INCUBIS

BAT FOR ENERGY SYMBIOSIS
A SUPPLEMENT TO THE ENERGY EFFICIENCY BREF

This project is funded by the Horizon 2020 Framework Programme of the European Union

Sustainable Process Industry through Resource and Energy Efficiency

Project Title: An Industrial Symbiosis Incubator for Maximizing Waste Heat/Cold Valorization in Industrial Parks and Districts

Project Acronym: INCUBIS | **Grant Agreement No:** 894800

INCUBIS

D5.1 BAT for energy symbiosis – A supplement to the energy efficiency BREF

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Contents

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1 Executive Summary

The Energy Symbiosis Opportunities System (ESOS) tool has been created to allow users of the INCUBIS platform with available waste heat streams (referred to as 'haves') to identify optimum uses for them either within their own company or in a symbiotic relationship with another company or organisation. Equally the tool will allow companies or organisations with heating needs (referred to as 'wants') to identify potential sources/suppliers to meet their needs. These may derive from waste heat found elsewhere in their own organisation or, again, by identifying a potential symbiotic relationship with another organisation.

As part of this process the tool is designed to identify, and provide details of, technologies that may be required to enable the symbiotic relationships. To facilitate the identification of potential relationships and enabling technologies to be recommended, applications of waste heat have been arranged in 16 categories, such as space heating or combustion gas pre-heating. Similarly, industries most likely to provide waste heat haves and wants have initially been arranged into 7 categories such as: glass manufacturing, cement manufacturing, iron and steel manufacturing, aluminium production, metal casting etc. While this approach limits, to some extent, the flexibility of the tool it controls the amount of data that needs to be analysed and makes the task of identifying symbiotic opportunities tractable. However, future development of the tool could see the number of categories increase as new routes to utilisation emerge and mature.

A suite of technologies has been identified and each associated with both the industries and applications to which they are suited. These technologies include established and commercially available technologies such as heat exchangers and less mature and less widely available technologies such as low temperature electricity generation using dual fluid cycles such as in the Kalina cycle. In the INCUBIS digital Platform each technology is ascribed characteristics such as level of maturity, capital cost etc. Potential users of ESOS Module which is under development,would then input their preferences in terms of, for example, their appetite for risk. The technology recommended to them will then account for its technical match with the process under consideration and its match with the aspirations of the user.

In this report we catalogue and describe the technologies that have been included in the INCUBIS Digital Platform. These descriptions and the characterisation of the technologies in the tool are intended to represent the current state-of-the-art in terms of the technology itself and its applications. The authors have therefore compared technology characteristics with the Energy Efficiency (ENE) Best Available Techniques Reference Document (BREF) on best available technologies for Energy Efficiency. This document was originally published in 2009 but updated and corrected in September 2021. It is a comprehensive document that considers all aspects of designing, implementing, operating and maintaining energy efficient processes. However, it focusses on methods to make a particular process more efficient by making changes to the process and does not consider related or combined processes. In short it does not consider symbiosis and its benefits even though the techniques and technologies used in symbiotic processes are mostly present.

It is the authors view that a section on waste heat to power – creating a symbiotic relationship between processes that may be remote and unrelated - would be a useful addition to the ENE BREF derived from the development of the ESOS tool as part of the INCUBIS project. The technologies, reviewed herein, to be proposed for inclusion in such a section would comprise: steam cycles; organic Rankine cycles; Kalina cycles and thermoelectric generation. The authors have therefore drawn up a proposal which has been submitted to the IPPC using the standard template included in Annex for a section on waste heat to power to be included in the ENE BREF. The response and feedback received is being reported as next steps.

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2 Lists of tables, figures and acronyms

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3 Energy symbiosis Best Available Techniques (BAT)

The Energy Symbiosis Opportunities System (ESOS) tool has been created to allow users of the INCUBIS platform to identify optimum uses for available waste heat streams (haves) and to identify potential supplies/suppliers to meet their process or other heating needs (wants). As part of this process the tool is designed to identify, and provide details of, technologies that may be required to realise the symbiotic relationships – installing a heat exchanger in a flu gas stream to recover waste heat from it for example. For potential relationships to be identified and technologies recommended, applications of waste heat have been arranged in 16 categories such as space heating or combustion gas pre-heating. Similarly, industries most likely to provide waste heat haves and wants, have been arranged into 7 categories such as: glass manufacturing, cement manufacturing, iron and steel manufacturing, aluminium production, metal casting etc. While this approach limits, to some extent, the flexibility of the tool in its initial form it controls the amount of data that needs to be analysed and makes the task of identifying symbiotic opportunities tractable. Future development of the tool could see the number of categories increase as new routes to utilisation emerge and mature.

Having identified categories of industries and typical waste heat applications, a suite of technologies has been identified and each associated with both the industries and applications where it is applicable. These technologies include established and commercially available technologies such as heat exchangers and less mature and less widely available technologies such as low temperature electricity generation using dual fluid cycles such as the Kalina cycle. In the ESOS tool each technology is ascribed characteristics such as level of maturity, capital cost etc. Users of ESOS can then input their preferences in terms of, for example, their appetite for risk. The technology recommended to them will then account for its technical match with the process under consideration and its match with the aspirations of the user.

In this report we catalogue and describe the technologies that have been included in the ESOS tool. These descriptions and the characterisation of the technologies in the tool are intended to represent the current state-of-the-art in terms of the technology itself and its applications. The authors have therefore compared technology characteristics with the existing EU reference document on best available technologies for Energy Efficiency. Where updates to that document are deemed to be required or where new technologies should, in the authors view, be added, the IPPC Bureau will be notified via the standard template for updates/additions which is included as an appendix to this report.

In the sections below brief descriptions and associated attributes are provided for the selected waste energy technologies.

3.1 Waste Heat to Heat Application Technology

3.1.1 Heat Exchangers

A heat exchanger may be defined as a device that facilitates heat transfer from a hot fluid to a cold fluid without the two fluid streams mixing. Such devices have been in use for over a century in industrial, commercial and domestic settings. They exist in many forms and are widely commercially available. Heat exchangers are an essential component of all waste heat recovery and re-use schemes. Even where a conversion technology such electricity generation via a steam turbine is used to extract value from a waste heat stream, a heat exchanger, in this case in the form of a heat recovery steam generator (HRSG) perhaps, will be required to transfer heat from flu gases to the working fluid.

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Herein we consider three basic, generic types/configurations of common heat exchangers that can be used in a wide range of applications, three application specific heat exchangers and a technology used to enhance the performance of heat exchangers – heat pipes.

Although each type of heat exchanger has characteristics peculiar to its design, there are some performance and operational characteristics that are common to all heat exchangers and therefore worthy of comment before specific types and applications are considered.

Designing a heat exchanger involves first selecting the type (shell and tube, plate and fin etc) and then calculating the necessary size where the defining characteristic is the area necessary to allow the desired amount of heat transfer to occur. Large areas require large heat exchangers which increases cost so it is desirable to make the area as small as possible. This provides motivation for schemes to enhance heat transfer per unit area such as, turbulence generators, fins or, more exotically, heat pipes.

Heat exchangers are limited in terms of the temperatures at which they can operate by the properties of the materials from which they are made. It is clearly not acceptable to expect a heat exchanger to extract heat from a fluid stream whose temperature exceeds the melting point of the metal from which the heat exchanger is constructed. Aluminium is an excellent material for the construction of heat exchangers. It easily worked into complex shapes of high surface area to volume ratio and has a high thermal conductivity. It is commonly used in plate and fin type heat exchangers for these reasons. However, its low melting point of around 660°C limits the range of applications for which it can be considered.

In operation heat exchangers can perform over extended periods with very little maintenance but there are some operational characteristics/risks worthy of note. Flu gases from which one might wish to extract waste heat often contain condensable gases – usually steam – along with other potentially soluble gases. Care should be taken – perhaps by limiting the amount of heat extracted – to manage or avoid corrosive condensates formed within the heat exchanger where these might cause damage or limit life expectancy.

Fluid streams are rarely completely free from contaminates and these can accumulate in narrow passages within a heat exchanger leading to a drop in performance or blockage. This is known as fouling and to avoid it periodic cleaning of the heat exchanger may be required. In some types of heat exchanger this can be achieved by disassembling the heat exchanger but where this is not possible techniques such as acid cleaning may need to be employed.

3.1.1.1 Plate-type Heat Exchanger

Description: Plate Heat Exchanger consists of a series of closely spaced separate parallel plates forming a succession of high surface area to volume ratio passages between them. Hot and cold fluids flow in opposite direction in alternate passages with gaskets used to maintain a seal and prevent the fluids from mixing. To enhance heat transfer the plates may be corrugated to increase their effective surface area.

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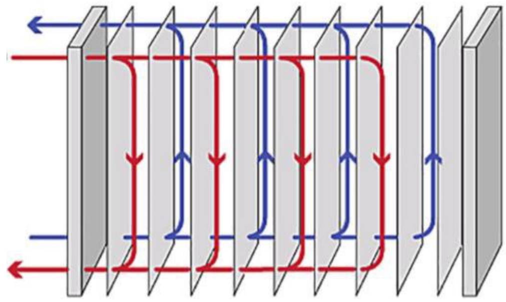

Figure 1: Schematic of a Plate Heat Exchanger

Type of waste to energy exchange: Gas to gas and liquid to liquid heat exchange

Typical waste heat sources: Exhaust from boilers, incinerators & turbines, drying, curing, and baking ovens

Typical waste heat application: Combustion air preheat, and space heat

Typical operating boundary conditions: 10 °C to 170 °C

3.1.1.2 Finned Tube Heat Exchangers/Economizers

Description: A finned tube heat exchanger is a type of cross flow heat exchanger consisting of a bundle of round tubes with attached fins that maximize surface area and heat transfer rates. They are a gas to liquid type of heat exchanger where liquid flows through the tubes and receives heat from hot gases flowing across the tubes. Typical applications include their use as economisers to pre warm water on its way to the boiler in a power station.

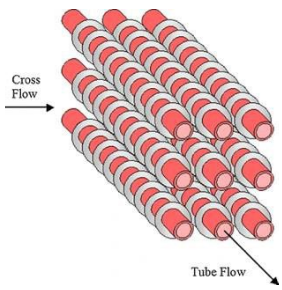

Figure 2: Schematic of a Finned Tube Cross Flow Heat Exchanger

Type of waste to energy exchange: Gas to liquid heat exchange

Typical waste heat sources: Industrial process flue gases

Typical waste heat application: Boiler feed water preheating, hot process liquids, hot water for space heating, and domestic hot water.

Typical operating boundary conditions: 230 °C to 650 °C

3.1.1.3 Tube Shell and Tube Exchanger

Description: A shell and tube heat exchanger is often used when the medium containing waste heat is a liquid or a vapor being is used to heat another liquid although liquid to gas is also common. The shell contains a tube bundle and usually internal baffles to direct the fluid in the shell over the tubes

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in multiple passes. The shell is inherently weaker than the tube, so that the higher-pressure fluid is circulated in the tubes while the lower pressure fluid flows through the shell.

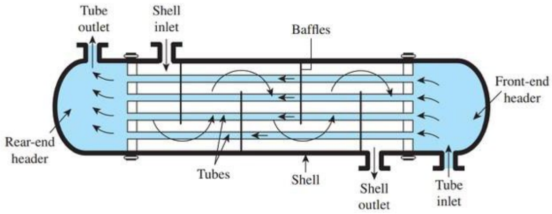

Figure 3: Schematic of a Shell and Tube Heat Exchanger

Type of waste to energy exchange: Gas to gas and gas to liquid heat exchange

Typical waste heat sources: Refrigeration condensates, waste steam distillation condensates, coolants from engines, air compressors, and bearings & lubricants

Typical waste heat application: Liquid feed flow requires heating

Typical operating boundary conditions: 230 °C to 650 °C

3.1.2 Recuperator

3.1.2.1 Description

Recuperators are an application specific type of heat exchanger designed to recover heat from exhaust gases and use it to pre-heat in-coming air. Typically they are used to recover heat from combustion exhaust gases and used to pre-heat air at the inlet to the combustor. Recuperators operate at high temperatures so construction materials need to be carefully considered. Metals may be used but in extreme circumstances they may be constructed from ceramic materials which benefit from very high melting points but typically low thermal conductivity. Recuperators reduce the amount of fuel required in the combustor thereby reducing fuel costs and combustion related emissions such as CO_2 and NO_x.

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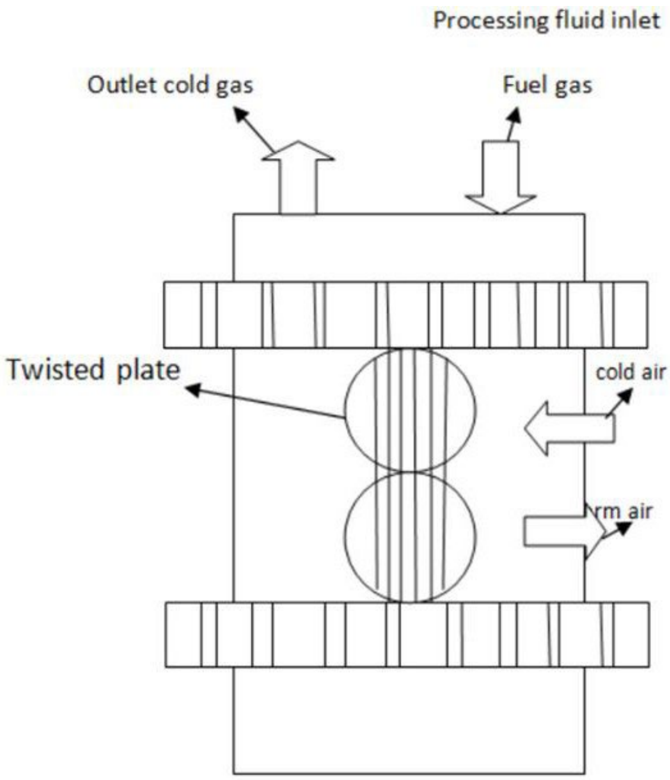

Figure 4: Schematic of the Recuperator

Typical types of recuperators include:

Metallic Radiation Recuperators

These types of recuperators are used in rolling mills. Hot flue gas flows through a duct lined with tubes containing incoming fuel gas – typically air. Metallic radiation recuperator has low efficiency and recovers less than 50% of waste heat.

Radiation and Convective Recuperators

To improve effectiveness of heat transfer, a combination of radiative and convective recuperators are used. This improves efficiency and recovers 50% or more of the waste heat.

Cross Flow Type Metallic U-Tube Recuperator

This type is the most efficient type of recuperator, it recovers up to 80% of waste heat. Cross flow type metallic u- tube recuperators are used in oil and gas furnaces.

Recuperator surface efficiency depends on two parameters:

- Surface area and time available at heat exchanger
- Recuperator material

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3.1.2.2 Typical Application

- Heat recovery for pre-heating the air at entrance to burners and heating of premises
- Pre-heating of air inside dryers and heating of premises
- Heat recovery from exhaust air without mixing of the two airflows
- Pre-heating of air in air-handling units

3.1.2.3 Typical operating boundary conditions

230 °C to 1650 °C (Temperatures ranges based on metallic and ceramic recuperators).

3.1.3 Regenerator

3.1.3.1 Description

A Regenerator is another special purpose heat exchanger characterised by the alternating flow of hot outgoing gases and cold incoming gases through a device with a high thermal energy storage capacity. They are typically used for large capacity furnaces. A typical embodiment might consist of two brick 'checker work' chambers through which hot and cold air flow alternately. As the combustion exhaust passes through one chamber, the bricks absorb heat from the combustion gas and there is an increase in their temperature. After the bricks pick up heat, the flow is then reversed so that the incoming combustion air passes through the chamber, which transfers heat to the combustion air entering the furnace. A minimum of two chambers are used so that while one is absorbing heat from the exhaust gases, the other is transferring heat to the combustion air. The direction of airflow is altered over a fixed interval of time. Important relations exist between the size of the regenerator, time between reversals, thickness of brick, conductivity of brick and heat storage capacity of the brick. The time between the reversals is an important aspect in a regenerator. Long periods mean higher thermal storage and hence higher cost. Also, long periods of reversal result in lower average temperature of preheat and consequently reduce fuel economy.

Regenerators are especially suited for high temperature applications with dirty exhaust gases. The major disadvantages are their large size and the capital costs, which are significantly greater than the costs of recuperators. Other disadvantages of regenerator are the accumulation of dust and slagging on the surfaces which reduce efficiency of the heat transfer. Heat losses from the walls of the regenerator and air in leaks during the gas period and out-leaks during air period also reduces the heat transfer efficiency.

Type of waste to energy exchange: Gas to gas heat exchange

Typical waste heat sources: Glass and steel melting furnaces waste heat/ exhaust

Typical waste heat application: Pre-heating the combustion air

Technology operating boundary conditions: 1100 °C to 1650 °C

3.1.4 Heat Pipe

3.1.4.1 Description

The heat pipe is a thermal device which allows an efficient transport of thermal energy by utilising the energy associated with the phase change of a working fluid contained within. It is composed of a

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closed pipe structure whose internal surface is lined with a thin layer of porous material, usually referred to as a wick. The container may have a cylindrical pipe shape but other shapes can be conveniently manufactured. The pores of the wick are filled with a working liquid appropriate to the application, and the vapour of the liquid occupies the open space along the centre of the pipe. The liquid and its vapour coexist in equilibrium so that the pressure inside the container is equal to the vapour pressure corresponding to the saturation conditions.

This relatively simple configuration allows for a very efficient transfer of heat from one end of the heat pipe to the other. At the hot end, absorbed heat causes the working fluid to evaporate. This creates a small pressure gradient and the vapour then makes it way to the cold end where it condenses releasing heat. The working fluid, in liquid form, then makes its way back the hot end via the wick under capillary action. By this cyclic process, heat is transferred from the hot end to the cold end far more effectively than if the heat pipe were a solid object through which heat was conducted under the same temperature conditions. A schematic of a heat pipe is shown in the figure below.

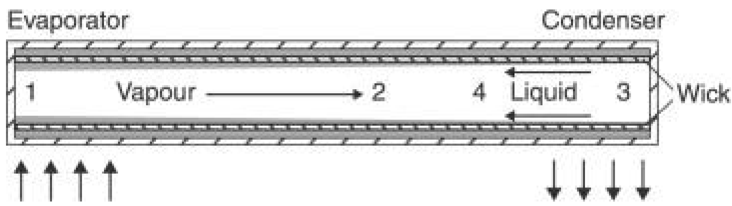

Figure 5: Schematic of a Heat Pipe

There is a great variety of heat pipes in terms of their geometry, function, and methods used to transport the liquid from the condenser to the evaporator. The above-described heat pipe, consisting of a working fluid, a wick structure, and an envelope, is the most basic type of heat pipe, and it is known as a constant conductance heat pipe. There are other more sophisticated heat pipe designs, namely: variable conductance heat pipes, thermal diodes, pulsating (oscillating) heat pipes, micro-heat pipes, rotating heat pipes, sorption heat pipes (SHPs), magnetic fluid heat pipes, loop heat pipes, and capillary pumped loops (LHPs and CPLs, respectively).

Type of waste to energy exchange: Gas to gas and gas to liquid heat exchange

Typical waste heat sources: Waste steam, air dryers, kilns (secondary recovery), reverberatory furnaces (secondary recovery), curing & baking ovens

Typical waste heat application: Preheating of boiler combustion air; Recovery of waste heat from furnaces; Reheating of fresh air for hot air driers; Recovery of waste heat from catalytic deodorizing equipment; Reuse of furnace waste heat as heat source for other oven; Cooling of closed rooms with outside air; Preheating of boiler feed water with waste heat recovery from flue gases in the heat pipe economizers; Drying, curing, and baking ovens; Waste steam reclamation; Brick kilns (secondary recovery); Reverberatory furnaces (secondary recovery); Heating, ventilating, and air-conditioning systems

Technology operating boundary conditions: 30 °C to >870 °C

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3.1.5 Waste Heat Boiler

3.1.5.1 Description

A waste heat boiler takes the heat formed as a by-product of another process, heat which would normally be wasted, and uses it to create steam. The steam can be used to drive turbines which produce electricity. Alternatively, the boiler can simply be used to heat water or other kinds of fluid. As it recycles some of the energy used, a waste heat boiler, or waste heat recovery boiler, can reduce the fossil fuel consumption and financial running costs of a system. This also means fewer greenhouse gases are released into the atmosphere. Waste heat boiler design comprises two main types: fire-tube boilers, or shell boilers, and water-tube boilers. In fire-tube boilers, a steel shell encloses a water-filled space with metal tubes inside. Hot gases produced from a combustion process, such as inside a furnace, pass back and forth through the tubes transferring heat to the surrounding water.

Fire-tube waste heat boilers have the advantage that they are relatively simple to construct, install and maintain. The heat energy stored in the water can be used to respond to a short-term extra demand, although if all the heat is used there is the disadvantage that it will take a long time to replenish. Another limitation of this kind of equipment is that it cannot operate at the higher pressures a water-tube boiler can. A waste heat boiler of the water-tube design is able to cope with much higher pressures of steam than a fire-tube boiler, but it is more difficult to construct and install. Inside this type of boiler, there are narrower tubes than inside a fire-tube boiler, and the tubes contain water instead of hot gases. In a reversal of the system inside a fire-tube boiler, waste heat, in the form of hot gases or furnace flames, surrounds the water-filled tubes. Insulating materials are used to protect the boiler tubes against flame damage. As well as tolerating high pressures, a water-tube waste heat boiler can respond quickly to changes in heat input.

Waste heat boilers can be used in what are known as combined heat and power, or CHP, plants. These are power plants where the heat that is normally created as a byproduct of generating electricity, improving efficiency from around 40 percent to around 70 percent. Maximum efficiency is achieved when the heat is used either on or very near the site of the plant, for example through industrial symbiosis.

Type of waste to energy exchange: Gas to liquid heat exchange

Typical waste heat sources: Exhaust from gas turbines, reciprocating engines, incinerators, and furnaces

Typical waste heat application: Hot water or steam generation

Technology operating boundary conditions: 230 °C to 650 °C

3.1.6 Heat Pump

3.1.6.1 Description

Heat pumps are used to raise the temperature of a heat source and comprise mainly two technologies: compression and absorption heat pumps.

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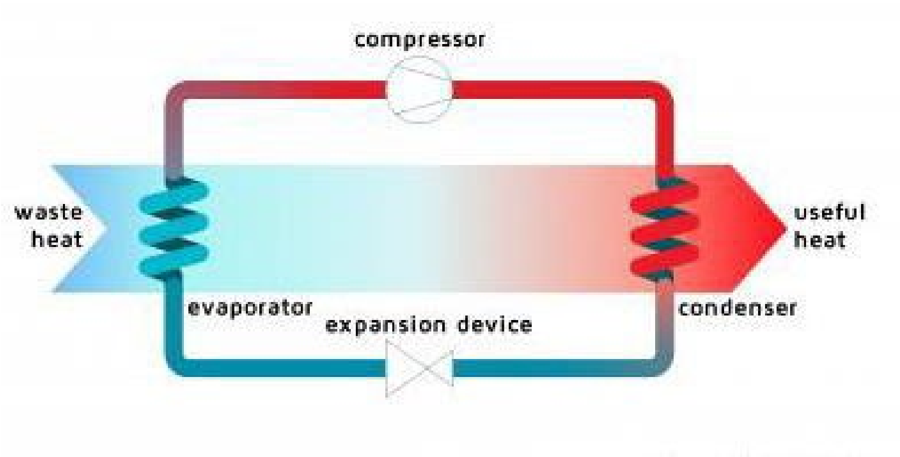

Figure 6: Compression Heat Pump

In a compression type heat pump the waste heat is transferred to a refrigerant which is evaporated in a heat exchanger (evaporator) at low refrigerant pressure and temperature. An electrically operated compressor brings than the refrigerant vapour to a higher pressure and temperature level which is high enough to exchange the heat (useful heat) with the heating water. The refrigerant condenses during the heat release. After heat exchange at the high pressure/temperature level, the refrigerant is expanded again to the low pressure/temperature level and re-circulated (closed refrigerant circuit).

The performance of a compression heat pump is indicated by the Coefficient of Performance (COP) which is defined for heating purposes as useful heat (output) divided by the electric energy (input). The maximum achievable efficiency is thermodynamically limited by the Carnot efficiency (Carnot-COP). This theoretical efficiency limit is determined by the temperature difference between high (supply temperature) and low temperature (temperature of the waste heat source) of the heat pump process.

In practice actual achievable COP values are considerably lower than the theoretical Carnot-COP limit. The ratio between actual COP and Carnot-COP is known as quality grade of a heat pump. COP values in the range of 50% to 70% of the Carnot-COP can be achieved (quality grade 0.5 to 0.7). This means that COP values of around 4 are practically achievable.

Type of waste to energy exchange: Gas to liquid heat exchange

Typical waste heat sources: Low temperature industrial processes flue gases

Typical waste heat application: Space heating and upgrading low-temperature waste heat

Technology operating boundary conditions: 100 °C to 190 °C

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3.2 Waste Heat to Power Technologies

According to the US Environmental Protection Agency[5] , waste heat to power (WHP) is the process of capturing heat discarded by an existing thermal process and using it to generate power as illustrated in figure 5. Energy-intensive processes—such as those occurring at refineries, steel mills, glass furnaces and cement kilns—all release hot exhaust gases and waste streams that can be harnessed with well-established and emerging technologies to generate electricity. The recovery of waste heat for power is a largely untapped type of combined heat and power (CHP), i.e. the use of a single fuel source to generate both thermal energy and electricity.

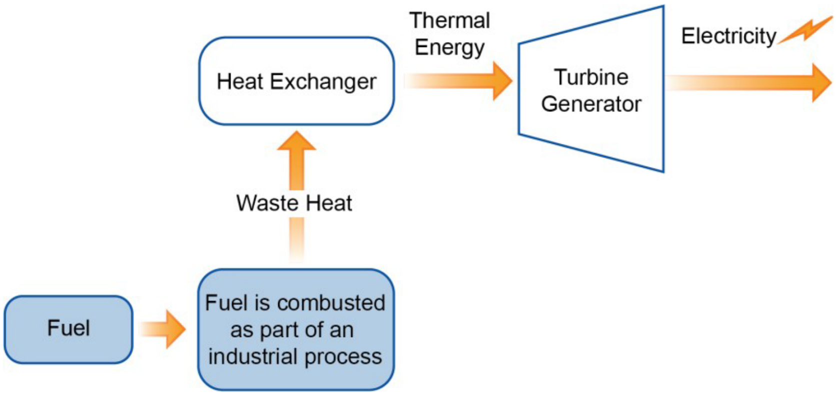

Figure 7: Waste Heat to Power[5]

Conventional CHP generally consists of a prime mover, a generator and a heat recovery system. CHP is a form of distributed power generation that is located at or near the energy-consuming facility.

The most common CHP configuration is known as a topping cycle, where fuel is first used in a heat engine to generate electricity, and it is the waste heat from the electricity generation process that is then recovered to provide useful thermal energy. As an example, where a gas turbine or reciprocating engine is used to generate electricity a heat recovery unit can be used to capture useful thermal energy from the exhaust stream and cooling system. Alternatively, where a steam turbine is used generate electricity using high-pressure steam, lower pressure exhaust steam can be directed to an industrial process or district heating system.

Waste heat streams can also be used to generate power in what is called bottoming cycle CHP—another term for WHP. In this configuration, fuel is first used to provide thermal energy, such as using fuel to power a furnace, and it is the waste heat from that process that is then used to generate electricity. The key advantage of WHP systems is that they utilize heat from existing thermal processes, which would otherwise be wasted, to produce electricity or mechanical power, as opposed to directly consuming additional fuel for this purpose.

WHP projects are less common than CHP projects. They have the advantage that they can be retrofitted to an existing system but the disadvantage that the heat source for power generation is necessarily of lower quality implying a reduced efficiency of conversion to electricity. Technologies for WHP designed to combat the lower quality heat input include the use of organic Rankine cycle power generation (ORC), dual fluid (Kalina) cycles e.g. (ammonia-water) and thermoelectric generators. Despite technology advances, utilising waste heat in liquid streams below 100 °C and gas streams

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below 250 °C remains economically challenging. Conversion to electricity is less efficient with all these

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technologies compared to traditional electric generators, and project costs currently run high for a variety of reasons, including the cost of the equipment. WHP is therefore generally only considered when other uses of the waste heat as heat have been excluded or other recovery methods are not practical within the facility. While the costs of these systems currently remain high, and commercial implementation is limited, the technologies continue to evolve and improve.

The US EPA list the following as barriers to WHP. It is worth noting that many of these apply to the recovery of waste heat generally regardless of whether or not the intended use is electricity generation.

Technical Barriers. The principal hurdle for WHP systems is the heat recovery itself. While the power generation equipment is commercially established and relatively standardized, each heat recovery situation presents unique challenges. Some of the project-specific technical issues that affect project economics include:

- The waste heat sources at a plant are dispersed and difficult to reach or consolidate, or are from non-continuous or batch processes.
- Seasonal and low-volume operations reduce the economic benefits of WHP.
- Waste heat sources often contain chemical and/or mechanical contaminants that impact the complexity, cost, and efficiency of the heat recovery process.
- There may be added cost and complexity for integrating the WHP system controls with existing process controls.
- Space limitations and equipment configurations make WHP systems difficult or impossible to site economically.

Business Barriers. Businesses may be reluctant to take on projects with perceived risks, such as energy recovery projects that are outside their core business. These concerns often lead to unrealistically high project hurdle rates for capital-intensive WHP projects. Small projects (i.e., less than $5 million) can be particularly difficult to develop because the returns are often reduced by the costs of due diligence, permitting, and siting. The economic downturn has exacerbated the inherent risk of financing projects with long paybacks, especially projects dependent on uncertain future fuel prices and variable electricity rates.

Securing financing from banks for WHP projects is a challenge because the systems can be technically complicated, and they combine the risk associated with power generation with the risk inherent in the primary business itself (i.e., there is no heat to recover if the plant shuts down).

End users also lack a general awareness of WHP technologies and how to implement them. Few technology demonstrations or case studies currently exist, and most projects are very site- and process-specific. There is resistance from businesses to accept new, unproven technology that could potentially jeopardize existing production processes, despite significant potential benefits.

3.2.1 Steam Rankine Cycle, Organic Rankine Cycle and Kalina Cycle

3.2.1.1 Description

The steam Rankine cycle (SRC) is the most commonly used system for power generation from waste heat and involves using waste heat to generate steam in a waste heat boiler, which then drives a

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steam turbine. Steam turbines are one of the oldest and most versatile prime mover technologies. Heat recovery boiler and steam turbine systems operate thermodynamically on the Rankine Cycle, as shown in Figure. In the SRC, the working fluid (i.e., water) is first pumped to elevated pressure before entering a heat recovery boiler. The pressurized water is vaporized by the hot exhaust and then expanded to lower temperature and pressure in a turbine, generating mechanical power that can drive an electric generator. The low-pressure steam is then exhausted to a condenser at vacuum conditions, where heat is removed by condensing the vapor back into a liquid. The condensate from the condenser is then returned to the pump and the cycle continues.

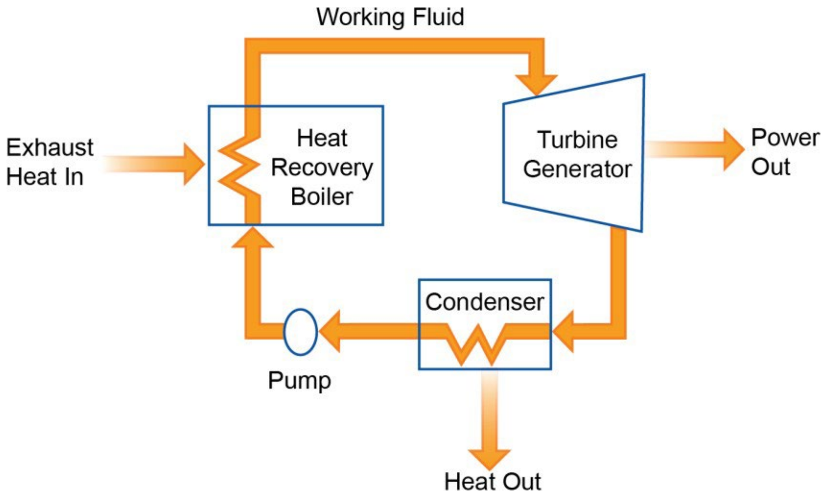

Figure 8: Rankine Cycle Heat Engine

Organic Rankine cycles operate in a similar way but involve using other working fluids with better efficiencies at lower heat source temperatures. ORCs use an organic working fluid that has a lower boiling point, higher vapor pressure, higher molecular mass, and higher density compared to water. Together, these features enable higher turbine efficiencies than in an SRC operaring under similar conditions. ORC systems can be utilized for waste heat sources as low as 150 °C, whereas steam systems are limited to heat sources greater than 250 °C. ORCs have commonly been used to generate power in geothermal power plants, which can be used by a variety of facilities, and more recently in pipeline compressor heat recovery applications.

The Kalina cycle is another adaptation of the Rankine cycle, using a mixture of fluids (usually water and ammonia) as the working fluid, which allows for a more efficient energy extraction from the heat source. The Kalina cycle has an operating temperature range that can accept waste heat at temperatures of 100 °C to 550 °C and is 15 to 25 percent more efficient than ORCs at the same temperature level. The EPA[5] note that SRC and ORC systems are much more prevalent in the United States with Kalina cycle systems growing in popularity elsewhere especially in geothermal power plants, where the hot fluid is often below 150 °C.

The three types of Rankine power cycles discussed above overlap to a certain degree. However, there are advantages to each:

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- SRC systems are the most familiar to industry and are in general economically preferable when the source heat temperature exceeds 400 °C.
- For lower temperatures, ORC or Kalina cycle systems can be used. These systems can be applied at temperatures lower than for steam turbines and are more efficient in moderate temperature ranges.
- Kalina systems have the highest theoretical efficiencies. Their complexity makes them generally most suitable for large power systems of several MWs or greater.
- ORC systems can be economically sized in small, sub-MW packages, and they are also well suited for using air-cooled condensers, making them appropriate for applications such as pipeline compressor stations that do not have access to water.

3.2.1.2 Application

Economically feasible WHP applications are generally based on recovering waste heat from combustion exhaust streams with temperatures above about 250 °C. Industrial processes that produce these temperatures include calcining operations (e.g., cement, lime, alumina, petroleum coke), metal melting, glass melting, petroleum fluid heaters, thermal oxidizers, and exothermic synthesis processes. Additionally, there are plentiful opportunities for lower temperature applications, and ORC systems can be economical in areas with high electricity prices, emissions or WHP incentives. Key WHP opportunities within these operations are provided below:

Primary metals. Primary metals manufacturing involves a large number of high-temperature processes from which waste heat can be recovered. Steel mills, for example, have various high-temperature heat recovery opportunities. In integrated mills, waste heat can be recovered from coke ovens, blast furnaces for iron production, and basic oxygen furnaces for steel production. There are also opportunities to recover waste heat from electric arc furnaces. In the aluminum industry there is energy recovery potential from the exhaust of the Hall–Héroult cells and secondary melting processes. Metal foundries have a variety of waste heat sources, such as melting furnace exhaust, ladle preheating, core baking, pouring, shot blasting, castings cooling, heat treating, and quenching.

Nonmetallic mineral product manufacturing. There are a number of strong opportunities for WHP in this sector. Calcining in rotary kilns is a high-temperature process that is used in the manufacture of cement, gypsum, alumina, soda ash, lime, and kaolin clay. The glass industry uses raw material melting furnaces, annealing ovens, and tempering furnaces, all operated at high temperatures.

Petroleum refining. Basic processes used in petroleum refineries include distillation (fractionation), thermal cracking, catalysis, and treatment. These processes use large amounts of energy, and many involve exothermic reactions that also produce heat. Modern refineries are highly integrated systems that recover heat from one process to use in other processes. However, many operations still release high-quality waste heat that could be recovered for power production. An example is the exhaust from petroleum coke calciners. Petroleum coke is heated to 1300 °C, and the exhaust is typically 500 to 550 °C leaving the calciner.

Chemical industry. There are several major segments of the industry in which high-temperature exhaust is released that could be recovered for power generation, including petrochemicals, industrial gases, alkalis and chlorine, cyclic crudes and intermediates (e.g., ethylene, propylene, and benzene/

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toluene/xylene), plastics materials, synthetic rubber, synthetic organic fibers, and agricultural chemicals (i.e., fertilizers and pesticides).

Fabricated metals. Processes generating waste heat include metal preheating, heat treatment, cleaning, drying, and furnace heating.

Natural gas compressor stations. There are 15 ORC power generation systems installed at natural gas compressor stations in North America. These systems have a total electric capacity of 85 MW using the exhaust heat from gas turbine–driven compressors.

Landfill gas energy systems. Landfills that use reciprocating internal combustion engines or turbines to produce power could generate additional power with ORC systems using exhaust gases. Other landfills could install ORC systems to generate power from the waste heat caused by flaring.

Oil and gas production. There are a number of flared energy sources in oil and gas production that could utilize WHP systems.

3.2.1.3 Economics

According to the US EPA[5], The total cost to install WHP systems include the costs associated with the waste heat recovery equipment (i.e., boiler or evaporator), power generation equipment (i.e., SRC, ORC, or Kalina cycle), and power conditioning and interconnection equipment. The total cost would also include the soft costs associated with designing, permitting, and constructing the system. The installed costs of SRC, ORC, or Kalina cycle power systems are fairly similar, differing more as a function of project size and the complexity of site integration than type of system. Table 1, below, shows a first-cut estimate of the cost of producing power from WHP systems. The representative costs shown cover a range of project sizes (50 kW to greater than 20 MW) and site complexity. Capital costs are amortized over a 10-year period based on a cost of capital of 15 percent10 and 7,500 annual operating hours.

Operation and maintenance (O&M) cost estimates can vary widely. Rankine cycle power systems themselves have relatively low maintenance costs. However, maintenance requirements of the heat recovery boilers and balance of plant must also be included, which can vary by technology and by site conditions. As an example, steam systems may require onsite boiler operators while ORCs can often run unattended. O&M costs of $0.005–$0.018 per kilowatt-hour (kWh) were used for Table to reflect the wide range of maintenance requirements that might be experienced. There are no fuel costs for true WHP projects (i.e., no supplemental fuel use).

Table 1: Combined Heat and Power Technology Fact Sheet Series: Waste Heat to Power, U.S. DOE, 2021.

Cost Component	**ORC**	**SRC**
Installed Costs, $/kW	$1,900–$4,500	$1,200–$3,000
WHP Generating Costs		
Amortized Capital, $/kWh	$0.055– $0.125	
O&M Costs, $/kWh	$0.009– $0.018	$0.005–$0.013
Total Power Cost, $/kWh	**$0.060–$0.125**	

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3.2.2 Supercritical CO2 Cycle

3.2.2.1 Description

The supercritical carbon dioxide (sCO_2) cycles use CO_2 as a working fluid that is in a supercritical state—at a temperature and pressure above its critical point where liquid and gas phases are not distinguishable. The supercritical power cycle takes advantage of the real gas behavior of the CO2 in order to achieve high thermal efficiency. The main improvement of the supercritical CO2 cycle is the reduced compressor work because of property changes in the region of the CP. Another benefit is the low critical temperature of CO2 (31°C), which makes it possible to use water at ambient temperatures as a coolant. This technology is still in its development phase and the authors are not aware of any applications for waste heat recovery to date.

Type of waste to energy exchange: Gas to liquid heat exchange

Typical waste heat sources: Gas turbine exhaust, boiler exhaust, cement kilns

Typical waste heat application: Electric power generation

Technology operating boundary conditions: 150 °C to 500 °C

3.2.3 Thermoelectric Generation

3.2.3.1 Description

Thermoelectric generators (TEG) are solid-state semiconductor devices that convert a temperature difference and heat flow into a useful DC power source. Thermoelectric generator semiconductor devices utilize the Seebeck effect to generate voltage. This generated voltage drives electrical current and produces useful power at a load.

The basic building block of a thermoelectric generator is a thermocouple. A thermocouple is made up of one p-type semiconductor and one n-type semiconductor. The semiconductors are connected by a metal strip that connects them electrically in series. The semiconductors are also known as thermoelements, dice or pellets.

The Seebeck effect is a direct energy conversion of heat into a voltage potential. The Seebeck effect occurs due to the movement of charge carriers within the semiconductors. In doped n-type semiconductors, charge carriers are electrons and in doped p-type semiconductors, charge carriers are holes. Charge carriers diffuse away from the hot side of the semiconductor. This diffusion leads to a buildup of charge carriers at one end. This buildup of charge creates a voltage potential that is directly proportional to the temperature difference across the semiconductor.

To create a thermoelectric generator module, many p-type and n-type couples are connected electrically in series and / or parallel to create the desired electrical current and voltage. The couples are placed between two parallel ceramic plates. The plates provide structural rigidity, a flat surface for mounting and a dielectric layer to prevent electrical short circuits.

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3.2.3.2 Advantages of Thermoelectric Generators

Reliability - Thermoelectric generators are solid-state devices. Having no moving parts to break or wear out makes them very reliable. Thermoelectric generators can last a very long time. The Voyager 1 spacecraft thermoelectric generator, as of this writing has been operational for 41 years. It has traveled over 13 billion miles without any maintenance or repairs.

Quiet - Thermoelectric generators can be designed to be completely silent.

No Greenhouse Gases - Thermoelectric generators do not require any greenhouse gases to operate. Some energy conversion technologies do.

Wide Range of Fuel Sources - Thermoelectric generators do not have restrictions on fuels that can be used to generate the needed heat. Many other energy conversion technologies do.

Scalability - Thermoelectric generators can be designed to output power levels smaller than microwatts and larger than kilowatts.

Mountable in Any Orientation - Thermoelectric generators operate in any orientation. Some energy conversion technologies are sensitive to their orientation relative to gravity.

Operation Under high and Zero G-forces - Thermoelectric generators can operate under zero-G or high-G conditions. Some other energy conversion technologies cannot.

Direct Energy Conversion - Thermoelectric generators convert heat directly into electricity. Many energy conversion technologies require intermediate steps when converting heat to electricity. For example, heat energy from fuel is converted in a turbine to mechanical energy, then mechanical energy is converted to electricity in a generator. Each energy conversion step adds losses in the form or waste heat. This makes thermoelectric generators less mechanically complex than some other energy conversion technologies.

Compact Size - Thermoelectric generators can be designed to be very compact. This leads to greater design flexibility.

Technology operating boundary conditions: 230 °C to 650 °C

3.2.4 Thermal Photovoltaic

3.2.4.1 Description

Thermo-photovoltaic generators convert radiant energy into electricity. These systems involve a heat source, an emitter, a radiation filter, and a PV cell. As the emitter is heated, it emits electromagnetic radiation. The PV cell converts this radiation to electrical energy.

Type of waste to energy exchange: Radiant energy into electricity

Typical waste heat sources: Not yet demonstrated in industrial applications

Typical waste heat application: Radiant energy into electricity

Technology operating boundary conditions: 230 °C to 650 °C

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3.3 Energy Efficiency BREF Review

The Energy Efficiency (ENE) Best Available Techniques Reference Document (BREF) was originally published in 2009 but updated and corrected in September 2021. It is a comprehensive document that considers all aspects of designing, implementing, operating and maintaining energy efficient processes. It goes beyond purely technical matters and, for example, considers issues of management and human resources, in the form of skills retention, in the operation of energy efficient processes.

In the document, best available techniques are considered in association with the processes for which they are relevant so, for example, recuperation and regeneration are considered in the context of improving the efficiency of combustion systems. Similarly, feedwater pre-heating is considered in the context of improving the efficiency of steam based systems. Associating techniques/technologies with particular applications is the same approach that has been adopted in the ESOS tool so that the ethos of the ENE BREF to some extent validates the approach in the ESOS tool. Moreover, a review of the ENE BREF document reveals that in the comprehensive coverage of opportunities for improved energy efficiency, the majority of the technologies included in the ESOS tool and reviewed herein are already covered. Heat exchangers are covered in the section on heat recovery and cooling, heat pumps are considered in the same section and again in the section on thermal drying techniques. As already noted, recuperators and regenerators are considered in the section on combustion systems – and so on. However, the authors do note what appears to be an omission from the ENE BREF and that is techniques/technologies associated with waste heat to power.

The ENE BREF focusses on methods to make a particular process more efficient by making changes to the process itself and does not consider related or combined processes. In short it does not consider symbiotic processes even though the techniques and technologies used in symbiotic processes are mostly present. Converting waste heat to electrical power that can be exported may not seem like a way to make a process more efficient or indeed like an example of symbiosis. However, it enables the energy in fuel used to provide heat to a given process to deliver more value elsewhere in the form of electricity thereby increasing the efficiency of its use. Moreover, given the wide range of uses to which electricity can be put and the long distances over which it can be transmitted, converting waste heat to power can create a symbiotic relationship between widely varying processes many kilometres apart with very few constraints, no investment in new equipment at the user end and an established Energy Services Company (ESCO) in the form of the distribution company ready and willing to buy the exportable power.

It is the authors view, therefore, that a section on waste heat to power would be a useful addition to the ENE BREF derived from the development of the ESOS tool as part of the INCUBIS project. The technologies, reviewed herein, to be included in such a section would include: steam cycles; organic Rankine cycles; Kalina cycles and thermoelectric. The authors have therefore submited a proposal to the IPPC using the standard template included in appendix A for a section on waste heat to power to be included in the ENE BREF.

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4 Next steps

After the submission of the form to the IPPC, we have received a response from the European IPPC Bureau.

The Technical Working Group for the Reference document on Best Available Techniques for Energy Efficiency (ENE BREF) is currently not active and there are no concrete plans for reactivation at the moment. If you grant your permission, we could share this information through BATIS (Best Available Techniques Information System) in the dedicated folder for interim activities of the ENE BREF and with other BREFs for which it could be relevant. If you believe the information is relevant to a specific sector covered by BREFs, please do not hesitate to indicate for which sector.

Our response has been to include share that information with the following sectors as relevant for other potential BREF contribute.

- Chemicals
- Steel
- Ceramics
- Non-Ferrous metals
- Cement
- Pluss waste incineration

We will report further update in the final report, about such task in case we receive further feedback.

5 References

1. https://www.recuperator.eu/en/
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4. https://www.energy.gov/energysaver/heat-pump-systems
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6. https://www.energy.gov/supercritical-co2-tech-team
7. https://www.pv-magazine.com/2021/08/11/recovering-waste-heat-from-solar-cells-via-a- thermoelectric-generator/

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6 Annexes

The following form is the one sent to the IPPC ENE BREF.

Template for describing a potential candidate Best Available Technique (BAT) or Emerging Technique

As per Article 3(10), Chapter 1 of Directive 2010/75/EU on industrial emissions (IED) '*best available technique' means the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent, and, where this is not practicable, to reduce emissions and the impact on the environment as a whole.*

As per Article 3(14), Chapter 1 of Directive 2010/75/EU on industrial emissions (IED) *'emerging technique' means a novel technique for an industrial activity that, if commercially developed, could provide either a higher general level of protection of the environment or at least the same level of protection of the environment and higher cost savings than existing best available techniques.*

In order to facilitate the use of the BREFs, all techniques to be considered in the BAT decision-making process will be presented according to a standard structure; this template is based on the standard structure presented in the Guidance Document on the practical arrangements for the exchange of information under the IED. For each row, we have provided more details/instructions on the specific data which are needed in order to derive useful BAT conclusions.

Description
Name and brief description of the type and purpose of the technique (or combination of techniques), indicating the type of installation where it is/can be applied. Title/summary containing the type and purpose of the technique (or combination of techniques), as well as the type of the combustion installation where it is applied. For example: drying of the wood chips with recirculation of the hot flue-gases in a biomass fired bubbling circulating fluidised bed boiler plant.
Waste Heat to Power: Many processes, even after steps to maximise their efficiency, produce heat laden waste, most commonly in the form of hot flu gases. There are a growing number of techniques by which such waste heat, even at low temperatures, can be converted to electricity and used in a myriad different ways. While this approach does not improve the efficiency of the heat producing process is clearly increases the efficieny with which the energy contained in the primary fuel is utlised. As such, waste heat to power techniques are an important class of techniques that should be considered in the context of the ENE BREF.

Technical description
A concise (2-3 paragraphs, 1 page maximum) technical description of the in-process and/or end-of-pipe technique (i.e. measures for pollution prevention and / or control). The information should be detailed enough to understand how the equipment works and may include, for example, special materials used, chemical or other type of equations, pictures, diagrams, flow charts, as well as the main controllable parameters (e.g. which chemical products are used, how temperature profile is maintained). Please refrain, as much as possible, from using any general textbook information. If more than 1 page is needed, the operator should indicate which additional data is available. In this case, the EIPPCB will consider that the additional data is readily available and can be provided, upon request, within few days.
The recovery of waste heat for power generation is effectively a type of combined heat and power (CHP) system i.e. the use of a single fuel source to generate both thermal energy (heating or cooling) and electricity. The most common CHP configuration is known as a topping cycle, where fuel is first used in a heat engine to generate power, and the waste heat from the power generation equipment is then recovered to provide useful thermal energy. Waste heat streams can also be used to generate power in what is called a bottoming cycle. In this configuration, fuel is first used to provide thermal energy, e.g. drive a chemcial process, and the waste heat from that process is then used to generate power. The key advantage of WHP systems is that they utilize heat from existing thermal processes, which would otherwise be wasted, to produce electricity or mechanical power, and hence obviate the use of additional fuel for this purpose. The steam Rankine cycle (SRC) is the most commonly used system for power generation from waste heat and involves using the heat to generate steam in a waste heat boiler, which then drives a steam turbine. Organic Rankine cycles work on the same principle but involve using other working fluids with lower boiling temperatures that can therefore operate with better efficiencies at lower heat source temperatures. ORCs typically use an organic working fluid that has a lower boiling point, higher vapour pressure, higher molecular mass, and higher density compared to water. Together, these features enable higher turbine efficiencies than in a SRC operating at the same temperature. ORC systems can be utilized for waste heat sources as low as 100 °C, whereas steam systems are typically limited to heat sources greater than 250 °C. The Kalina cycle is another Rankine cycle, using a mixture of two fluids with different boiling temperatures, such as water and ammonia, as the

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working fluid, which allows for a more efficient energy extraction from the heat source due to the variation in boiling temperature of the mixture. The Kalina cycle has an operating temperature range that can accept waste heat at temperatures of 100 °C to 550 °C and is 15 to 25 percent more efficient than ORCs at the same temperature level.
Thermoelectric generators (TEG) are solid-state semiconductor devices that use the Seebeck effect to develop a potential difference and electromotive power from a semiconductor device exposed to a temperature difference. Semiconductor TEGs comprise a thermocouple made from p and n type semi conductor materials exposed to a temperature difference that causes mobile charge carriers to diffuse from the hot to cold regions thereby creating a potential difference.

The main potential environmental benefits to be gained through implementing the technique. This may include: reduced consumption of energy/raw materials, reduced emissions of specific pollutants to air/water/land, production yield increases, reduced waste generation, etc.

The benefit is derived from the fact that primary fuels (such as natural gas) used to drive heat dependent industrial processes (chemical reactions for example) can be used to provide other services in remote locations by converting waste heat to electricity and using it elsewhere in the plant or by exporting it to the local power grid. The latter option provides revenue to the plant operator and both achieve carbon emission reduction by replacing conventional electricity generation. The amount of carbon savings can be estimated from knowledge of the local grid emission factor (gCO2/kWhr).

Environmental performance and operational data

Actual plant-specific performance data obtained applying the technique (or combination of techniques) and any other information on how to design, operate, maintain and control the technique. The data in this section may address the following issues, only if they are relevant for understanding better how the reported good performance of the technique is achieved:

Emissions data (if not provided elsewhere in the questionnaire, e.g. questions 6.3 and 7.4):

- both the concentration and, if available, specific load of pollutant(s) or the data needed to derive this information;
- the quantity of pollutant before and after the abatement system in order to determine the abatement efficiency (this should be provided only if actual measurements were performed and not on general 'catalogue' information);
- for pollution prevention measures, the quantity of pollutant before and after the implementation of the technique (this should be provided only if actual measurements were performed and not on general 'catalogue' information);
- details of relevant operating conditions, such as: percentage of full capacity, fuel composition, bypassing of the abatement technique, inclusion or exclusion of other-than-normal operating conditions, reference conditions (e.g. for air emission – dry, standard conditions, reference oxygen concentration);
- issues related to emission data, such as: type of averaging period, method to obtain data, uncertainties, number of points considered for deriving the average values.

Consumption data:

- the type and amount of fuel, energy (heat, electricity), water and raw materials / chemicals consumed / used by the technique.

Waste:

- the type and quantities of waste generated and treatment / disposal methods and / or techniques to prevent waste.

Others:

- equipment design characteristics;
- pressure drop;
- the efficiency of the technique over the range of operating conditions;
- encountered constraints of technique performance;
- the integration of the technique into the overall operation of the combustion installation;
- the operation availability of the technique, expressed as days / year (i.e. the minimum amount of downtime needed for the maintenance of the equipment);
- sensitivity and durability of the technique;
- operation / control / maintenance issues and procedures which enable the good performance;
- issues regarding accident prevention.

If more information can be provided, the operator should indicate which additional data is available. In this case, the EIPPCB will consider that the additional data is readily available and can be provided, upon request, within few days.

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The temperature of the waste heat stream dictates the efficiency with which power can be generated and for economically viable WHP applications waste streams at temperatures of 250 oC or above are preferable. Industrial processes that produce these temperatures include calcining operations (e.g. cement, lime, alumina, petroleum coke), metal melting, glass melting, combusters, and exothermic chemical reactions. There are, however, many more opportunities where lower temperature waste stream exist. Conversion efficiencies decrease with temperature but ORC, Kalina or TEG systems can still be economical especially where electricity prices are high or where there are WHP incentives.

Cross-media effects

Relevant negative environmental effects due to implementing the technique (for assessing the impact on the environment as a whole). This may include information on: high consumption of energy/raw materials, increased emissions to other media (air/water/land), increased risk of accidents, increase of waste generation, use of hazardous substances, use of chemical products which have stratospheric ozone depletion potential, use of persistent/toxic/bioaccumulable components (including metals), limitation of the ability to reuse or recycle residues/waste, generation of noise and/or odour.

Careful consideration should be given to the working fluids used in ORC systems since these tend to be refrigerants and may be toxic if leaked and potentially of damage to atmospheric ozone.

Technical considerations relevant to applicability

Indication if the technique can be applied throughout the sector (i.e. indication of the type of plants or processes within the sector to which the technique cannot be applied) and information on the main general technical restrictions on the use/implementation of the technique. Indicate which local conditions (e.g. lack of water) may influence the implementation.

The principal technical hurdle for WHP systems is the heat recovery itself. While the power generation equipment is commercially established and relatively standardized, each heat recovery situation presents unique challenges. As noted by the US Environmental Protection Agency [1], some of the project-specific technical issues that affect project economics include:

- The waste heat sources at a plant can be dispersed and difficult to reach or consolidate, or are from non-continuous or batch processes.
- Seasonal and low-volume operations reduce the economic benefits of WHP.
- Waste heat sources often contain chemical and/or mechanical contaminants that impact the complexity, cost, and efficiency of the heat recovery process.
- There may be added cost and complexity for integrating the WHP system controls with existing process controls.
- Space limitations and equipment configurations may make WHP systems difficult to site economically.

Economics

Information on costs and possible savings, including details on how these costs have been calculated. If a project included other parts of industrial installation, estimate the costs related only to the combustion installation.

Installation expenditure:

- cost data should be provided in the original currency, stating the year when the purchase occurred; if additional costs (or savings) were incurred during the project, they should be added to (or subtracted from) the original price;
- one value for general capital/investment costs should include: project definition/design/planning, building and civil works (including foundations/supports, erection, piping, insulation, painting, etc.), engineering, construction and field expenses, contractor selection costs and contractor fees, pollution prevention/control expenditure (including equipment costs, auxiliary equipment, instrumentation, any associated freight of equipment/materials), performance testing, start-up costs, etc.;
- one value for local specific capital / investment costs should include: purchase of land, general site preparation (including removal of underground interferences and modification of existing equipment), use of special materials which increased the costs (specify which and how much it influenced the final value), etc.;
- decommissioning costs (if any) should be reported separately.

Operation and maintenance(O&M) costs:

- one value for variable O&M costs per year, including consumables (energy (electricity, heat, fuel), raw water, chemicals), environmental services (waste treatment and disposal services), etc.;
- one value for fixed O&M costs per year, including labour costs (for operation, supervisory and maintenance staff (and its training)), overhead costs (insurance premiums, licence fees, administration (calculated proportionally)), replacement parts (for all the parts which are replaced over a period longer than 1 year, annualised costs should be considered), etc.

Revenues, avoided costs and benefits:

- one value for total revenues, avoided costs and benefits per year, including revenues (sale of materials generated on site (e.g. ash, gypsum, effluent for irrigation)), savings (on raw materials, chemicals, energy use, labour, maintenance, disposal costs), benefits (improved system effectiveness, increase of fuel utilisation), etc.;
- one value for total revenues per year from each emission trading scheme (e.g. Greenhouse gases, SO_x).

Additional economic considerations:

Some issues may have a significant impact on the investment and O&M costs and, in this case, provide enough information on how this influenced the reported values. Some examples follow:
- local conditions, such as seismic/storm conditions, wetland terrain, which require special provisions, inducing high investment and/or operating costs;
- total duration of the project (from the general site preparation untill plant start-up) and the 'downtime' of the installation (i.e. time during which the installation was not operating due to the installation of the new equipment); the costs incurred with this loss of production can be reported separately;
- payback time for the investment;
- tax incentives and subsidies, such as for the reduction of water consumption, for the increase of the use of renewable energy; the costs saved with this item can be reported separately.

If more information can be provided, the operator should indicate which additional data is available. In this case, the EIPPCB will consider that the additional data is readily available and can be provided, upon request, within a few days.

Details of CAPEX and OPEX for WHP systems are commercially sensitive and not always publically available. Summary data provided by the US EPA [1] suggests that CAPEX for ORC power plant are approximatley 50% higher than steam based power plant of similar capacity but that OPEX costs are similar.

Driving force for implementation

Rationale behind the choice of technique, i.e. local conditions or requirements (e.g. legislation, safety measures, local environmental quality standards for emission, type/quality of receiving raw materials/fuels/waters), non-environmental triggers (e.g. increased yield, improved product quality, savings (on raw materials, chemicals, energy use, labour, maintenance, disposal costs), economic incentives etc.), which stimulated the implementation of the project.

The technical potential of industrial waste heat in Europe is vast, it was recently estimated to be around 300TWh/year, so that the motivation to exploit waste heat derives from fuel cost savings and carbon emission reductions - especially where the latter attract emission costs or are mandated by local policy. Much of the waste heat is available at relatively low temperature that falls below the limit for the efficient application of conventional heat to power conversion technologies. Where this is the case, the use of waste heat as heat, i.e. process integration where waste heat from one part of a process is used to provide heat to another - using a recuperator to capture exhaust heat and pre-heat inlet combustion air in a gas turbine for example - is almost invariably the most cost effective way to recover it. Where this is not possible, other technologies for conversion of heat to power, such as those described herein, may become applicable. Basic thermodynamics dictates that conversion efficiencies of heat engines rely on the temperature of the heat source and hence these will inevitably be reduced for low temperature waste heat applications with obvious implications for economic viability. The case for waste heat to power applications will depend heavily on energy prices and local regulations relating to carbon emissions and these will need to be assessed on a case by case basis. The case for the application of thermoelectric generators is similar but with some features peculiar to this technology. TEGs can be made to be extremely small scale and compact and given their low maintenance requirements, they can be included in regions with limted access. TEGs are therefore a candidate for energy harvesting applications e.g. extracting power from a process to drive instrumentation as part of process control without the need for an external power source.

Example plants

References to plants where the technique has been implemented; indication of the degree to which the technique is in use in the European Union and worldwide.

There are numerous examples of the use of ORC based power plant to valorise waste heat. A comprehensive list of installations can be found at https://orc-world-map.org. Details of installations can also be found on manufacturers websites e.g. Turboden, Enertime. Similarly there are a growing number of examples of applications of power plant used to recover waste or low grade heat using the Kalina Cycle. Examples can be found from Kalina Power Ltd. Applications of thermoelectric generators are less numerous and tend to be on a smaller scale. They have, however, found applications in the automotive sector extracting energy from exhaust gases and in the domestic arena in the form of fans used to distribute heat from stoves and driven by the heat of the casing.

Reference literature

Literature or other reference material that was used in writing the section and that contains more detailed information, specifying the relevant page / table / figure number.

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1. "Waste Heat to Power Systems" US Environmental Protection Agency (https://www.epa.gov/sites/default/files/2015-07/documents/waste_heat_to_power_systems.pdf)
2. "Organic Rankine Cycles for Waste Heat Recovery" 2020, Edited by Silvia Lasala, IntechOpen, ISBN 978-1-78985-473-2
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