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THE IMPACT OF INNOVATIVE WHR TECHNIQUES ON IMPROVING THE ENERGY EFFICIENCY OF TECHNOLOGICAL PROCESSES

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Resumen

El calor residual es una fuente importante de energía generada por varios procesos tecnológicos en las industrias. Sin embargo, este valioso recurso a menudo se desperdicia y se libera a la atmósfera, lo que resulta en un mayor consumo de energía y contaminación ambiental.

Se han desarrollado técnicas innovadoras de recuperación de calor residual (WHR) para aprovechar esta energía y mejorar la eficiencia energética de los procesos tecnológicos.

Palabras clave

Calor residual, energía, WHR, eficiencia, procesos tecnológicos

Abstract

Waste heat is a significant source of energy that is generated by various technological processes in industries. However, this valuable resource is often wasted and released into the atmosphere, resulting in increased energy consumption and environmental pollution. Innovative waste heat recovery (WHR) techniques have been developed to harness this energy and improve the energy efficiency of technological processes.

This thesis aims to investigate the impact of innovative WHR techniques on improving the energy efficiency of technological processes.

Keywords

Waste heat, energy, WHR, efficiency, technological processes

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Introduction and objectives

Waste heat is a significant source of energy that is generated by various technological processes in industries. This valuable resource is usually wasted and released into the atmosphere, resulting in increased energy consumption and environmental pollution. Innovative waste heat recovery (WHR) techniques have been developed to harness this energy and improve the energy efficiency of technological processes.

This thesis aims to investigate the impact of innovative WHR techniques on improving the energy efficiency of technological processes. The study will begin by providing an overview of waste heat recovery and its significance in energy conservation. Then, it will explore the various innovative WHR techniques available and their applications in different industries.

The thesis will also analyse the economic and environmental benefits of implementing innovative WHR techniques. Economic benefits such as reduced energy consumption, increased productivity. Environmental benefits such as reduced greenhouse gas emissions and minimized environmental impact will also be examined.

Case studies of industries that have implemented innovative WHR techniques will be conducted to provide a practical understanding of the effectiveness of these techniques. The challenges encountered in implementing these techniques and their potential solutions will also be analysed.

Finally, the thesis will provide recommendations for industries that are considering the implementation of innovative WHR techniques. The recommendations will be based on the findings of the study and will focus on the factors that should be considered when choosing the most suitable WHR technique for a particular process.

Overall, the thesis aims to contribute to the understanding of the impact of innovative WHR techniques on improving the energy efficiency of technological processes. It is hoped that the findings of this study will encourage more industries to implement these techniques and contribute to a more sustainable future.

Waste Heat Recovery

Waste heat is the energy produced during industrial processes but not put to use, which is then lost, wasted, and released into the environment. Diverse waste heat recovery technologies can be used to recover waste heat and produce useful energy sources while lowering overall energy consumption [1].

The traditional energy sources are becoming less available as a result of the depletion of fossil fuel reserves. Even so, energy is still being wasted, particularly in the form of heat. Besides waste heat can be used to improve the energy efficiency of process locations, leading to primary energy savings.

In order to lessen waste heat's harmful effects on the environment and boost efficiency in various industries, waste heat is being captured and used in various ways, such as by using it to produce electricity or heat.

Also simplified mathematical models of waste heat recovery using heat as primary energy source, including organic Rankine Cycles, absorption heat pumps and absorption chillers are developed to support this methodology. When evaluating the possibility of recovering usable energy from waste heat, these models are used [2].

Using waste heat recovery systems in industrial processes has been crucial as one of the key areas of research to lower harmful emissions, fuel consumption and to increase efficiency and production. We can classify heat loss into high temperature, medium temperature and low temperature, then the WHR systems are developed in order to achieve the highest efficiency.

We have to start implementing these measures, since energy consumption (Fig. 1) is increasing, as for example in the UK manufacturing industry.

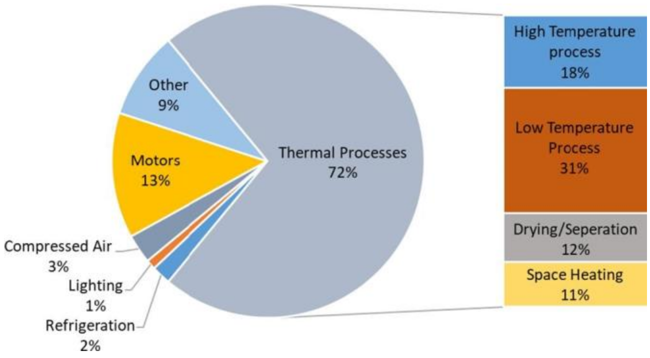


Figure 1. Energy consumption in the UK manufacturing industry

The quantity or the amount of available waste heat can be calculated using the next equation.

$$Q = V\ x\ \rho\ \ x\ Cp\ x\ \Delta T$$

Equation 1

Q) Heat content

V) Flowrate of the substance (m3/s)

p) Density of the flue gas (kg/m3)

Cp) Specific heat of the substance (J/kg.K)

ΔT) Difference in substance temperature (K) between the final highest temperature in the outlet and the initial temperature in the inlet of system.

Significance in energy conservation

Waste heat recovery is a crucial aspect of energy conservation because it allows for the reuse of energy that would otherwise be lost in various industrial processes. Waste heat recovery is useful for generate electricity or for heating water. This reduces the amount of energy that needs to be generated from other sources, leading to significant energy savings and reduced greenhouse gas emissions.

Besides, waste heat recovery helps to improve the efficiency of industrial processes, and reduces the energy required to carry out these processes. This will be beneficial for the economy of the business and will reduce environmental impact.

By 2050, WHR technologies could cut the world's energy consumption by up to 9% [3], according to the International Energy Agency (IEA). Furthermore, it has been predicted that the application of WHR technologies could result in energy savings of up to 3.2 exajoules (EJ) by 2030.

Finally, waste heat recovery is very important for sustainability and energy efficiency (Fig.2). Additionally, to cutting down on energy use and greenhouse gas emissions, it also helps businesses save money. Industries can increase their productivity and lessen their impact on the environment by implementing waste heat recovery techniques.

Figure 2. Significance in energy conservation

WHR Techniques

Waste heat recovery methods include capturing and transferring the waste heat from a process with a gas or liquid back to the system as an extra energy source. The energy source can be used to create additional heat or to generate electrical and mechanical power.

There are different waste heat recovery techniques that are used to capture and utilize waste heat generated on industrial processes. The different types of WHR technologies are presented below.

Heat exchangers

Heat exchangers allow heat to be transferred between two fluids without allowing them to mix. Makes the process easier of heat exchange between two fluids that are at different temperatures. Heat exchangers are used to extract heat from hot exhaust gases and transfer it to a cooler fluid, such as water, in waste heat recovery applications. Following that, the heated water can be used in a variety of ways, including industrial processes or heating up rooms.

Heat exchangers are used in a wide range of engineering applications, such as power plants, refrigeration, heating and air-conditioning systems, chemical and food processing systems, automobile radiators and waste heat recovery units. These are some examples of heat exchangers: Air preheaters, evaporators, superheaters, economizers, condensers and cooling towers in power plants [4].

The operation of a heat exchanger involves 4 main steps (Fig.3):

1) In a shell and tube heat exchanger, one fluid enters the tubes and flows through them, while the other enters the shell and flows around the tubes. In a plate and frame heat exchanger, the fluids flow through channels formed by the plates. In a finned-tube heat exchanger, one fluid flows over the finned tubes while the other flows through the tubes.

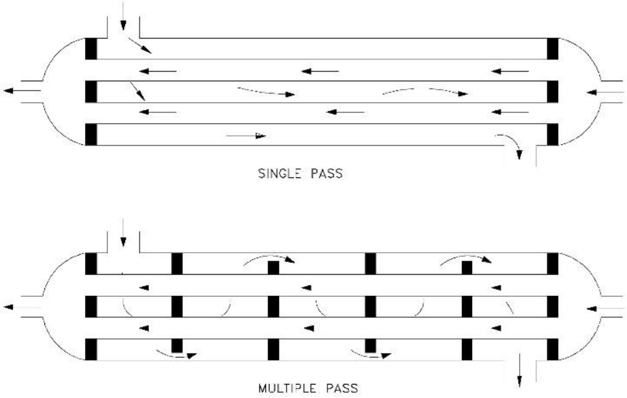


Figure 3. Operation of a heat exchanger

2) The walls of the tubes, plates, or fins serve as conduits for the transfer of heat from the hotter fluid to the cooler fluid.

3) The fluids leave the heat exchanger with different temperatures than the beginning of the process, with the cold fluid being hooter and the hot fluid being cooler.

4) The heat exchanger requires a conditioning process (Fig.4) because fluid deposits can build up on its walls over time. These deposits may need to be cleaned because they can decrease the heat exchanger's efficiency.

Figure 4. Conditioning process of a heat exchanger

Organic Rankine Cycle (ORC) systems

The ORC unit is a system (Fig.5) for the generation of thermal and electrical power based on a closed-loop thermodynamic cycle that is particularly suited for distributed generation. ORC systems can generate thermal and electric power with renewable energy, such as biomass, geothermal or solar energy), waste incinerators, waste heat from industrial processes, engines or gas turbines.

The Rankine Cycle is a thermodynamic cycle that serves for convert heat into work. Usually, water is used as the working fluid and the heat is supplied to a close loop. The Rankine Cycle based on water provides the 85% of the world electricity production.

Figure 5. ORC system

The fundamental idea behind the Organic Rankine Cycle (Fig.6) is that thermal energy is converted into mechanical energy by a turbogenerator, which then turns into electrical energy by way of an electrical generator. The ORC system does not use water to create steam; rather, it vaporizes an organic fluid with a molecular mass greater than that of water. This results in a slower rotation of the turbine, lower pressures, and no erosive wear on the turbine's metal components and blades.

A suitable organic working fluid is heated and vaporized in the evaporator (4>5) of the ORC turbogenerator using medium- to high-temperature thermal oil. The organic fluid vapor rotates the turbine (5>6), the turbine is coupled to the electric generator, where we obtain electric power. The exhaust vapor goes through the regenerator (6>7), where it heats the organic liquid (2>3) and then it flows through the condenser and the cooling circuit (7>8>1). The closed-cycle operation is then completed by pumping the organic working fluid (1>2) into the regenerator and evaporator [5].

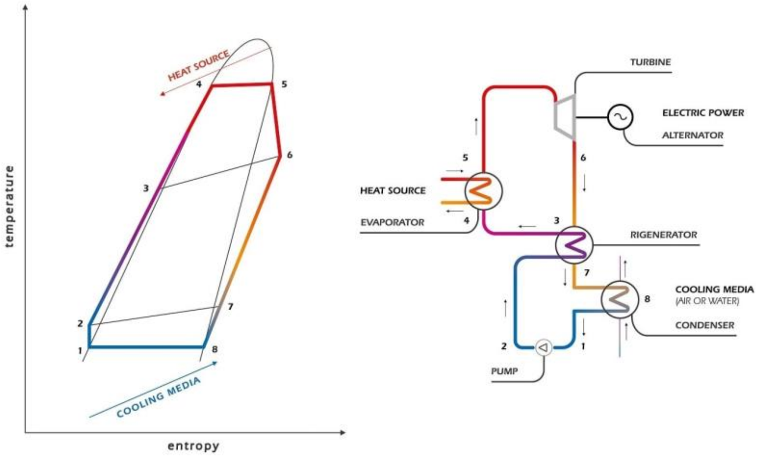


Figure 6. Operation of a Organic Rankine Cycle

Besides the Kalina cycle is a thermodynamic process used to convert thermal energy into mechanical power. High efficiency systems for energy generation, especially geothermal and waste heat recovery. It contains a combination of a Rankine cycle and an ammonia-water mixing cycle. In this system, a mixture of ammonia and water is used as the working fluid, which evaporates and condenses to drive the turbine.

Both the Kalina cycle and the Organic Rankine cycle (ORC) are thermodynamic cycles used to obtain energy from low temperature heat sources but they have many differences between them:

- Efficiency: Kalina cycles are known to be more efficient than ORCs because they can operate with variable ratios of ammonia to water concentration. ORCs have a limited range of efficiencies due to the robust working fluid.
- Working fluid: ORC uses an organic fluid such as a refrigerant or hydrocarbon. Kalina system uses a mixture of ammonia and water as the working fluid.

- Cost: Kalina cycles are more expensive to install and maintain than ORC because they require corrosion-resistant materials and special equipment.
- Maintenance: Kalina cycles require more maintenance than ORC because of the corrosive nature of the ammonia-water mixture used as the working fluid.
- Operating pressure: Kalina cycles operate at higher pressures than ORCs, allowing them to extract more energy from the same heat source.

Seeing all these differences we can obtain the following conclusions. Kalina cycles are more efficient but require more maintenance and cost more to install, while ORCs are less efficient but have lower maintenance and installation costs. The choice of system to use depends on the specific needs of the application and available resources.

They also have different applications. For ORC systems we have different applications such as:

-Waste heat recovery: ORC systems are particularly suitable for recovering waste heat from exhaust gases from industrial processes, gas turbines or geothermal sources. Electricity can be generated from low quality heat sources unsuitable for conventional steam turbines.

-Combined heat and power (CHP) systems: ORC systems can be combined with CHP systems to produce heat and electricity. Waste heat from an ORC system can be used for space heating or other industrial processes to increase efficiency.

The European Union (EU) has several regulations on combined heat and power (CHP) to improve energy efficiency and reduce greenhouse gas emissions. Some of the most important rules are:

- The European Union on the promotion of cogeneration establishes a framework for promoting high-efficiency cogeneration based on useful heat demand. This directive obliges member states to encourage and support cogeneration and remove obstacles to development. It also sets efficiency standards and environmental standards for cogeneration plants and requires member states to report on the implementation of these directives [6].

● The Energy Efficiency Directive (EED)which sets EU member states binding targets to increase energy efficiency by 20% by 2020 and include provisions for CHP. This directive obliges member states to promote the use of highly efficient cogeneration and to ensure that cogeneration is included in national energy efficiency targets. It also calls on member states to carry out energy audits of large enterprises and adopt energy efficiency measures [7].

● The EU Emissions Trading System (EU ETS), the largest carbon pricing mechanism in the world. The EU ETS applies to more than 11,000 power plants and industrial facilities in 31 countries and aims to reduce greenhouse gas emissions by putting a price on carbon. CHP plants that produce electricity and heat are eligible for permit trading and can receive credits if they reduce their permits below their allowances [8].

-Renewable energy: ORC systems can be used to generate electricity from renewable sources such as solar, biomass and geothermal. They can convert the low-temperature heat from these sources into useful electricity.

-Off-grid power generation: ORC systems can be used in remote locations where access to electricity is not available.

-Marine propulsion: ORC systems can be used to generate electricity for ship propulsion while reducing fuel consumption and emissions.

In conclusion, ORC systems offer a promising alternative to conventional steam cycles, especially in many applications where lower quality heat sources may be used.

For Kalina systems we have different application such as:

-Waste heat recovery: The Kalina cycle is an efficient way to recover waste heat in various industrial processes such as steel production, cement production and gas turbines.

-Power generation: The Kalina cycle can be used to generate electricity from a variety of heat sources, including solar, geothermal and waste heat from industrial processes.

-Combined heat and power (CHP) systems: Kalina cycles can be combined with cogeneration systems to generate electricity and provide heat for industrial processes or space heating.

-Solar power plants: The Kalina cycle can be used to generate electricity from concentrated solar power (CSP) system in a solar power plant.

-Marine propulsion: The Kalina cycle can be used as a marine engine power cycle because the waste heat generated by the engine can be used to generate additional electricity and improve fuel economy.

In conclussion, the Kalina system is a versatile and efficient way to recover waste heat for a variety of industries and generate electricity.

Absorption chillers

Absorption chillers (Fig.7) produce chilled water for air conditioning or refrigeration using waste heat. They work using a refrigeration cycle with heat.

Because the absorption chiller can be powered by low-grade thermal energy, alternative energy sources like solar energy, geothermal energy, waste heat from industrial processes, and waste steam can all be used to power the device. Additionally, this system uses environmentally friendly working fluids [9].

Since 1950 a few U.S. manufacturers since use water/lithium bromide ($H2O/LiBr$) as the working fluid for their absorption chiller systems. Also, water is used but it has a disadvantage, the limited temperature of refrigeration is above 0ºC. The coefficient of performance of these machines is a ratio between the driving heat input and the refrigeration capacity. The coefficient has a range between $0.7 < COP < 1.3$, depending on the temperature of driven heat and the cycle configurations.

Figure 7. Example of absorption chiller

We can distinguish 2 configurations of H2O/LiBr absorption chiller:

Single-effect: For a single-effect, absorption cycle using water/lithium bromide as working fluid may be the simplest system of absorption technology. One generator and one absorber combine to create the cooling effect in the single-effect absorption chiller.

The absorption process works (Fig.8) by using a liquid refrigerant, such as lithium bromide, which has a high affinity for water vapor. The refrigerant absorbs water vapor, which heats up and vaporizes the refrigerant. After that, the vapor is converted back into a liquid, discharging the heat that it had previously absorbed. By doing this, a temperature difference is produced that can be used to cool the air.

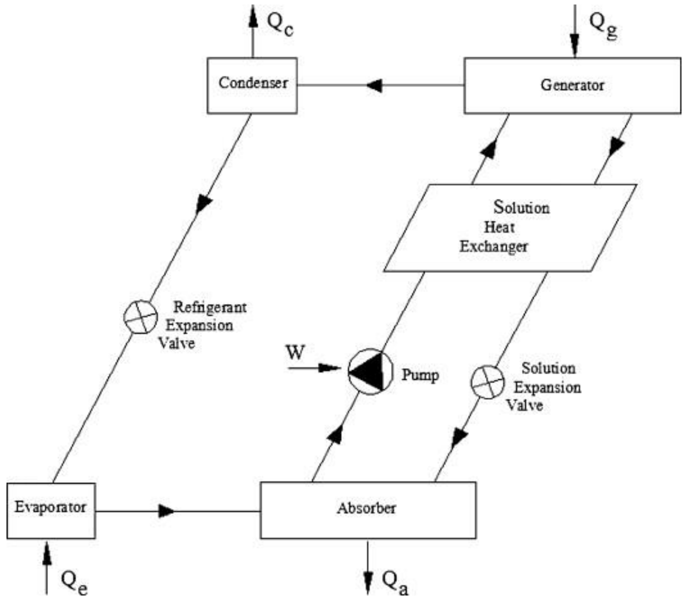


Figure 8. Operation of a single-effect absorption chiller

Double-effect: It uses two stages of absorption to create the chilled water, which makes it more effective than a single-effect chiller. This is why it is called a "double-effect" chiller. The operation is as follows (Fig.9):

1) Lithium bromide solution is heated with hot water or steam until it boils and releases water vapor.

2) A separate stream of water absorbs the water vapor, creating a more concentrated solution in lithium bromide.

3) The concentrated solution is heated again to get more water vapor, then is absorbed by another stream of water and we get an even more concentrated solution.

4) This concentrated solution is used to cool water in a heat exchanger, which produces chilled water for applications like air conditioning.

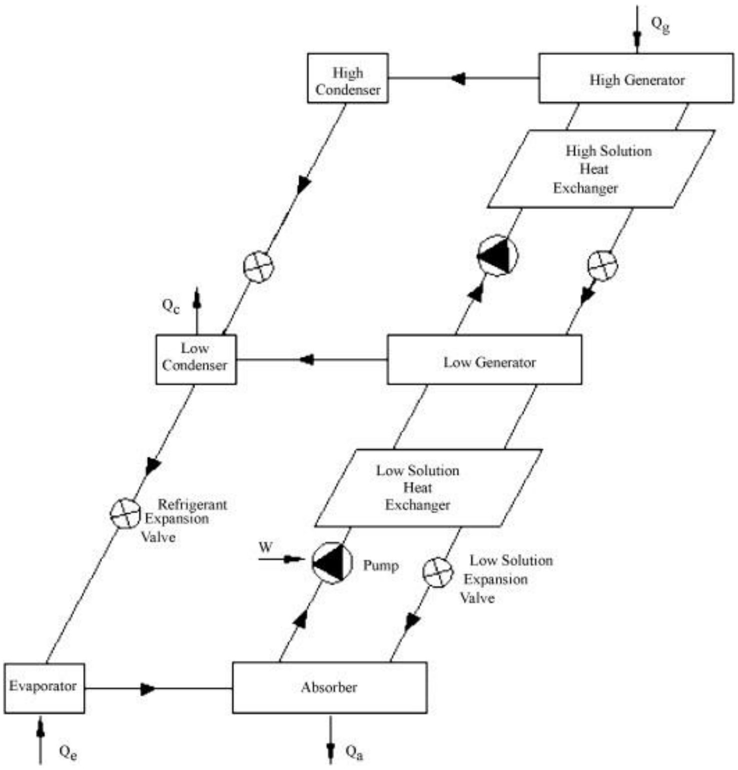


Figure 9. Operation of a double-effect absorption chiller

Thermal energy storage

Waste heat can be kept in thermal energy storage systems for later use. This is frequently achieved by utilizing materials with a high heat capacity, such as water. which can absorb and store heat during periods of excess heat generation and release it when needed.

When low grade thermal energy is the source energy form that should be stored, thermal energy storage has a round-trip efficiency of between 50 and 100 percent. For thermal electricity generation facilities like a nuclear reactor or a concentrating solar power plant (CSP), TES is the best storage technology. When storing high-grade electrical energy as the source energy, battery storage has a round-trip efficiency of between 80% and 100% [10].

Thermal energy storage simple purpose is to prevent the loss of thermal energy by storing excess heat until it is consumed. TES holds the key to breaking our reliance on burning fossil fuels. Our failure to harvest and store energy from clean renewable sources has resulted in the burning of fossil fuels. In the absence of thermal energy storage, thermal energy simply dissipates into the environment, necessitating the burning of fossil fuels.

There are many types of thermal energy storage systems, next, we will talk about some of them:

1) Sensible heat storage: By increasing the temperature of a substance, like water or rocks, sensible heat storage systems store thermal energy. By passing the heated substance through a heat exchanger, the heat that has been stored can be released when it is required.

2) Latent heat storage: By altering a material's phase, such as a phase-change material (PCM), latent heat storage systems store thermal energy. The material is melted or solidified, which releases or absorbs thermal energy, to release or absorb the heat that has been stored.

We have an example of how a thermal energy storage system works (Fig.10):

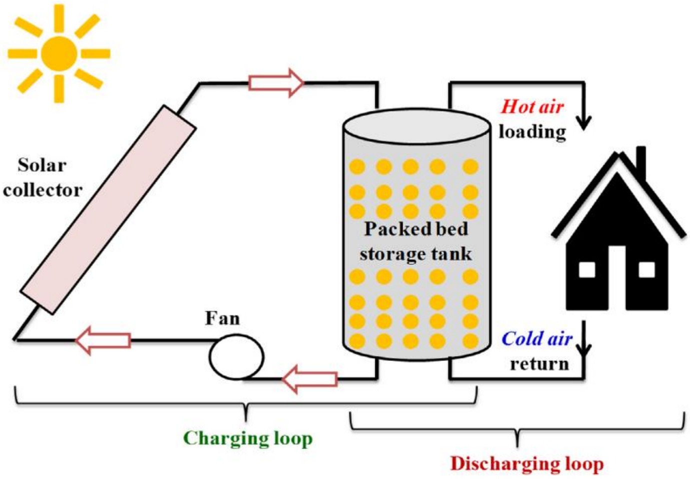


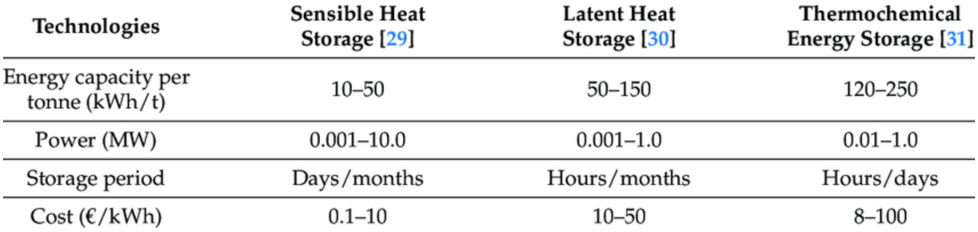
Figure 10. Operation of a thermal energy storage system

3) Thermochemical storage: Thermochemical storage systems use a chemical reaction to absorb or release heat in order to store thermal energy. The hydrates can be heated to release the water and recover the thermal energy when the heat that has been stored is needed.

4) Adiabatic compressed air energy storage: Systems for storing thermal energy using adiabatic compressed air compress air and store it in a container. The compressed air is expanded through a turbine, which generates electricity, when the energy reserves are needed.

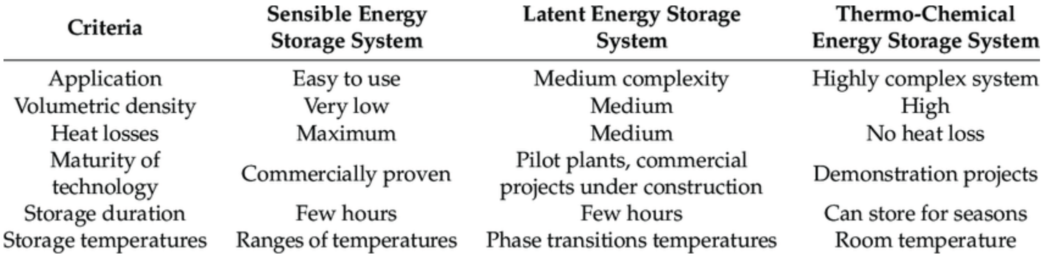
Here we have the characteristics (Tab.1) of each type and the conditions (Tab.2) of use:

Table 1. Characteristics of an absorption chiller



Technologies	Sensible Heat Storage [29]	Latent Heat Storage [30]	Thermochemical Energy Storage [31]
Energy capacity per tonne (kWh/t)	10–50	50–150	120–250
Power (MW)	0.001–10.0	0.001–1.0	0.01–1.0
Storage period	Days/months	Hours/months	Hours/days
Cost (€/kWh)	0.1–10	10–50	8–100

Table 2. Conditions of use of an absorption chiller



Criteria	Sensible Energy Storage System	Latent Energy Storage System	Thermo-Chemical Energy Storage System
Application	Easy to use	Medium complexity	Highly complex system
Volumetric density	Very low	Medium	High
Heat losses	Maximum	Medium	No heat loss
Maturity of technology	Commercially proven	Pilot plants, commercial projects under construction	Demonstration projects
Storage duration	Few hours	Few hours	Can store for seasons
Storage temperatures	Ranges of temperatures	Phase transitions temperatures	Room temperature

Applications of WHR techniques in different industries

To increase energy efficiency and lessen their impact on the environment, various industries are increasingly adopting waste heat recovery techniques. Industries are finding it more and more appealing to use waste heat as a way to lower energy costs and greenhouse gas emissions. It's crucial to consider the source and usefulness of the waste heat produced when evaluating waste heat recovery options for industrial processes in order to determine which waste heat recovery method is most appropriate.

Here are a few examples of how different industries are utilizing waste heat recovery techniques:

Power generation industry

Due to the significant energy loss during the creation of electricity, the power generation industry (Fig.11) plays a significant role in the production of waste heat. Power plants' overall efficiency can be increased by using waste heat recovery systems to capture this extra heat and produce more electricity.

Here are some examples of WHR systems used in power generation industries:

1) Steam turbines: WHR systems are used to recover heat from exhaust gases of the turbine, and then we can use them for preheat the feedwater for the boiler. This results in substantial energy savings because it lowers the amount of fuel needed to produce steam.

2) Gas turbines: As steam turbines, WHR systems are used to recover heat from exhaust gases of the turbine to generate steam.

3) Combined heat and power (CHP) systems: Also known as cogeneration systems can generate electricity and fuel form a single source. We can use WHR systems to recover heat from exhaust gases of the power generation, which can be used for domestic hot water, space heating or industrial processes.

4) Geothermal power plants: This power plants generate electricity by utilizing the heat energy from the Earth´s core. WHR systems can be used for recover the heat from the geothermal fluids that are employed to produce steam. This heat has many useful uses in industry.

Figure 11. Power generation industry

Cement industry

Due to the significant amount of heat lost during cement production, the cement industry (Fig.14) is another significant source of waste heat generation. This heat can be recovered using waste heat recovery systems, which will also produce more electricity that can be used in the manufacturing process or returned to the grid.

With 7% of all carbon dioxide emissions coming from the cement industry, it is one of the major global contributors. As a result, using waste heat recovery techniques can significantly lower greenhouse gas emissions and boost energy efficiency in this sector.

Here are some examples of Waste Heat Recovery systems are being applied in the cement industry:

1) Preheater and cooler waste heat recovery: Preheater and cooler WHR systems are used for recover heat from the gases that are leaving the preheater and cooler sections of the cement kiln.

   In a mixing chamber, hot air released from the cooler and exhaust gases from the preheater combine before entering the HRSG. Due to heat transfer between the water and the hot gases in the HRSG, in different parts of HRSG including the evaporator, super heater and economizer, water converts into steam. This steam is directed to a steam turbine to produce power (Fig.12).

   Here is the schematic diagram of the cycle (Fig.14):

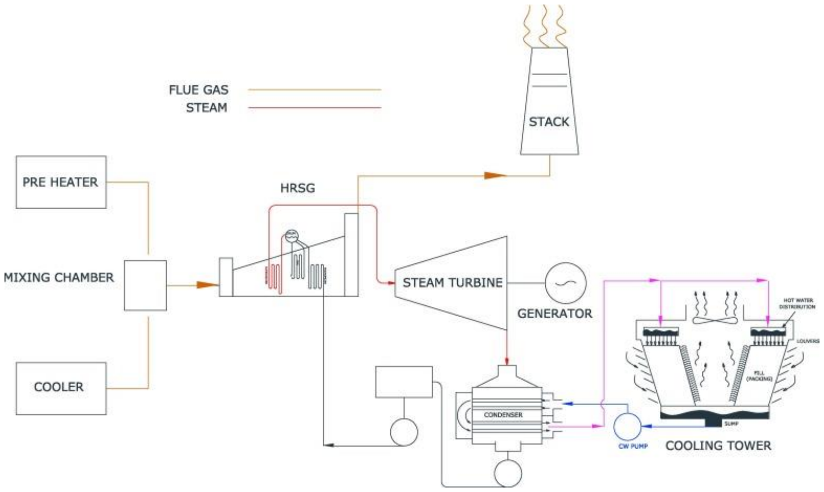


Figure 12. Operation of a preheater and cooler WHR system

WHR boilers: Waste heat recovery (WHR) boilers (Fig.13) are employed to recover heat from the exhaust gases produced during the manufacture of cement. Steam, which has a variety of uses, including the production of power and heating, can be produced using this recuperated heat. This method can lessen the cement plant's energy usage and negative environmental effects.

Figure 13. Waste heat recovery boilers

2) Organic Rankine cycle: The preheater, cooler, and kiln exhaust gases in the cement industry can all be used in ORC systems to recover heat. The electricity produced from the recovered heat can be used for a variety of purposes, including powering the cement plant or being returned to the grid.

Figure 14. Cement industry

Steel industry

One of the industries with the highest energy consumption is the steel industry (Fig.16), which uses 5% of the global total and spends 30% of its total production costs on energy. As a significant amount of heat is lost during the production of steel, the steel industry is another significant source of waste heat generation. In order to recover this heat and produce additional electricity that can be used in the production process or sold back to the grid, waste heat recovery systems can be used.

A common method of waste heat recovery in the iron and steel industry is from clean streams of gases from production processes. For instance, Jouhara et al. in an experiment demonstrated that for a heat source of 450 °C, the use of a Flat Heat Pipe (FHP) in the wire cooling line of a steel production facility can offer a recovery of heat up to 15.6 (kW) [1].

Here are more examples of WHR techniques that have been implemented in the steel industry:

1) Top Gas Recovery Turbine (TRT): Is a WHR system that uses hot gases produced during the steelmaking process to recover energy.
 Since almost every modern iron and steel plant has a blast furnace, TRT has been widely accepted because of its high efficiency, speed, excellent safety, and good maintainability. TRTs come in two varieties: wet and dry [12].
 This is how it looks like (Fig.15):

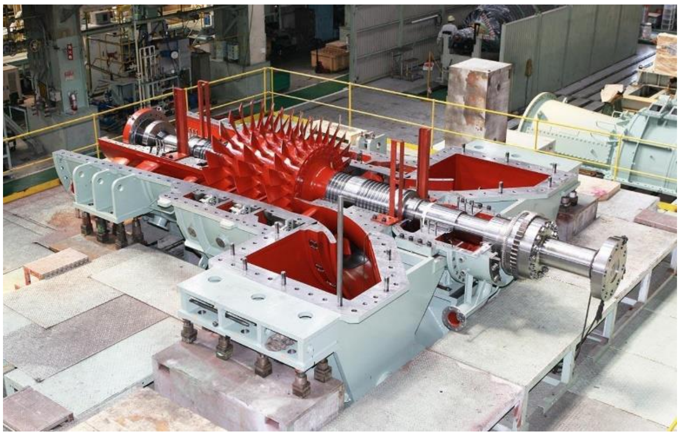


Figure 15. Top Gas Recovery Turbine

2) Steam generation: The waste heat from the steelmaking process is used to create steam, which is then sold to other industries or used in other plant processes.

Results show how the size of the steam generator and the turbine can be reduced of about 41% with respect to traditional solutions, while increasing electric power production by 22% [13].
Combining PCM-based heat extraction with steam generation enables the evolution of current waste heat to power systems for the steel industry towards the production of high temperature superheated steam with minimal variability.

3) Heat exchangers: Heat exchangers are a critical component of waste heat recovery systems in the steel industry. Their application can help reduce energy consumption, lower operating costs, and improve overall energy efficiency.
   We can distinguish between many types of heat exchangers used in steel industry: Recuperative Heat Exchanger, Plate Heat Exchanger, Shell and Tube Heat Exchanger or Air-to-Air Heat Exchanger.

   The iron and steel industry frequently uses clean streams of production-process gas for waste heat recovery. For instance, Jouhara et al. in an experiment demonstrated that for a heat source of 450 °C, the use of a Flat Heat Pipe (FHP) in the wire cooling line of a steel production facility can offer a recovery of heat up to 15.6 (kW) [1].

4) Waste Heat Boilers: The exhaust gases produced during the steelmaking process are used to recover heat in waste heat boilers. Steam, a byproduct of the recovered heat, is then produced and used for various plant operations.

Figure 16. Steel industry

Chemical industry

Due to the substantial heat loss experienced during various chemical reactions, the chemical industry is another important source of waste heat generation. Systems for recovering waste heat can be used to capture this heat and supply energy for additional industrial processes.

Here are more examples of WHR techniques that have been implemented in the chemical industry:

1) Heat exchangers: Heat can be recovered from high-temperature process streams and moved to lower-temperature streams using heat exchangers. As a result, the energy needed for heating or cooling processes may be significantly reduced, increasing energy efficiency.
   We can distinguish between many types of heat exchangers used in chemical industry: Shell and Tube Heat Exchangers, Plate Heat Exchangers, Finned Tube Heat Exchangers, Regenerative Heat Exchangers or Spiral Heat Exchangers (Fig.17).

Figure 17. Spiral Heat Exchanger

2) Heat pumps: Heat pumps are used to recover low-grade waste heat and transform it into higher-grade heat for use in other processes. This is especially helpful for chemical reactions that need high-temperature heat.

   The most applicable industries for heat pump technology are those that require a lot of heat in the temperature range between 200°C. According to this study, the industries with the highest heat demand above 200°C are the paper industry (842 PJ), other industries (634 PJ), the food industry (450 PJ), and the chemical sector (436 PJ) [14].

3) Adsorption chillers: Adsorption chillers are cooling systems that absorb a refrigerant, like water or ammonia, on a solid material and release it later to produce cooling. Adsorption chillers use the natural process of adsorption and desorption to produce cooling, in contrast to traditional vapor compression systems that use a compressor to circulate refrigerant. Adsorption chillers can be used for generate cooling and recover waste heat. This will be very useful in chemical processes that require cooling.

Here are some examples of some adsorption chillers that are used in chemical industries: Silica gel/ water adsorption chillers (Fig.18), activated carbon/ammonia adsorption chillers, zeolite/water adsorption chillers or metal-organic framework (MOF) adsorption chillers.

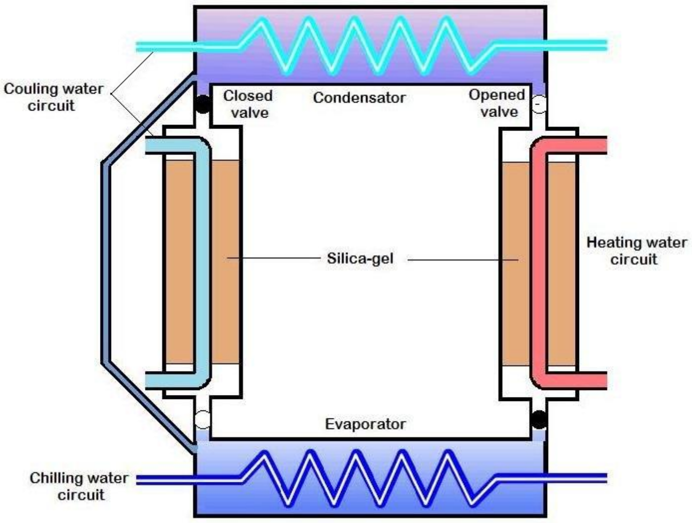


Figure 18. Silica gel/ water adsorption chiller diagram

4) Organic Rankine cycle (ORC) systems: ORC systems can recover waste heat from low-temperatures streams and turns into electricity. This is especially helpful in chemical processes that produce waste heat at low-temperatures.

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Building heating and cooling industry

Buildings can use waste heat recovery systems to provide heating and cooling, lowering the energy consumption needed for heating, ventilation, and air conditioning systems (HVAC). Hot water can be produced by these systems and used for a variety of purposes.

Here are some examples of waste heat recovery methods used in the building heating and cooling industries:

1) Heat recovery ventilation (HRV): With the help of HRV systems, which use heat recovered from exhaust air to warm incoming fresh air, less energy is needed for heating and cooling.

   In order to increase building efficiency, insulation and weatherstripping are used in conjunction with airtightness-increasing construction techniques. Building ventilation suffers as a result because natural ventilation is no longer adequate. With improved insulation standards, ventilation load has grown in importance. Currently, ventilation uses 30% or more of the energy required for HVAC. Heat recovery ventilators (HRVs) can recover up to 70% of this energy. Many types of HRVs have been used, including compact air-to-air type, rotary wheel, heat pipe, runaround loop, thermosyphon, and twin tower enthalpy recovery loop [15].

2) Heat pumps: Refrigerants are used by heat pumps to transfer heat from the air, the ground, or water sources to heat structures or supply hot water. Heat pumps can use waste heat from various building systems, including data centers and refrigeration systems, as a source of heat.

3) Absorption chillers: Absorption chillers employ heat to produce cold water that can be applied for cooling purposes. Absorption chillers can use waste heat from various building systems as a heat source. Due to their energy efficiency and positive environmental effects, they are becoming more and more common in the building heating and cooling industries.

   In large commercial and industrial structures like offices, universities, and hospitals, absorption chillers are frequently used. They can offer cooling for entire buildings or just certain rooms inside of them.

4) Combined heat and power (CHP) systems: The waste heat from the production of electricity is used by CHP systems to heat buildings or provide hot water. The systems function by producing electricity on-site and heating and cooling the building with the waste heat produced during electricity process.

Here are some examples of combined heat and power systems that are used for building heating and cooling: Microturbines, fuel cells, reciprocating engines or gas turbines.
This is how it works (Fig.19):

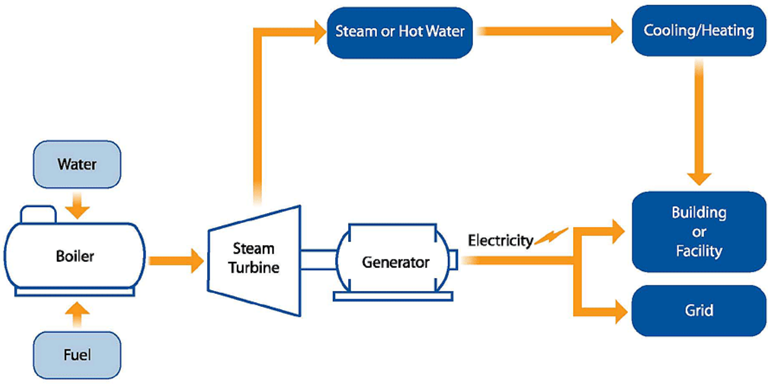

Figure 19. Operation of a CHP system

In consequence, using waste heat recovery techniques can help businesses become more efficient, use less energy, and produce fewer greenhouse gases. The type of industry, the waste heat source, the temperature and quantity of the waste heat, and other variables all affect the choice of waste heat recovery system.

Waste heat recovery systems have a positive overall effect on energy efficiency and environmental sustainability in industrial settings. Cost savings, improved productivity, and a reduction in carbon emissions are all advantages for businesses that use these systems. However, the implementation of waste heat recovery systems necessitates careful consideration of a number of factors, including the system's technical requirements, cost-effectiveness, and viability.

Economic benefits of implementing innovative WHR techniques

We will now focus on the economic benefits of implementing waste heat recovery techniques that are becoming more and more popular due to their ability to provide economic benefits. Businesses can cut their energy costs, lower their carbon footprint, and increase overall efficiency by putting new WHR practices into practice.

A fundamental advantage is the reduction of energy costs. Recovering waste heat we can reuse this energy instead of having to get more energy from an external source. Over time, this may lead to significant cost savings that can be put back into the company in other areas.

The use of waste heat recovery techniques can improve a company's marketability. Companies can offer customers more competitive pricing by lowering their energy costs.

Also, the general effectiveness of a business can also be increased by WHR techniques. Reusing waste heat can optimize operations and cut down on overall energy. This may result in improving productivity, less downtime and increase profitability.

Environmental benefits of implementing innovative WHR techniques

Energy is a major part of how humans live their daily lives. Unfortunately, a large portion of the energy we use is created by burning fossil fuels, which causes the atmosphere to be filled with dangerous greenhouse gases and accelerates climate change.

We can lessen our reliance on fossil fuels and lessen our environmental impact with the implementation of waste heat recovery techniques. We can reduce our energy usage and carbon footprint using these techniques. Besides WHR can also aid in the improvement of air quality by reducing emissions of pollutants like particulate matter or nitrogen oxides.

We can achieve a more sustainable future by utilizing WHR techniques because they have a significant positive impact on the environment. By utilizing this technology, we can lessen our negative effects on the environment while also increasing our bottom line.

Installing waste heat recovery technology is one way to cut back on energy use and emissions' negative effects on the environment. This change in attitude can be partially attributed to a greater understanding of the significance of the sustainability and stability of the environment as well as the effects that human activity is having on the planet [16].

According to a study by Karellas, for a typical cement plant, waste heat recovery can provide about 6 MW of electric power, making it practical for the cement industry. The heat sources for the heat recovery systems are the exhaust gases from the preheater and clinker cooler [17]

In conclusion, implementing waste heat recovery techniques we can reduce greenhouse gas emissions, reduce air pollution, increase energy conservation and improve resource efficiency.

Case studies of industries

We will analyze real cases of industries that have applied these innovative techniques and the results they have obtained thanks to them.

Case 1

According to a study by Xu, Huang & Yang, nearly half of the coal that is available in China is used by coal-fired power plants, and the resulting CO2 emissions account for more than 40% of all national emissions. As a result, energy efficiency in coal-fired power plants is crucial to China's efforts to reduce greenhouse gas emissions and ensure energy security [18].

We optimized the design of the heat recovery system using boiler exhaust gas and performed a techno-economic analysis. However, only a few studies have focused on utility boiler flue gas heat recovery, as most studies have focused on the implementation of existing designs. Thermodynamic, heat-transfer, and hydrodynamic principles are adhered to in this study. Four typical flue gas heat recovery schemes are quantitatively analysed from a thermodynamics point of view using information from an existing 1000 MW typical power generation unit in China.

The annual coal-saving revenue of various cases can be determined using the above analysis of net coal conservation rate, as shown in (Fig.20). The following fundamental economic presumptions are made: (1) The assumed coal price, 120 USD per ton standard coal, was the average cost to China's electric generators in 2012. (2) A 6.25 CNY/USD exchange rate is the default. (3) The unit's 5000 h of annual usage are designated.

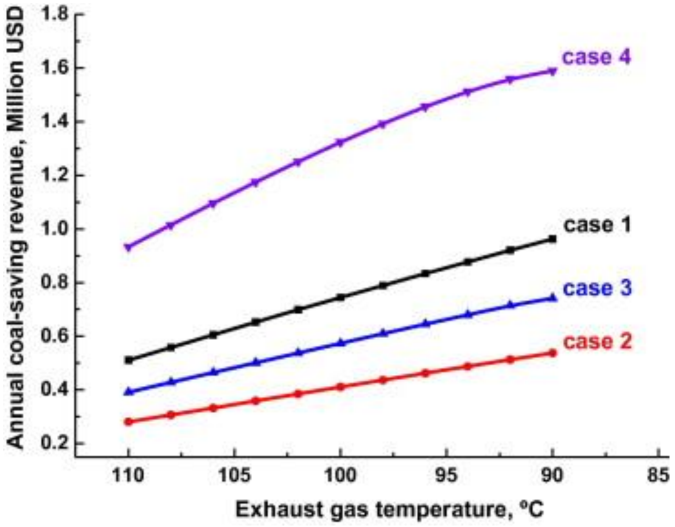

Figure 20. Variation curves of annual coal-saving revenue

With low exhaust gas temperatures (90 °C), the annual amount and revenue of coal saved in this case can reach nearly 13,000 tons and 1.56 million USD.

Different conclusions were obtained from this study:

- The degree of substitution of the extraction steam has a determining influence on the energy saving effect.

-The energy-saving benefit is affected by large heat exchange areas

- According to techno-economic analysis, the high-stage steam substitute scheme does not always perform at its best when the amount of recovered heat is increased. When the price of coal is relatively high, it is appropriate to use a design with more heat surfaces to recover more waste heat, which will also significantly increase the economic benefits of waste heat recovery.

Case 2

According to a study by Utlu & Önal demonstrate how the number of TPV applications is increasing and how this has a big impact on productivity and energy conversion. TPV systems are used in automotive, industrial or residential business. It is evident that it has entered the market and introduced a substitute to produce electricity. This study will be focus in iron and steel industry in Turkey [19].

First of all, we will describe what TPV systems are, is a technology that is used as a waste heat recovery system, capturing and converting heat that is generated from various processes and then we use it to generate electricity. To turn waste heat into electricity, TPV systems combine thermophotovoltaic cells and a heat exchanger. The thermophotovoltaic cells use the waste heat that the heat exchanger collects and transfers it to them to produce usable electricity. In this study we will focus on photovoltaic cells with a band gap ratio between 0.38-0.7 eV, this is called InGaAsSb-cell TPV systems, we adjust this value depending on the ratio of the elements.

The photovoltaic system works with the next circuit (Fig.21):

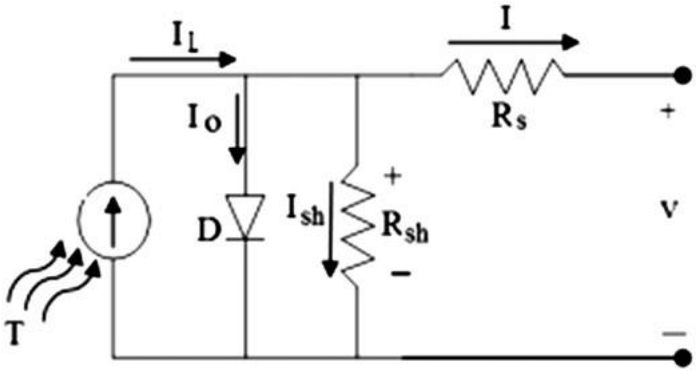

Figure 21. Equivalent circuit of the photovoltaic system

It has been found that TPV applications in Turkey's iron and steel industry can result in energy efficiency. It has been determined that the annual TPV systems in the iron and steel industry have a recoverable energy potential of 11.44 TJ, and 7.31 percent for InGaAsSb-cell TPV systems. It is preferable to apply waste heat, TPV applications from industrial areas because the amount of waste heat obtained from the iron and steel industry is higher and the steel products are more frequently recycled in machinery.

In conclusion, reducing the amount of fuel burned while simultaneously producing electricity for the iron and steel industry, this application can also reduce environmental pollution. Another benefit is that while TPV systems can produce electricity for 24 hours in continuous processes like making iron and steel. The first of these is that cells have a higher power density by producing electricity more effectively due to the different band spacing in TPV systems, which is one of the two most significant advantages over today's widely used PV systems.

Case 3

According to other study made by Engin & Ari about the analysis of a dry type rotary kiln system operating in a Turkish cement plant. The capacity of the kiln is 600 ton-clinker each day. About 40% of the total input energy was lost because of hot flu gas (19.15%), kiln shell (15.11%) and cooler stack (5.61%). This study shows that 15.6% of the lost energy could be recovered [20].

The clinker cooler discharge and the kiln exhaust gas are the most readily available and, consequently, the most economically advantageous waste heat losses. The air discharged from the cooler stack has a temperature of 215 °C, while the exhaust gas from the kilns has an average temperature of 315 °C. In order to transfer the available energy to water, both streams would be directed through a waste heat recovery steam generator (WHRSG). Steam could be produced thanks to the available waste energy. The steam would be used to power a steam turbine driven electrical generator. The amount of electricity purchased would be partially offset by the electricity generated, thereby lowering the need for electricity.

The operation of WHRSG works like this (Fig.22):

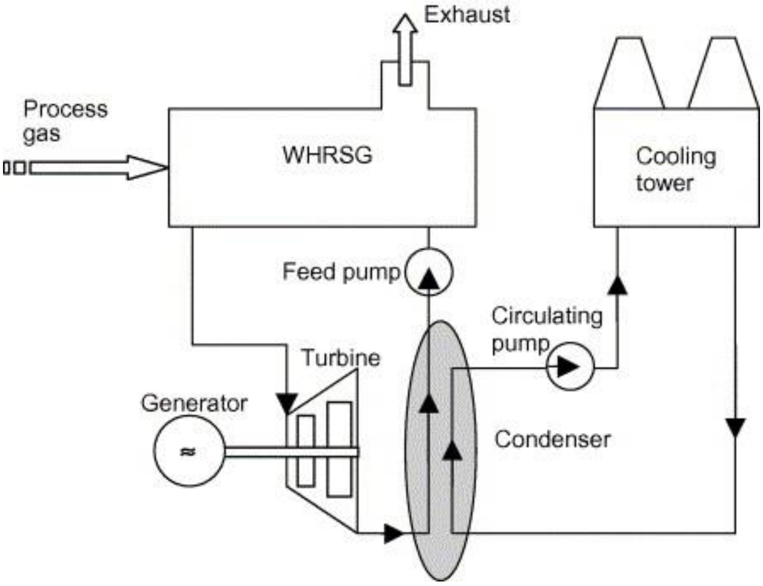

Figure 22. Process schema of a typical WHRSG application

To calculate the size of the generator we should apply this equation:

$$Q_{WHRSG} = Qavailable\eta$$

Equation 2

Where η is the WHRSG efficiency.

Then we should calculate the energy saved:

$$Energy\ saved = (Power\ generated)x(hours\ of\ usage)$$

Equation 3

$$Energy\ saved = (1000kW)x(8000h/yr) = 8x10^6kWh/yr$$

We assume that the price of electricity is 0.07 USD/kW h, so the cost saving will be:

$$Cost\ savings = 0.07x8x10^6 = 560{,}000USD/yr$$

Finally, the overall system efficiency would increase because of the energy savings provided by a WHSRG system. It should be noted that these calculations represent a rough estimate and may change depending on economic factors and plant conditions.

Practical solution

Now we will try to find a company where we can apply these techniques. I came up with a company located in Valladolid,Spain, my place of birth. The company is called Lingotes Especiales, S.A., is an industrial company dedicated to design, development, casting, machining and assembly of grey and spheroidal iron parts for components used in the automotive, electrical appliances and civil works sectors, mainly.

The business operates in modern facilities with cutting-edge production techniques. It has advanced facilities and technology for the manufacture of premium bars and custom specifications. As needed by its customers, it also offers value-added services like cutting, machining, and heat treating ingots.

Studies demonstrate that heat recovery system optimization results in significant energy savings. We consider it a metallurgical industry, and we will try to find the Waste Heat Recovery system that best suits and produces the most benefits for this company.

In this company they have smelting furnaces (Fig.23), which are in charge of melting the iron, which it melts at 1538ºC. This process generates gases with very high temperatures that are not used later. We could use heat exchangers to take advantage of this heat from the gases. An air/water exchanger would be used in order to heat the water that is in the exchanger and get hot water, which could be used for the water in the changing rooms of the factory.

Figure 23. Smelting furnaces

Implementing this heat exchanger could bring a lot of benefits such as:

- Energy efficiency: The system lessens the need for extra energy sources like electric heaters or boilers by using waste heat or ambient air to heat water or cool air to extract heat from water. Lower energy use and operating expenses are the results of this.
- Cost savings: Through the use of heat exchangers, energy efficiency can be achieved while saving the user money. Businesses can significantly lower their energy costs by using less traditional heating and cooling techniques.
- Environmental impact: Utilizing heat exchanger air/water systems can help protect the environment. Reduced reliance on conventional energy sources and a smaller carbon footprint are the results of using waste heat or ambient air. This is in line with initiatives to lessen the effects of climate change on the environment.

It's crucial to remember that the precise advantages and results of installing a heat exchanger air-to-water system can change depending on the application, system design, and operating circumstances.

Recommendations for industries

Waste heat recovery (WHR) technology can be used in many industries to improve energy efficiency and reduce greenhouse gas emissions. However, it is important to choose the best WHR method for your specific process to achieve the desired results. Here are some recommendations based on recent research for industries considering implementing innovative WHR methods.

We should consider different factor when choosing the waste heat recovery method that is best for a particular process. Some factors are the flow rate of the heat stream and the temperature, the size and cost of the equipment, the availability of suitable heat sinks, the compatibility of the waste heat recovery system with the existing process, the sustainability of the waste resource and the industrial waste heat sources.

These factors have been considered:

● Temperature and flow rate: Waste heat flow temperature and flow rate are important factors in determining the most appropriate WHR technology. For example, the hot waste heat stream can be used to generate electricity using a steam turbine or an Organic Rankine (ORC) system. On the other hand, low temperature waste heat streams can be used for heating and cooling using heat pumps or absorption chillers.

● Size and cost of the equipment: The amount and cost of equipment required for WHR also play a role in choosing the most appropriate technology. When we are using large-scale power generation steam turbines requires significant investment in infrastructure and equipment. When we are using small-scale waste heat recovery systems such as heat absorption chillers or heat pumps may be more suitable due to their smaller footprint and lower cost.

● Availability of suitable heat sinks: Having the right heat sink is another important factor. A heat sink is required to absorb the recovered waste heat, and heat sink selection depends on factors such as temperature, flow rate, and process compatibility. Some examples of suitable heat sinks are water, air and other process streams.

● Compatibility with existing processes: Compatibility of the WHR system with existing processes is an important issue. WHR systems must integrate seamlessly with existing processes and must be designed so as not to disrupt process operations or product quality. WHR systems must also be reliable and require minimal maintenance.

● Sustainability of the waste resource: Waste heat could be reused internally or externally. For internal usage waste heat will increase the energy efficiency of industrial processes. On the other hand, for external usage waste heat recovery can provide an energy incentive for other industrial processes and utilities that can meet energy demand with lower quality energy.

● Industrial waste heat sources: Therefore, as we can see in the image (Fig.24) direct heat recovery technologies for waste heat recovery include heat pumps, heat exchangers, heat pipes, boilers and refrigeration cycles, while power cycles such as Organic Rankine Cycle, Kalina Cycle, are representative of indirect technologies that converts waste heat into vother forms of energy such as mechanical or electrical energy.

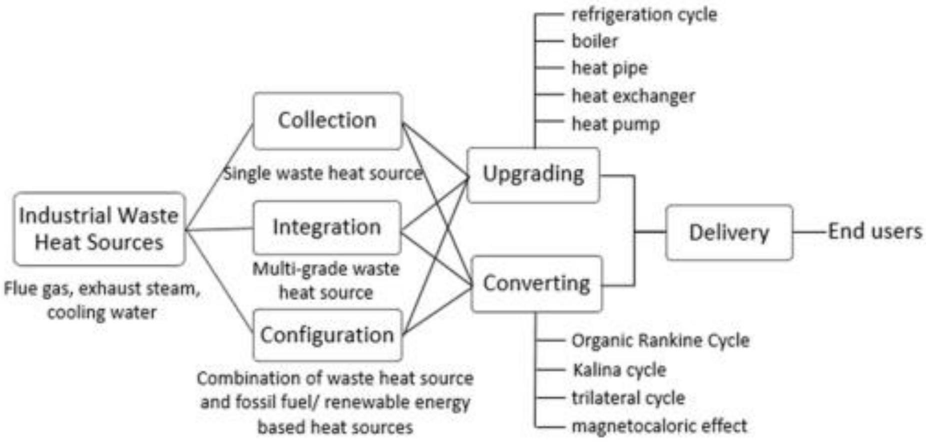

Figure 24. Industrial waste heat sources

These are the most important factors that industries should consider, but industries also must take into account the process that must be carried out to implement these techniques. We will list the main steps to implement these techniques:

1) Conduct a waste heat audit: A waste heat audit is a comprehensive assessment of a facility's energy consumption and waste heat resources.

During an audit, it is possible to identify areas where waste heat is generated and can be recovered and where energy efficiency can be improved.

2) Choose the right waste heat recovery technology: There are several waste heat recovery technologies like heat exchangers, steam turbines, Organic Rankine Cycle systems…The choice of technology depends on the temperature and volume of the waste heat source and the energy needs of the facility.

3) Optimize processes to reduce waste heat generation: In addition to waste heat recovery, industries can optimize processes to reduce energy consumption and waste heat production. This could include optimizing equipment operation or reducing process temperatures.

4) Evaluate the economic feasibility: The implementation of waste heat recovery methods requires an initial investment and the industry must evaluate the economic feasibility of the project. This could be analyzing the potential energy savings, the payback period or the cost of the waste heat recovery technology.

5) Train staff on waste heat recovery techniques: Personnel must be trained in the operation and maintenance of waste heat recovery equipment to ensure optimal performance.

6) Consider government incentives and regulations: Governments provide incentives and regulations to encourage industry to adopt waste heat recovery technologies. Industry needs to study these incentives and regulations and determine how they can benefit from them.

In conclusion, when considering the implementation of innovative WHR methods, industry should carefully consider the factors discussed above to select the most appropriate method. By choosing the right WHR technology, industry can improve profits while reducing energy consumption and greenhouse gas emissions.

Conclusions

Innovative methods for recovering waste heat can significantly increase the energy effectiveness of technological processes. These methods involve utilizing heat that would otherwise be lost from waste heat produced during industrial processes.

Industries can lower their energy use, lower their carbon footprint, and lower their energy costs by implementing waste heat recovery techniques. Furthermore, by lowering thermal stress and component wear, waste heat recovery can lengthen the useful life and reliability of industrial equipment.

Innovative waste heat recovery technologies include technologies such as heat exchangers, Organic Rankine Cycle (ORC) systems, absorption chillers, thermal energy storage. These systems are adaptable and efficient because they can be tailored to meet the unique requirements and restrictions of each industrial process.

Additionally, waste heat recovery has the potential to support the growth of a circular economy, in which waste is utilized as a resource and priceless materials are recycled and reused. By recovering waste heat, industries can use fewer fossil fuels in the future and help to build a more sustainable world.

Overall, waste heat recovery methods have a positive impact on improving energy efficiency of technological processes and have the potential to create a more sustainable and circular economy.

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