG preheating.
- Preheating of service water.

Steel Making — Basic Oxygen Process Area

The exhaust gases from the basic oxygen process vessel are the main source of waste heat in this area. The flow of gases, and therefore the amount of heat, are variable, with large peaks during a short period of time of the total cycle. The gases reach very high temperatures, greater than 1,100°C, but they have the handicap of containing all kinds of contaminants, including particles. Basic oxygen processes typically have a non–steaming hood to collect the exhaust gases. These hoods are not–water cooled and the gases are cooled before being taken to a scrubber.

The best option for the heat recovered from the basic oxygen process vessel would be the production of steam with the use of large accumulators.

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<u>Caster Area</u>

The de–gasser of this area uses 250 psig steam that is de–superheated before is used.

The main source of waste heat from the caster area is the steam from the de–superheater degasser steam: This steam is discharged at the end of the de–superheater, not being possible to be returned because it produces condensate and contaminated steam.

3.3.2 Coke Plant

Several coke oven batteries can be housed within the same coke facility, which in turn includes equipment for the recovery of by–products from the coke manufacturing process. Coke facilities use large COG–fired boilers (with natural gas as a supplemental fuel) to produce steam at over 4 MPa to generate power that is often used internally in other processes of the plant. A small amount of steam (around 10%) is returned. It is common to use an incinerator for the final "cleaning" of the exhaust gases generated by boilers.

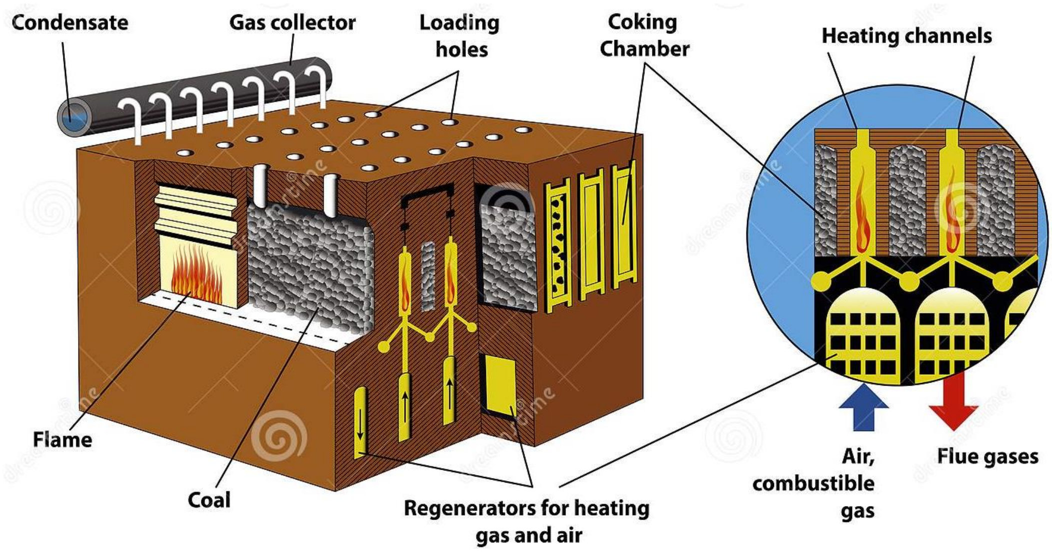

Figure 9: Coke oven process (9)

The main sources of waste heat from coke plants are listed below:

- **Waste heat from hot coke discharged from batteries:** The heat contained in the hot coke is the largest source of waste heat in coke plants (heat is lost due to the quick quenching of coke), containing around 300 kWh/ton. There is a commercially proven technology that has been used in several facilities that is based on dry quench system of the hot coke, with the aim of using the recovered heat for energy production.
- **Waste heat from hot coke oven gas:** This gas is discharged from the batteries at around 815°C, but has the handicap of containing contaminants, such as sulfur compounds, condensable liquids and particulates. The gas is quenched at around 82°C and then cooled to around 30°C. The heat contained in the gases is wasted as hot water from the COG cooling system, being in the order of 88–117 kWh/ton of coke.

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- **Waste heat from exhaust gases from coke oven batteries:** The exhaust gases are at 200–320°C due to the batteries usually include a regenerative heat recuperator for the hot gases. These gases, which are discharged into the atmosphere through the chimneys, contain some particles that can be considered relatively clean. There is no widespread method for recovering waste heat from exhaust gases from coke oven batteries. Low temperature power generation would be an option to be considered.
- **Waste heat from clean boiler flue gases at low temperatures:** The heat contained in these gases can be recovered through direct or indirect heat exchangers and used to heat water. Carbonic acid condensation could be a problem, unless a slight increase in acidity does not **affect the system or the water is used as "once–through water".**
- **Waste heat from the incinerator:** It is possible to use a regenerator or a recuperator for waste heat recovery, taking into account that the energy used in the incinerator is relatively low, so the payback period could be long.

3.3.3 Rolling Mill and Finishing Area

Reheat furnaces, annealing furnaces and continuous annealing lines are often used in rolling and finishing processes. The furnaces, which include a recuperator to preheat combustion air, use BFG, COG (Coke Oven Gas) and natural gas as mixed fuel. The outlet temperature of the slabs is 1,180 °C. In old facilities (before the 1980s), the air temperature is sometimes very low (less than 370°C), while the exhaust gas temperature is usually 540–680°C, with a large percentage of O2 (sometimes higher than 8%).

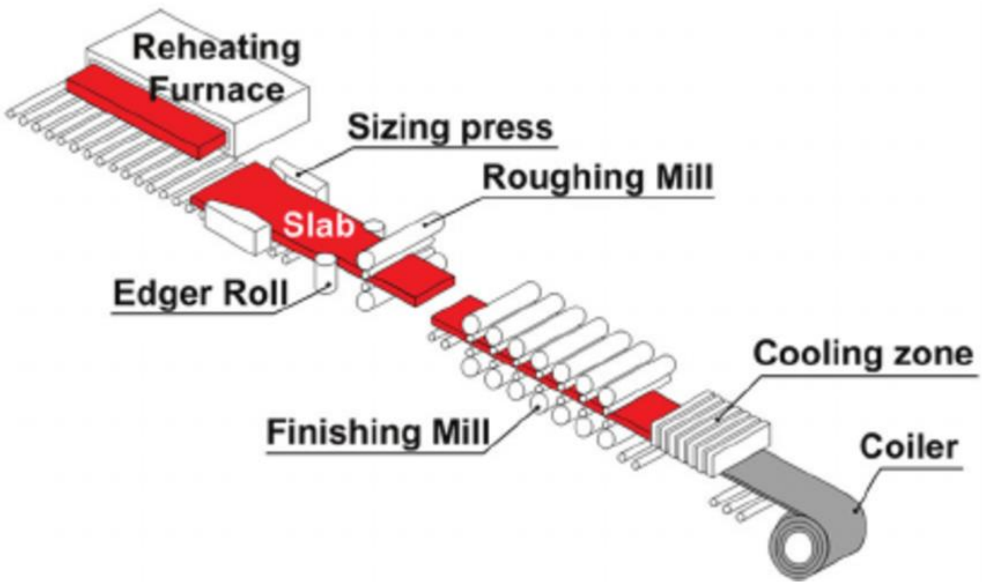

Figure 10: Steel coils rolling mill process (10)

The main sources of waste heat from the finishing area and rolling mills and are listed below:

- **Waste heat from furnace exhaust gases:** These gases are free of condensable vapours or particulates, so they are relatively clean, although in some cases they contain large amounts of excess air. The benefit of using recuperators for waste heat recovery would increase if the O2 content of the gases were reduced.

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- **Waste heat from furnace openings:** The loading and unloading ends are the main sources that generate radiation heat, as well as other areas to a lesser extent, such as the roof and parts of the shell or the walls of the furnace.
- **Waste heat from hot rolled steel forms:** It is not usual for waste heat to be recovered from rolled steel forms, but it is an important focus to take into account, although it is complex at the same time.

3.4 Steel – Mini Mill and EAF Mill

A mini mill is referred to scrap based steel plants. This term is nowadays less widely used. Steel mini mill plants are also referred to as electric arc furnace (EAF) mill plants.

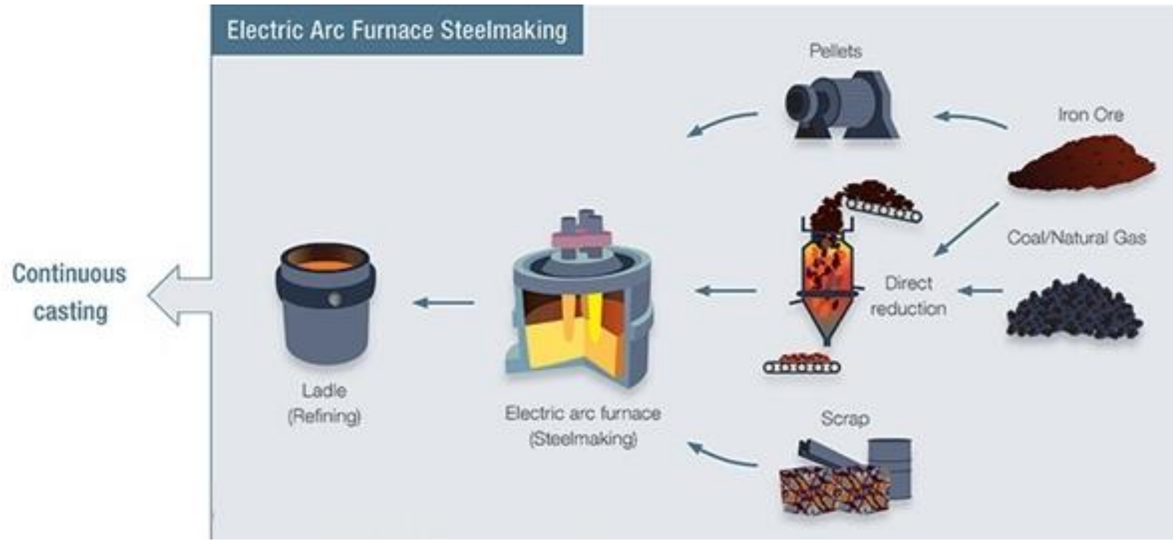

Figure 11: Electric Arc Furnace (EAF) steelmaking process (7)

The main sources of waste heat from a EAF mills are listed below:

- **Waste heat from clean exhaust gases from reheat furnaces, ladle heaters and tundish heaters:** The temperature of reheat furnace gases is around 540°C, while the temperature of ladle heater and tundish heater gases is higher, around 980°C. These gases do not contain any significant pollutants, only natural gas combustion elements, being therefore feasible the recovery of the waste heat that they house.
- **Waste heat from the gases discharged from the electric arc furnace:** The temperature of these gases is high, but they have the handicap of containing large amounts of contaminants. In addition, the gas flow is cyclical (and often unpredictable). There is no industry accepted method for waste heat recovery from these gases.
- **Waste heat from the walls of ladle heaters and tundish heaters:** The surface areas present economic and logistical problems. Potentially usable systems such as Thermoelectric Generators (TEGs) are very expensive.

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3.5 Chemical and Petroleum Refining

The chemical and petroleum refining industry encompasses a wide variety of processes (which in turn use a large amount of fuel for heat generation) and products from various raw materials (mainly hydrocarbons). Due to this variability, it is complex to perform a waste heat recovery analysis for all types of plants and processes. However, it is possible to perform a waste heat recovery analysis focused on a "typical" petrochemical plant.

The following areas of waste heat are representative of the main petrochemical processes:

- **Waste heat from exhaust gases from boilers and power generation equipment (combustion turbine plus HRSG):** When natural gas is used as a fuel, the generated exhaust gases are generally clean, so it is feasible to use widely spread waste heat recovery technologies. The waste heat discharged is at a temperature of 95–180°C (in the case of systems that use by–products as fuel, the temperature of the waste gas stream could be even higher).
- **Waste heat from exhaust gases from thermal oxidizers:** Thermal oxidizers are often used for process heating equipment, generating exhaust gases at 760–980 °C, which contain chlorinated gases or gases with other non–organic contaminants that are highly corrosive. The presence of corrosive gases is a handicap for waste heat recovery equipment, since the combination with high temperatures significantly increases the cost of heat exchangers. One option would be to quench the gases, transmitting heat to the scrubbing liquid (this option has the problem of having to add water).

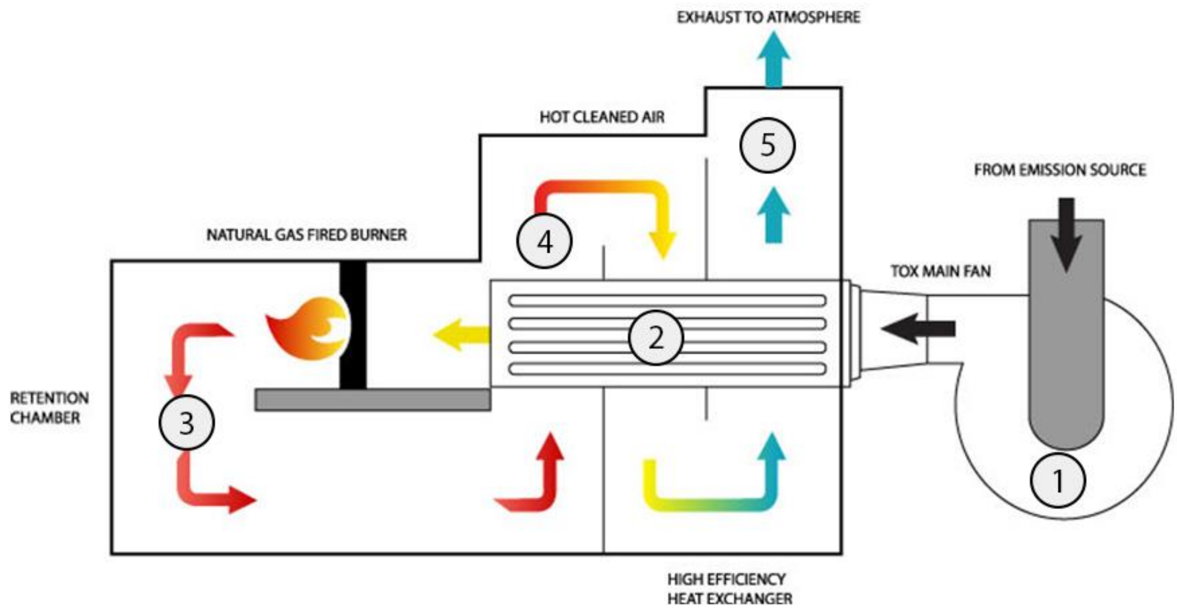

Figure 12: Thermal oxidation process (11)

- **Waste heat from exothermic processes in reactors:** Waste heat can be recovered from the hot water that is generated due to the quenching of some products. In addition, it might be possible to generate power using steam produced at high pressures (around 4–10 MPa). There is no industry accepted method for waste heat recovery from exothermic processes in reactors.

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- **Waste heat from stack gases:** It is possible to recover waste heat from these streams and use it to heat liquids or gases: The positive aspect is that in most plants there are multiple stacks. The negative aspects are: the logistical difficulty of collecting these gases, their chemical components (thinking about the materials of the heat transfer surfaces) and the limited space available for the installation of heat exchangers. A possibility would be the use of micro-channel heat exchangers.
- **Waste heat from gases that contain water vapours discharged evaporators:** A big percentage of the heat of these gases is in the form of vapours, so that in order to recover the latent heat it is necessary to cool them below their condensation temperature. The use of conventional heat exchangers is usually not possible due to the content of contaminants in the vapours and the size of the units available on the market. The development of smaller condensing heat exchangers would enable the recovery of waste heat in these types of gases.
- **Waste heat from hydrocarbon processing units:** The amount of heat in the form of low pressure steam is enormous in this type of process. Sometimes the cost of pumping cooling water, together with the availability of water, are significant constraints for waste heat recovery, as well as the limited uses for the resulting hot water. due to all of the above, waste heat recovery from hydrocarbon processing units is sometimes a challenge.
- **Waste heat from flared gases:** The biggest handicap is the periodic and unpredictable nature of this source of waste heat, making it difficult to couple recovery with demand, so it makes more sense for them to work as support together with another stable heat source.

3.6 Glass — Fiberglass Manufacturing

The main sources of waste heat from fiberglass manufacturing are listed below (the waste heat sources in other industries of the glass sector are very similar to those in the fiberglass manufacturing industry, being the most representative the manufacture of float glass; see Figure 13):

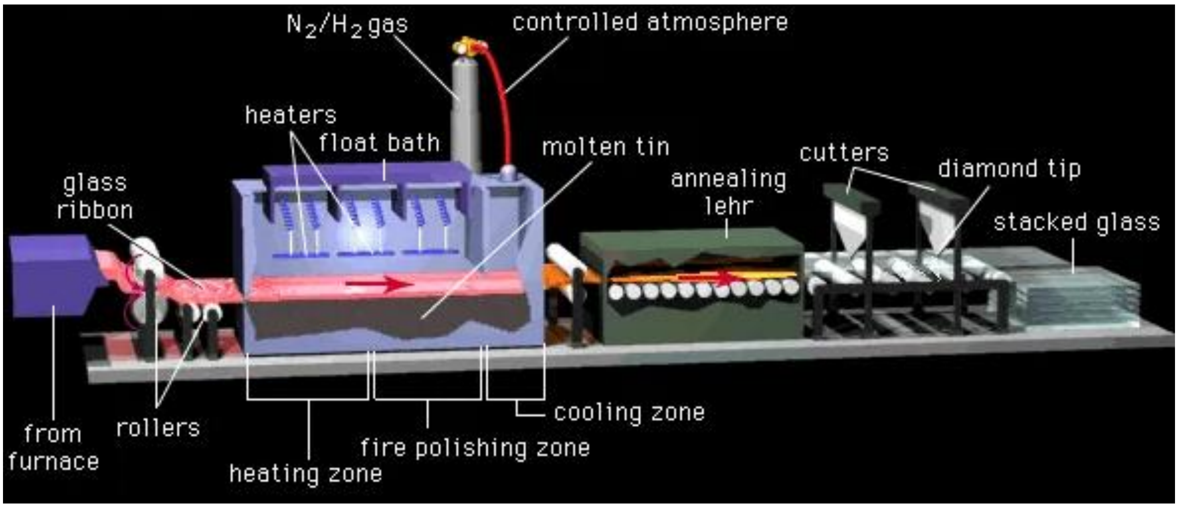

Figure 13: Float glass manufacturing process (12)

- **Waste heat from glass melters:** The heat sources commonly used to melt glass are electricity, natural gas burners with preheated air or oxy–fuel burners (an electrical boost can be implemented when natural gas–fired burners are used). Glass melters include gas–fired

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channels that discharge large amounts of hot gases that are vented directly into the environment.

The main sources of waste heat in glass melters are the exhaust gases from the furnace and the channels, which are at very high temperatures (above 1,370 °C), but which have the handicap of containing a large amount of contaminants, such as inorganic particles and vapours of elements that condense in a certain temperature range (the nature of this elements depends on the type of glass). These gases are quenched by being mixed with a large amount of air. In some glass plants, a recuperative or regenerative system is used, with the gases in the system at a temperature of 230–480°C, while the gases discharged from the baghouses used to collect the particles are at a lower temperature (can reach temperatures of up to 230°C).

- **Waste heat from the fiberizing process:** In order to maintain the temperature conditions required in the fiberizing process, a large amount of natural gas is used. The adjustment of the heating parameters of the system can become very complex, because the desired quality specifications for the fibers have to be achieved. The energy demand of the heating system is high, so plants are constantly looking for ways to reduce the consumption. The main source of waste heat in the fiberizing process is the hot gases generated by the system, which are at a low temperature (sometimes less than 250°C) due to the high content of air and steam in the mixture. In addition, the gas collection process is complex.

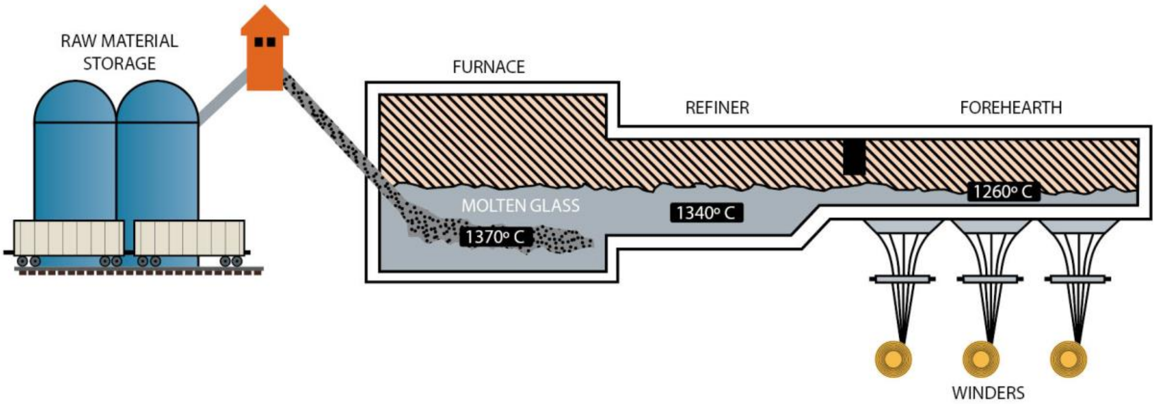

Figure 14: Fiberglass manufacturing process (13)

- **Waste heat from curing ovens:** Natural gas burners with recirculation fans are used in the curing ovens, which reach an operating temperature of 230–290°C. Curing ovens are not sealed (they tend to have large air leaks), so the volume of exhaust gases is usually much bigger than the volume of combustion products from the burners. Exhaust gases are normally incinerated in order to eliminate the organic content contained in them. It is usual to use regenerative heat recovery systems in incinerators, discharging gases at a temperature of up to 190 °C. The waste heat source would therefore be the clean gases at low temperature.

Glass manufacturing plants often have heated areas (particularly finishing, packing, and shipping areas, where heat from furnaces is not available) because the glass must not undergo sudden changes of temperature. Therefore, waste heat recovery could be used to support the heating system used by the plant, especially during the winter months in plants located in cold climates.

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3.7 Cement — Dry Process and Shaft Furnaces

In the Figure 15 it is shown a simplified flow diagram of the Cement production by dry process.

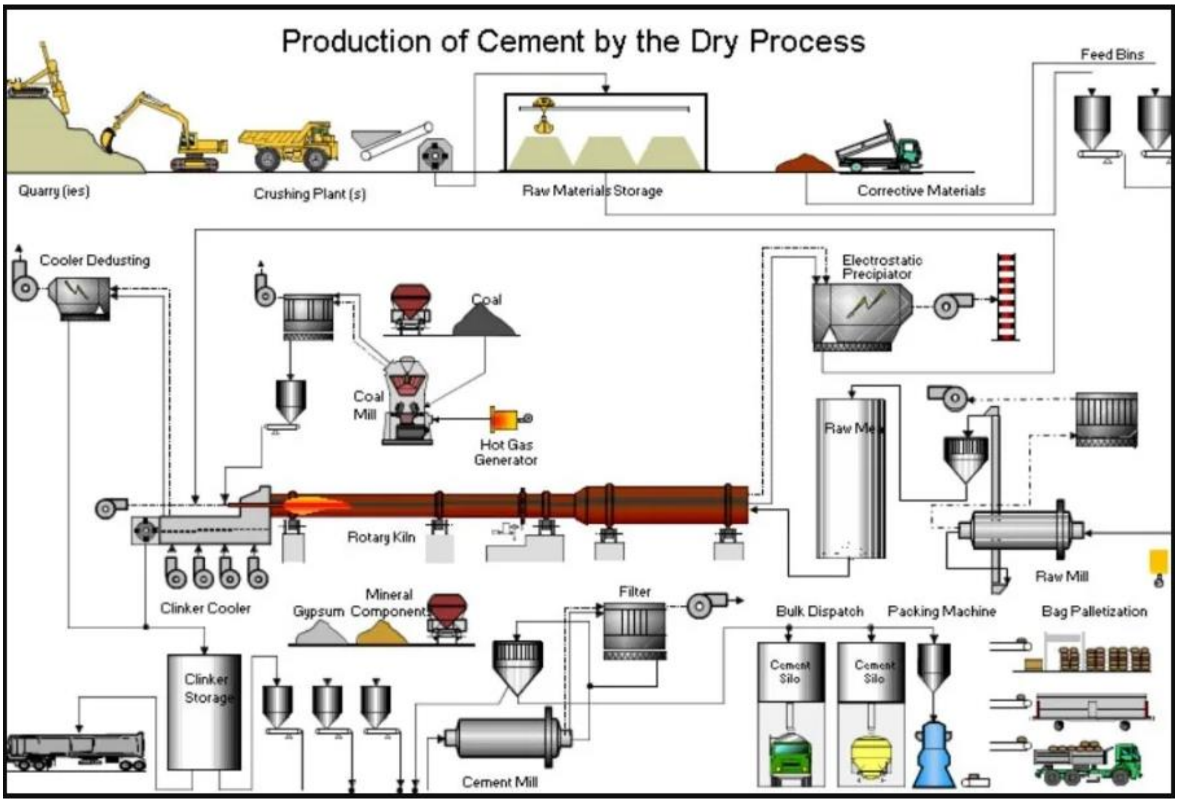

Figure 15: Cement production by dry process (14)

The main sources of waste from the cement sector (dry process and shaft furnaces) are listed below:

- **Waste heat from the clinker cooling air of the cooling bed:** The air temperature is in the range of 180–480°C. The most common waste heat recovery technology is the preheating of the combustion air in steam boilers for power generation. This technology can be considered mature and widely spread.
- **Waste heat from exhaust gases from the preheaters:** The temperature of these exhaust gases is in the range of 150–260°C, with a high CO_2 content. The CO_2 is generated by the calcining reaction and combustion products from the fuels used in the kiln and the pre–calciner. It is common for the exhaust gases to be mixed with the clinker cooling air, being the heat recovered in boilers.
- **Waste heat from hot shell or surfaces of kilns and pre–calciners:** The temperature of these surfaces is in the range of 260–430°C. There is no widely extended technology for the recovery of this waste heat, on the contrary, the focus of study is on redesigning the insulation–refractory system to reduce the temperature of the kiln shell.

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3.8 Paper — Pulp Mill

Next, the main sources of waste heat in pulp mills are analysed. It must be taken into account that there are two different processes for the production of paper, the Kraft process (see Figure 16), which is the most widespread, and the sulphite process. The main difference between both processes is the way in which the treatment of wood chips is carried out, using a hot mixture of water, sodium hydroxide and sodium sulphide in the Kraft pulp, while in the sulphite pulp it is carried out with sulphite or bisulphite salts of sodium, calcium, potassium, magnesium, etc. Also, the efficiency of the sulphite process is higher and the cellulose fibers produced are stronger than those of the Kraft process.

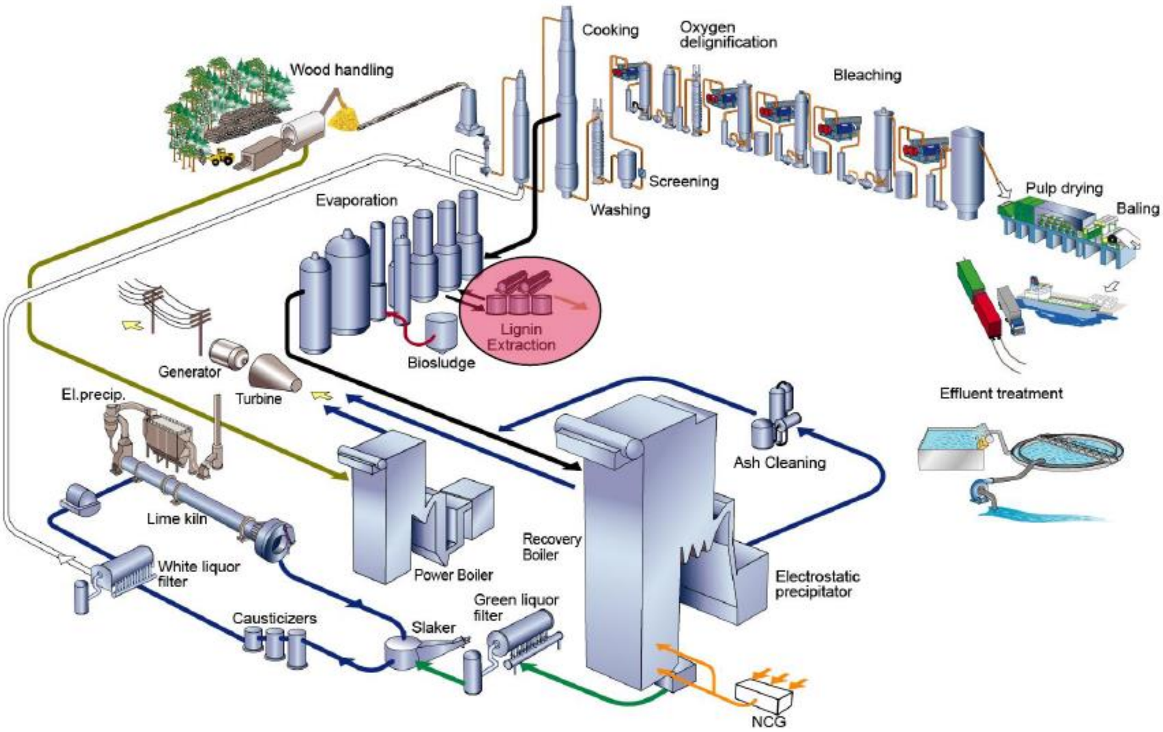

Figure 16: Kraft pulp mill production process (15)

The main sources of waste heat from pulp mills are listed below:

- **Waste heat in the form of dilutions or hot water from various processes:** These fluids may contain contaminants or impurities, and it is common for them to contain paper fibers in some areas of the process. The recovery of heat from these fluids does not present great complexities, beyond the chemical treatment and the filtration prior to the heat exchanger used (usually plate heat exchangers).
  It is common to use this type of waste heat source to generate hot air currents in biomass dryers, thus avoiding the use of fossil fuels, such as natural gas. This achieves an increase in the calorific value of the biomass, assuming savings in the consumption of the biomass boiler.

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Figure 17: Biomass dryer of ENCE Navia pulp mill (SO WHAT demo-site)

- **Waste heat from the exhaust air of paper machine dryers:** The water vapour content of this air stream is high, as well as being able to contain small amounts of paper fibers. The temperature is relatively low, between 60 and 80°C. The high moisture content together with the existence of solid contaminants poses a problem of accumulation of solids on the heat transfer surfaces, which implies a reduction in the heat transfer capacity of the equipment together with the possibility of clogging them.
- **Waste heat from the exhaust gases of lime kilns:** The temperature of these gases is above 300°C, being the source of waste heat from pulp mills with the highest temperature. The main handicap for waste heat recovery is the pollutant content of these gases, which implies high costs in terms of materials for the heat transfer surfaces of the recovery equipment.

Figure 18: Pulp mill lime kilns (16)

- **Waste heat in the form of fluids in need of cooling:** In various processes there is a need for cooling (an example occurs during the effluent treatment process prior the decanters) which is met by cooling towers. There is the possibility of taking advantage of the need for cooling for space heating, avoiding or reducing the use of cooling towers.

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3.9 Food Processing — Snack Manufacturing

The food industry encompasses a wide variety of processes and final products. Due to this variability, it is complex to carry out a waste heat recovery analysis for all types of plants and processes. However, it is possible to perform a waste heat recovery analysis focused on a "typical" snack manufacturing plant.

The main sources of waste from food processing, particularly for a snack manufacturing plant, are listed below:

- **Waste heat in the form of clean exhaust gases:** These gases are produced as a result of combustion from boilers, gases from dryers, toaster ovens, etc. Its moisture content is variable, with a temperature of 150–300°C. It is common to recover waste heat from these gases for conventional uses such as preheating combustion air or heating water for other processes. Regarding the recovery technologies used, they could be considered mature and widely spread.
- **Waste heat in the form of exhaust gases with high moisture content and oil vapours:** These exhaust gases are mainly produced in fryers, with a temperature of around 180ºC. It is necessary to eliminate the oil vapours prior to the recovery of waste heat, since there is no widely used previous treatment for carrying out this task. It is common the use of filters or demisters that remove large amounts, but are incapable of removing the 100%. The cooling of these gases during a conventional heat recovery process would produce the condensation of the oil vapours not eliminated in the previous treatment, which would generate fouling problems in conventional heat exchangers and therefore, problems in the transfer of heat.
- **Waste heat in the form of hot wash water:** The temperature of the wash water is low, normally less than 40ºC. It is possible to recover its waste heat to preheat make–up water during the winter, or the coldest months of the year. It can be an attractive solution for plants located in very cold areas.

3.10 Coatings — Vinyl Coating Mill

The main sources of waste heat from vinyl coating mills are listed below:

- **Waste heat from ovens:** Ovens are used to heat vinyl (or other coating materials) with different substances up to a temperature of 150–200ºC and cure the material. During the heating process, volatile organic compounds (VOCs) are generated that mix with the make–up air or with the air that is filtered into the ovens. Waste heat comes in the form of sensible heat from the air and chemical heat from VOCs. These gases cannot be considered as a direct source of waste heat, since they must be incinerated to remove air pollutants.
- **Waste heat from dryers:** The ink drying process uses air heated by ratio–type burners. The exhaust air is clean and its temperature is above 150°C, which represents more than 50% of the total heat input to the dryer.
- **Waste heat from regenerative thermal oxidizers (RTOs):** Vinyl coating mills use RTOs to destroy the VOCs generated in the ovens. RTOs generate clean exhaust air at a temperature of 180–200°C. It is possible to recover waste heat from the exhaust air of the RTOs and use it to supply heat in the ovens or for generation of hot water needed in other processes.
- **Waste heat from steam boilers:** Boilers are used to supply steam to various processes. The waste heat sources are exhaust gases (with temperatures around 260°C) and boiler

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blowdown water (with operating pressures above 1 MPa). Waste heat can be recovered by widely spread technologies.

- **Waste heat from oil heaters:** Some ovens use a recirculating oil system for the supply of hot air. The oil is heated by combustion gases generated by natural gas burners with a residual temperature of less than 180ºC. The waste heat recovery from these exhaust gases is possible by widely spread recovery technologies.

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4 Barriers to Waste Heat Recovery

This chapter summarizes the barriers to waste heat recovery from the point of view of the type of waste heat source and the industrial sector.

4.1 Barriers by Type of Waste Heat Source

The main barriers to waste heat recovery from the point of view of the waste heat source are listed below, following the same structure established in the chapter 2 (Waste Heat Sources in the Industrial Sector).

Exhaust Gases or Vapours

The main barriers to waste heat recovery in exhaust gases or vapours are listed below:

- **High temperature combustion products or flue gases (clean):**
    - Material limitations (particularly in metals) require that the gases be diluted, so the thermodynamic potential for heat recovery is reduced.
    - The flue gas side limits the heat transfer in steam generation or other power generation applications (ORC: Organic Rankine Cycle).
    - The different coefficients of thermal expansion of materials create sealing problems for heat exchanger designs with metallic and non–metallic (ceramic) components.
- **High temperature combustion products or flue gases with contaminants:**
    - High cost and low availability of materials designed to resist the corrosive effects of contaminants.
    - Lack of designs that allow self–cleaning of heat recovery equipment (particularly heat transfer surfaces) to reduce maintenance.
    - The flue gas side limits the heat transfer.
- **Heated air or flue gases containing high (>14%) O2 without large amount of moisture and particulates:**
    - Heat exchanger size limitations (such as for plate or tube heat exchangers).
    - Lack of availability of small combustion systems (less than 300 kW) to use exhaust gases with low O2 content as combustion air for fired systems.
- **Process gases or by–product gases and vapours that contain fuels:**
    - The very high cost of steam concentrators for the recovery and reuse of organic–combustible components. Concentrated fluids can be used as fuel in heating systems (such as in ovens).
    - Non–existence of compact waste heat recovery equipment (large regenerators).
- **Process or make–up air mixed with combustion products, large amounts of water steam or moisture:**
    - Plugging of conventional heat exchangers, which means a rapid drop in their heat transfer capacity (efficiency).
    - Lack of designs that allow self–cleaning of heat recovery equipment (particularly heat transfer surfaces) to reduce maintenance (such in recuperators).

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- Lack of designs that allow the use of condensing heat exchangers (gas–water) without the consequences of the corrosive effects of carbonic acid produced from CO_2 of the combustion products.
- **Steam discharged as vented steam or steam leaks:**
    - There are no major technical barriers, the main one being the cost and return on investment for the steam and condensate collection, the cooling system and sometimes the cleaning system.

Heated Water or Liquids

The main barriers to waste heat recovery in heated water or liquids are listed below:

- **Clean heated water discharged from indirect cooling systems:**
    - Lack of demand for low–grade heat and lack of (economically justifiable) waste heat recovery technologies that convert low–grade heat into an useful form of energy (such as electricity).
- **Hot water that contains presence of large amount of separable solids:**
    - There are no major technical barriers, taking into account that the removal of separable solids is not a complex process.
    - Lack of demand for low–grade heat and lack of (economically justifiable) waste heat recovery technologies that convert low–grade heat into an useful form of energy (such as electricity).
- **Hot water or liquids containing dissolved precipitable solids or dissolved gases:**
    - There are no major technical barriers, taking into account that the filtering of dissolved solids is not a complex process.
    - The content of CO_2 and SO_2, in addition to other dissolved gases, raises the PH values of the water, being no simple methodology for the neutralization of water.
    - Lack of demand for low–grade heat and lack of (economically justifiable) waste heat recovery technologies that convert low–grade heat into an useful form of energy (such as electricity).

Heated Products or By–Products

The main barriers to waste heat recovery in heated products or by–products are listed below:

- **Hot solids that are cooled after processing by natural or forced air cooling:**
    - High cost of the cooling air collection system.
    - Lack of demand for low–grade heat and lack of (economically justifiable) waste heat recovery technologies that convert low–grade heat into an useful form of energy (such as electricity).
    - The presence of microscopic particles in the cooling air together with its temperature variations do not allow its use in combustion systems (such as burners).
- **Hot solids that are cooled after processing by water or a mixture of air and water:**
    - There are no major technical barriers, taking into account that the filtering of solids is not a complex process.

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- Lack of demand for low–grade heat and lack of (economically justifiable) waste heat recovery technologies that convert low–grade heat into an useful form of energy (such as electricity).

- **Hot liquids and vapours that are cooled after thermal processing:**
    - There are no major technical barriers, as long as the stream temperature is high enough.
    - Lack of demand for low–grade heat and lack of (economically justifiable) waste heat recovery technologies that convert low–grade heat into an useful form of energy (such as electricity).

High–Temperature Surfaces

The main barriers to waste heat recovery in high–temperature surfaces are listed below:

- **Furnace or heater walls:**
    - There are no widely extended waste heat recovery technologies, especially if we are talking about mobile facilities, such as conveyors or rotary kilns.
    - Conversion technologies that are installed on hot surfaces are expensive and have low efficiency (such as thermoelectric systems).
- **Extended surfaces or parts used in furnaces or heaters:**
    - There are no widely extended waste heat recovery technologies, especially if we are talking about mobile facilities, such as furnace rolls.
    - Conversion technologies that are installed on hot surfaces are expensive and have low efficiency (such as thermoelectric systems).

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4.2 Barriers by Industrial Sector

The following tables subchapters summarize the main sources of waste heat, heat recovery opportunities and barriers for waste heat recovery for each of the industrial sectors analysed in this deliverable.

4.2.1 Barriers to waste heat recovery in the Aluminium Industrial Sector

Table 2: Barriers to waste heat recovery in the Aluminium Industrial Sector (17)

Waste Heat Source	Heat Recovery Opportunities	Barriers to Waste Heat Recovery
Calciner exhaust gases at 180–200°C containing particles and more than 50% moisture.	Recovery of sensible and latent heat of moisture.	High moisture content, presence of particulates (alumina) and low temperature. Lack of use of low–grade heat in the form of hot water or air within the plants.
Hot alumina from calciner operation.	Hot alumina from calciner operation.	Easy and convenient method of recovery and use of this heat within the plants.
Smelting — Heat from side walls that vary in temperature from 290–400°C.	Heat recovery in the form of electricity using TEG devices.	Recovery of heat without affecting the temperature profile within the pots.
Off gases at around 100°C. from smelting operations before entering a scrubber.	Recovery of low–grade (temperature) sensible heat from hot gases.	Low temperature and presence of particulates.
Products of combustion at 200–320°C from anode baking operations.	Recovery of chemical and sensible heat from low–temperature exhaust gases.	Presence of condensable tar vapours and particulates at low temperature.
Exhaust gases from melting furnaces.	Recovery of sensible and latent heat from flue gases.	High temperature (870–1,100°C), variations in temperature and presence of particles in gases. In some cases the gases need to be cooled for particle collection in a baghouse.
Low–medium temperature (or grade) heat available in the form of exhaust gases from heating and heat treating furnaces (normally batch operations).	Recovery of heat from low–medium temperature combustion products.	Low temperature, variable flow and temperature due to batch operations, lack of use of low–grade heat in the plants.

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4.2.2 Barriers to waste heat recovery in the Steel Industrial Sector

Table 3: Barriers to waste heat recovery in the Steel Industrial Sector (17)

Waste Heat Source	Heat Recovery Opportunities	Barriers to Waste Heat Recovery
Blast Furnace Gas (BFG).	Maintaining the heating value to reduce or eliminate the use of supplementary fuel (such as natural gas).	Moisture removal method for BFG at relatively high temperature.
Coke Oven Gas (COG).	Use of sensible heat and chemical heat of COG: Elimination of need to cool or quench the COG as discharged from the coke oven batteries.	Presence of particulates, vapours of condensable material and certain gaseous impurities (such as, CO_2 and SO_2) that present problems of condensation and corrosion in transmission and use of hot gases.
Steam from the liquid steel refining area.	Recovery of steam heat and condensate return.	Presence of gases and particulates that need to be removed before its use in heat exchangers to condense the steam and collect clean and reusable condensate to be returned to the boiler water system.
Hot coke discharged from coke ovens.	Recovery of high–grade sensible heat from hot coke.	Highly combustible material and the need to be cooled to a fairly low temperature without ignition. Need for fast cooling (quenching) using inert gas.
Hot products discharged from furnaces (such as reheat furnaces, annealing furnaces and heat treating furnaces).	Recovery of heat from high–temperature (700–1,200°C) steel products.	Design of a cooling system that can cool a product without affecting its surface or other qualities. Economically justifiable method of collection and use of a low–medium temperature cooling medium (such as air or water).
Waste heat from the recuperator or a regenerative burner system used on various heating or heat treating furnaces.	Recovery of sensible and latent heat from fly–use gases.	Use of low–grade heat usually in the form of hot air or water. Economically justifiable energy conversion from hot gases to electricity, a transportable energy form.
Low–grade heat available in the form of hot water used in cooling systems (such as, caster, reheat furnaces, and roll cooling).	Recovery of heat from low–temperature water (normally <50°C).	Use of low–grade (less than 40°C) recovered heat, economic justification for use of systems such as thermally driven heat pumps.
Radiation — Convection heat loss from furnace walls.	Recovery of heat for use within the plant (internal use of waste heat).	Low temperatures and large surface areas present economic and logistical problems. Potentially usable systems such as TEGs are very expensive.
Electric Arc Furnace (EAF) exhaust gases.	Recovery of chemical and sensible heat.	High temperatures, variable flow rates and temperatures of gases, and the presence of contaminants (such as, particulates, condensable vapours, and fuel gases).

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4.2.3 Barriers to waste heat recovery in the Chemical and Petroleum Refining Industrial Sectors

Table 4: Barriers to waste heat recovery in the Chemical and Petroleum Refining Industrial Sectors (17)

Waste Heat Source	Heat Recovery Opportunities	Barriers to Waste Heat Recovery
Clean exhaust gases from boilers, crackers, fired heaters, combustion turbines and other sources.	Low–temperature (<260°C) heat recovery from combustion products with moisture content of 15–20%.	No major technical barriers. Economics of heat recovery system installation and use of recovered heat within the plants are two major barriers. Cost and reliability of currently low–temperature power generation systems (such as ORC).
Exhaust gases from Regenerative Thermal Oxidizers (RTOs).	Heat recovery from high–temperature gases (sensible and latent heat).	The gases are at high temperature and are highly corrosive, containing chlorinated gases and other gases, being necessary to be quenched, hence loss of useful energy.
Hydrogen from chlorine process.	Heat content of hydrogen.	The gas contains chlorine and it can turn into hydrochloric acid (if it reacts with H2 and dissolves in aqueous condensate), which will be corrosive to the heating systems. Proper treatment is required.
Heat from various exothermic processes.	Heat recovery of reaction to produce steam at high pressure with end goal of using steam in processes or for electric power generation.	Simple method of integrating steam generation within the process reactors.
Heat from hot products from reactors.	Sensible heat recovered from hot products.	No simple method of recovering the heat (heat recovery equipment for solid or liquid to air or gas).
Exhaust gases from multiple stacks.	Use of sensible heat and latent heat of liquid–water vapour. Reduction in water use at the plants.	Microchannel heat exchanger with small may pose maintenance problems.
Heat from gases containing water vapours discharged from evaporators and other units.	Use of sensible heat and latent heat of liquid–water vapour. Reduction in water use at the plants.	Quality of water steam, which may contain gaseous and solid contaminants. The heat exchangers (condensers) are usually large equipment. Vapour filtration or water purification system availability.
Low–pressure steam.	Latent heat of steam and water.	Dry coolers to eliminate use of water.
Low–temperature cooling water.	Sensible heat of water.	Availability of water at low temperatures. Lack of availability of indirect dry (air) coolers that can replace cooling towers or conventional water to water heat exchangers.
Flared gases with high hydrocarbon content.	Heating value of gases or feedstock recovery.	Periodic and unpredictable nature of the source of gases.
By–product solids or residues.	Sensible heat and heat content of the material.	Material handling and combustion systems for contaminated solids.

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4.2.4 Barriers to waste heat recovery in the Glass Industrial Sector — Fiberglass Manufacturing

Table 5: Barriers to waste heat recovery in the Glass Industrial Sector — Fiberglass Manufacturing (17)

Waste Heat Source	Heat Recovery Opportunities	Barriers to Waste Heat Recovery
Melting furnace flue gases with regenerators.	Medium–temperature (<480°C) heat recovery for power generation. The gases may contain some particulates but no condensable components.	Availability of reliable and efficient heat exchangers, small size boilers and steam turbine power generation system that can be used for relatively small and low–temperature waste heat sources.
Melting furnace flue gases with oxy–fuel systems.	Cleaning or filtering particulates from high–temperature (>870°C) exhaust gases containing corrosive components. This will allow recovery of heat from exhaust gases at higher temperatures without pre–cooling them.	Availability of reliable and efficient heat exchangers, small size boilers and steam turbine power generation system that can be used for relatively small and low–temperature waste heat sources.
All fuel–fired melting systems.	Using heat of low–temperature clean exhaust gases (<200°C) discharged from baghouses.	Cost and reliability of currently low–temperature power generation systems (such as ORC).
Melters and fore–hearth outer surfaces or casing.	High–temperature (>200°C) furnace walls.	Cost and reliability of currently low–temperature power generation systems (such as ORC).
Annealing furnaces (temperature controlled kilns), tempering furnaces or drying ovens.	Reducing air leakage from inlet–outlet sections or areas.	The equipment design and operational components that require flexibility of operation. Availability of low–temperature heat recovery systems, cost of combustion system using preheated air.

4.2.5 Barriers to waste heat recovery in the Cement Industrial Sector

Table 6: Barriers to waste heat recovery in the Cement Industrial Sector (17)

Waste Heat Source	Heat Recovery Opportunities	Barriers to Waste Heat Recovery
Hot clinker.	Recovery of sensible heat.	No major technological barriers. The use of available waste heat within the plants present a logistical barrier.
Exhaust gases from pre–heaters and other areas.	Recovery of sensible heat.	No major technological barriers. The use of available waste heat within the plants present a logistical barrier.
Hot surfaces — Kiln shell.	Heat recovery in the form of electricity using TEG devices.	Availability of materials and method of their use for the kiln walls to reduce the surface temperature. There is no simple recovery of heat without affecting the temperature profile within the kiln.

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4.2.6 Barriers to waste heat recovery in the Paper Industrial Sector — Pulp Mill

Table 7: Barriers to waste heat recovery in the Paper Industrial Sector — Pulp Mill (17)

Waste Heat Source	Heat Recovery Opportunities	Barriers to Waste Heat Recovery
Paper machines.	Low–temperature (<300°C) heat recovery for heating water, air, or power generation. The gases contain some particulates and large amount of water steam (wet steam).	Materials for heat exchangers. Corrosion of materials is a big issue for gases containing acidic constituents (such as, SO_2 and CO_2) that can tolerate presence of small particulate or fibrous materials and variable amount of water steam. Availability and cost of reliable and efficient low–temperature condensing heat exchangers.
Boilers fired with waste materials.	Use of exhaust gas heat and heat recovery from waste (ash) material that may contain some combustible material.	Materials for heat exchangers. Corrosion of materials is a big issue for gases containing acidic constituents (such as, SO_2 and CO_2) that can tolerate presence of small particulate or fibrous materials and variable amount of water steam.
Waste materials with organic content or having heat value.	Recovery and use of heating value content of the waste material.	Economic justification and availability of combustion equipment that can burn such waste economically.

4.2.7 Barriers to waste heat recovery in the Food Industrial Sector — Snack Manufacturing

Table 8: Barriers to waste heat recovery in the Food Industrial Sector — Snack Manufacturing (17)

Waste Heat Source	Heat Recovery Opportunities	Barriers to Waste Heat Recovery
Clean exhaust gases from boilers, products dryers, oil heaters and other sources.	Low–temperature (<260°C) heat recovery from combustion products with moisture content of 20–40%.	No major technical barriers. Economics of heat recovery system installation and use of recovered heat within the plant are two major barriers. Cost and reliability of currently low–temperature power generation systems (such as ORC).
Exhaust gases from fryers. These gases contain moisture and oil vapours.	Recovery of sensible heat, use of heating value content of oil vapours and latent heat of moisture.	Presence of oil vapours prevents use of conventional waste heat recovery technologies (such as condensing heat exchangers).
Hot wash water (50–80°C) from various sources.	Sensible heat of water.	Presence of particulates, economics of heat recovery, and lack of use of low–grade heat in the forms of warm water or air in the plants.
Waste material with organic content or heat value and moisture.	Recovery and use of heating value content of the waste material.	Economic justification, availability of combustion equipment that can burn or process such waste economically.

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4.2.8 Barriers to waste heat recovery in the Coatings Industrial Sector — Vinyl Coating Mill

Table 9: Barriers to waste heat recovery in the Coatings Industrial Sector — Vinyl Coating Mill (17)

Waste Heat Source	Heat Recovery Opportunities	Barriers to Waste Heat Recovery
Volatile Organic Compounds (VOCs) that are mixed with the make-up air or with the air that is filtered to the ovens.	Waste heat comes in the form of sensible heat from the air and chemical heat from VOCs.	These gases cannot be considered as a direct source of waste heat, since they must be incinerated to remove air pollutants.
Clean exhaust gases from ink dryers.	The exhaust gases temperature is above 150°C.	No major technical barriers. Waste heat can be recovered using widely spread technologies.
Clean exhaust air generated by the Regenerative Thermal Oxidizers (RTOs).	Recovery of waste heat from the exhaust air of the RTOs (180–200 °C) to supply heat to the ovens or to generate the hot water needed in other processes.	No major technical barriers. Waste heat can be recovered using widely spread technologies.
Steam boilers exhaust gases.	The exhaust gases temperatures are around 260°C (with operating pressures greater than 1 MPa).	No major technical barriers. Waste heat can be recovered using widely spread technologies.
Combustion gases generated by natural gas burners used in some oven to supply hot air through an oil recirculation system (oil heaters).	The residual temperature of the combustion gases is lower than 180ºC.	No major technical barriers. Waste heat can be recovered using widely spread technologies.

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5 Recovery of Waste Cold

It is estimated that cooling needs will rise exponentially over the years due to climate change that is leading to a continuous increase in temperatures, while the demand for heating will be stagnant (see Figure 19). For this reason, the recovery of waste cold is of vital importance.

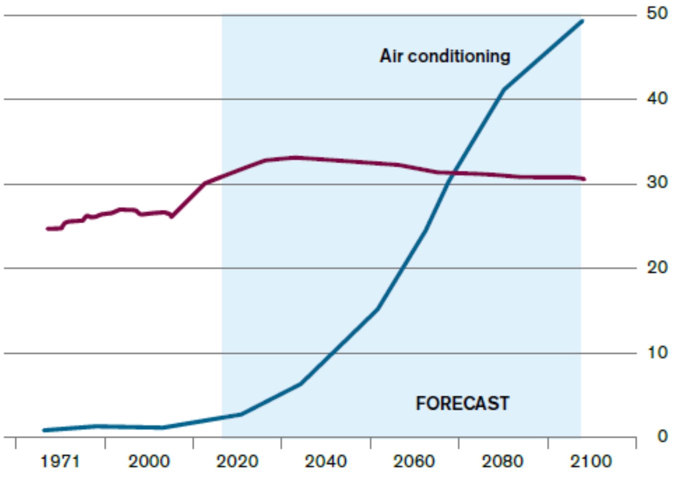

Figure 19: Worldwide forecast energy demand for space heating and space cooling (Exajoules) (18)

Regarding the recovery of industrial waste cold, the main source of cold waste energy is that released during the regasification of liquefied natural gas (LNG). LNG is transported in a liquid state at a temperature of -160°C to consuming countries. The regasification energy can be recovered and used for the production of electricity, either by means of ORC machines or by driving generators through the direct energy of the expansion of the gas. Another option is to use the cold from LNG regasification to improve the efficiency of other processes (cooling of air compressor inlet air, cooling of electrical rooms or server rooms, distillation facilities, etc.).

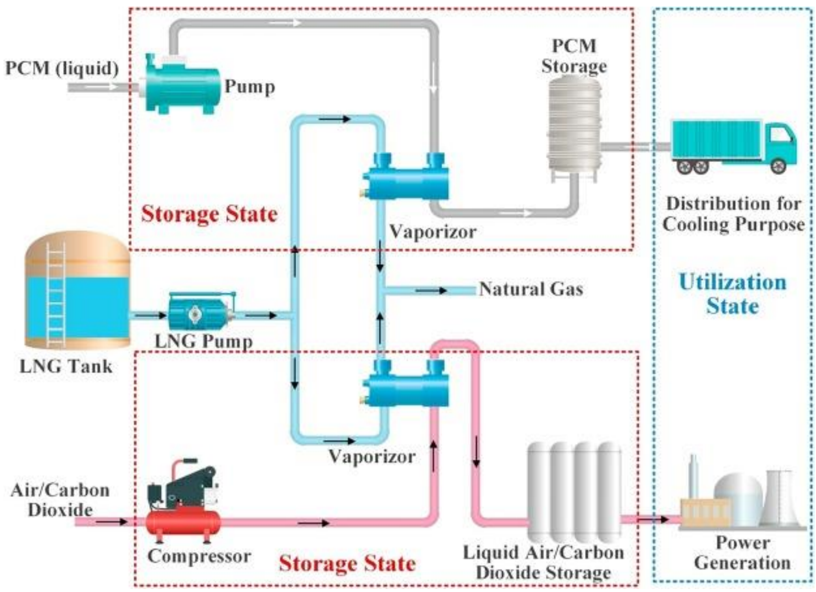

Figure 20: LNG regasification process (19)

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There are some projects studying the construction of a complete cold economy where cold waste recovery is a key technology (see Figure 21).

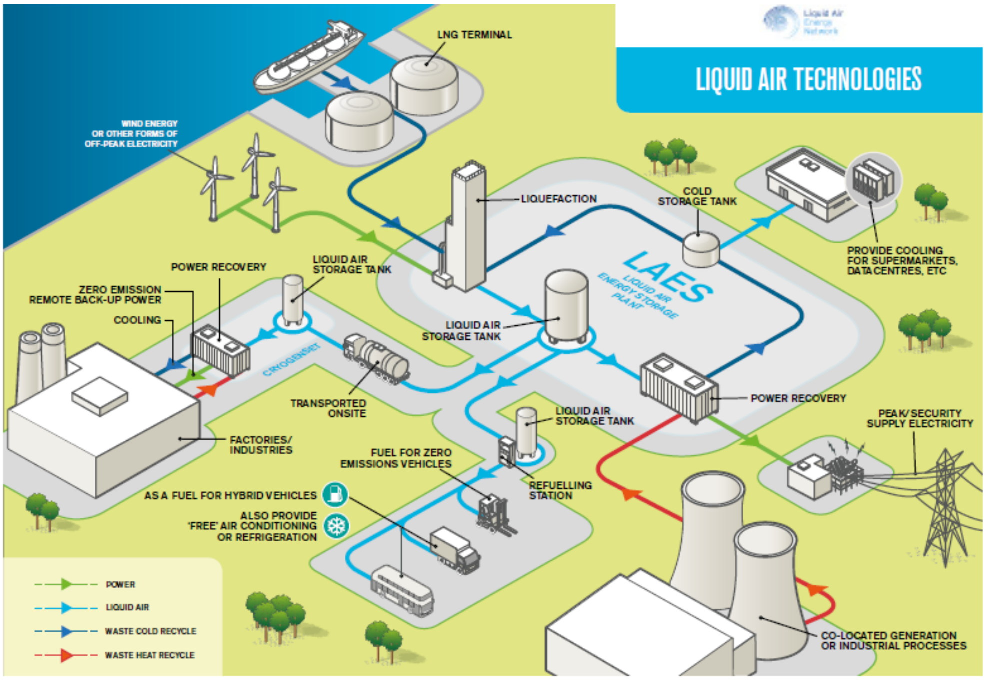

Figure 21: Diagram of potential of cold economy (18)

Another application where industrial waste cold recovery can be implemented is 5th generation district heating and cooling networks. These networks supply the demand for heat and cold through hot or cold water respectively (see Figure 22).

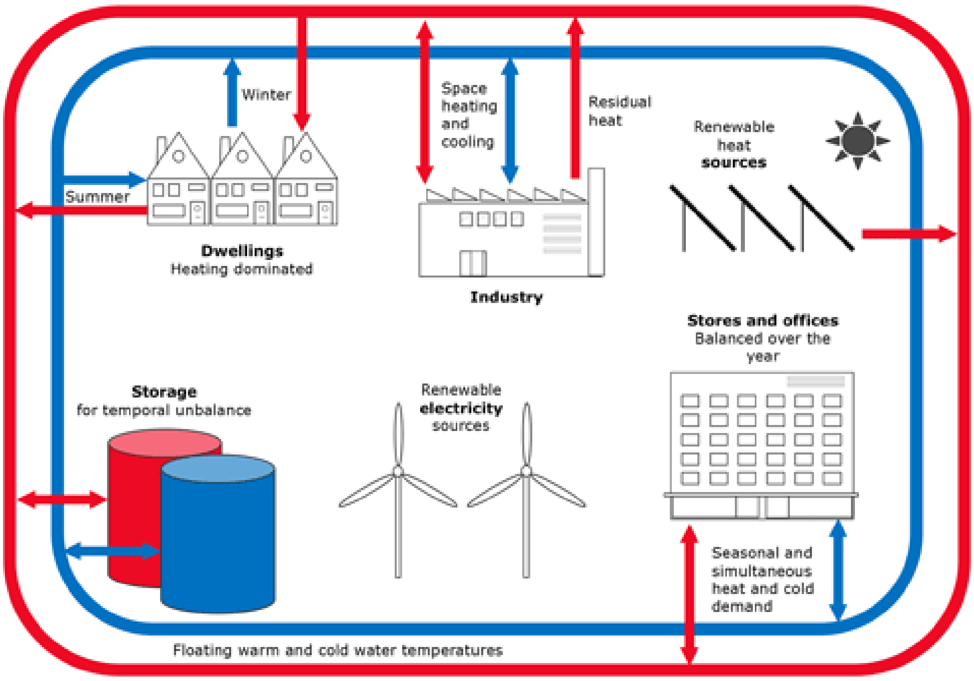

Figure 22: Diagram of a 5th generation district heating/cooling network (20)

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6 Conclusion

The analysis carried out for the implementation of industrial waste heat recovery consists of a summary of three main tasks:

- Search for available sources of waste heat.
- Search for processes (internal or external to the plant) with heat demand that can be fully or partially covered by the recovered heat (end use).
- Choice of the waste heat recovery technology that best suits the parameters of both, the waste heat source and the process that demands the heat (working fluids):

The main parameters that define the waste heat stream are the following:

- Temperature, flow and pressure.
- State of the waste heat stream (solid, liquid, gas, or a mixture).
- Content of contaminants and/or particles.
- Type of waste heat generation (continuous, discontinuous, stable, unstable, etc.).

In a simplified way, the temperature, flow and pressure together with the state of the waste heat stream (working fluid needed in the heat-demanding process) define the type and size of waste heat recovery technology to be implemented, while the content of contaminants and/or particulates define the materials of the heat transfer surfaces and the need to implement a pre-treatment of the waste heat stream before it enters to the waste heat recovery equipment. The type of waste heat generation defines the simultaneity between waste heat generation and demand (synchronization), which implies the need or not to install waste heat storage technologies for the viability of the recovery and reuse of the waste heat.

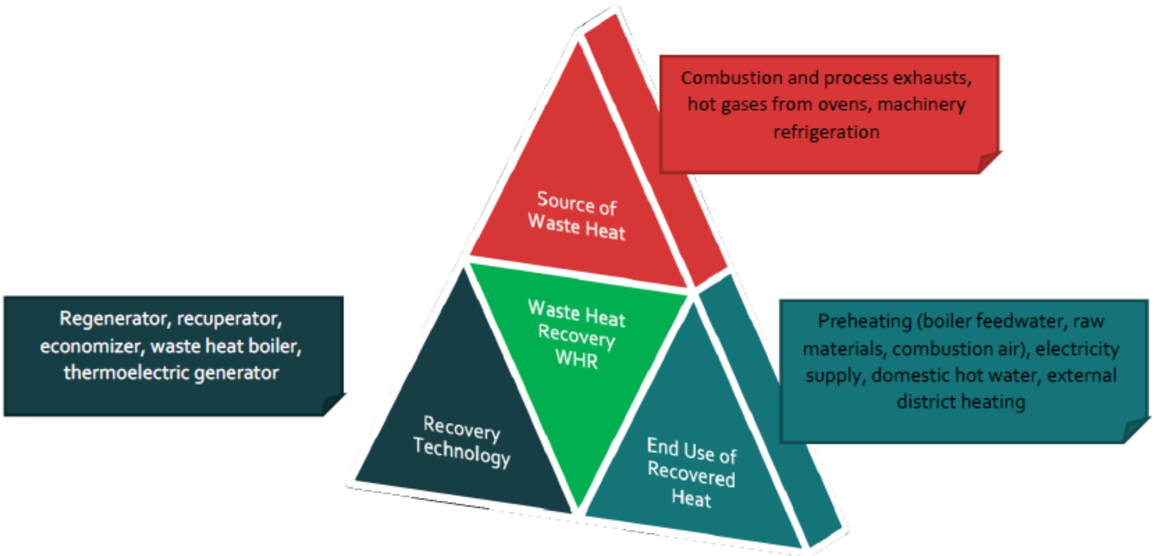

Figure 23: Essential components for Waste Heat Recovery (21)

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The content of contaminants and/or particles in the waste heat stream can be considered the barrier or the most limiting factor in terms of waste heat recovery, the main consequences being summarized below:

- Fouling of the waste heat recovery equipment and therefore, reduction of its heat transfer capacity.
- Increased cost of waste heat recovery equipment, mainly due to the need to use materials on the heat transfer surfaces that will withstand the contaminants from the waste heat stream.
- Need to install a previous treatment, which increases the cost of the facility and therefore, also increases the return period of the investment.

Despite not being a technical barrier, it should be noted that waste heat recovery is not the main business model of the industrial sectors, so during the investment decision process it is common to prioritize projects that are directly related to the main business of the industrial sector.

Moreover, it can be concluded that, regarding the recovery of industrial waste cold, we are at a very early stage, but since the need for cooling will increase over the years, it is expected that it will be an incipient field of study and investment over the next few years.

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