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low-grade waste heat Grade recovery from power generation plants and process sites

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1 Abstract

Many studies have been conducted in recovering the low-grade waste heat as it can decrease the emission rate and also increase the efficiency of the system. A review of some technologies with their advantages and disadvantages is represented in this study. Organic Rankine cycle shows advantages over traditional steam cycle due to lower temperature source utilization comparing with water. Kalina cycle is a good example of the ORC. Absorption refrigeration is another technology that is used for many years like the VCRC which is applied in many application although it is more costly than ORC. A heat pump is a method when requiring a lower amount of water for cooling and more heat recovery. Heat transfer is a technology that limited to Nuclear technology although it has a lower capital cost. The CO_2 utilization cycle is promising because it is available, with lower toxicity, non-flammable fluids but it has lower efficiency. Boiler Feed Water Pre-Heating is the traditional methods that have been used for many years but it requires a large footprint and not high efficiency.

2 Introduction

In response to increasing emissions and waste, governmental bodies have been forced to impose strict laws and regulations on power plants and process sites to tackle the catastrophic effects of global warming and climate change. This action, coupled with the increase in energy costs, requires these industries to react accordingly through energy-efficient designs. This report will focus on one of these designs: recovering low-grade waste heat from power plants and process sites. Low-grade waste heat is primarily generated from manufacturing plants and is often discarded hen the term 'waste'. The term 'low-grade' refers to low-temperature differences to ambient temperature. This thermal energy can be generated through various chemical, mechanical and electrical processes, all of which can be recovered for electrical power generation and process heating. Several technologies have been explored in this report which ranges from Organic Rankine Cycle to Absorption Refrigeration processes and from heat pumps to transformers. These techniques will attract such industries to re-use and utilize low-grade waste heat in an effective way to increase energy efficiency and reduce waste emissions.

3 Technologies, Techniques and Methodologies

3.1 Organic Rankine Cycle

Organic Rankine cycle (ORC) is a technology that is primarily used for the conversion of low-grade waste heat into power. According to Landelle et al. (2017), ORC has been utilized since as early as the 19th century to convert energy from sources such as solar, geothermal, biomass and waste heat produced in industrial processes. This technology has undergone significant improvement over the years and is now capable of producing 10 kWe to 10 MWe from heat sources ranging between 80°C to 300°C.

The working principles of ORC are closely related to the conventional steam Rankine cycle by having four main components which are pump, evaporator, turbine and condenser. The working fluid is firstly pressurized by the pump and then heated within the evaporator to produce saturated vapour. Shaft work is generated by the turbine and the vapour outlet is then condensed within a condenser before being fed back into the system for a new cycle (Dong et al., 2017). However, the major difference between these two technologies is that the steam Rankine cycle uses steam as the working fluid meanwhile ORC uses organic working fluid.

According to Tchanche et al. (2011), organic compounds such as hydrocarbons, hydrofluorocarbons and alcohols are among the suitable working fluid for ORC. This technology has several advantages when compared with the conventional steam Rankine cycle as it requires less energy during the heating process, operates at lower temperature and pressure during the evaporation process, produces condensate that is within the vapour region which reduces the risk of blade erosion as well as smaller temperature change between evaporation and condensation which allows the use of single-stage turbines.

Numerous studies have been conducted on the types of working fluid with respect to the performance of ORC. However, other factors may also be taken into consideration when selecting an appropriate working fluid such as cost, impact on the environment, thermal stability, toxicity as well as flammability. A study was carried out by Chen et al. (2010), using 35 different organic compounds such as R-21, R-22, R-23, R-32 etc. and analysed the cycle performance based on the thermodynamic properties of each compound. The result showed that compounds with higher density and latent heat produce higher shaft work during the expansion process. Also, dry and isentropic substances are the preferred choice as a working fluid for ORC. A similar type of research was conducted by Satanphol et al. (2017) by comparing ORC efficiency using pure organic fluid and zeotropic working fluid, which is a mixture of working fluid. They found that the cycle efficiency ranges between 8.78% to 10.30% when using pure organic fluid meanwhile zeotropic working fluids is between 8.90% to 9.59%.

Additionally, research was performed by Dong et al. (2017) on the performance of ORC using a radial turbine. According to the authors, most studies relied on the assumption that turbine efficiency remains constant, whereby in actuality, it is heavily influenced by the interaction with the working fluid and operating condition. Using pentane, R123, R245fa and R365mfc as the working fluid. the result showed that maximum turbine efficiency of 89.98% was achieved at 110°C using pentane, followed by 89.91% at 120°C using R245fa, 89.79% at 130°C using R123 and lastly R365mfc which produced the lowest turbine efficiency at temperatures ranging between 120°C to 135°C.

Another aspect of ORC was investigated by Tchanche et al. (2011) on the implementation of the technology in relation to the nature of the energy source. Based on the findings, solar-driven reverse osmosis (Solar ORCRO) is only available at the research stage. Conversely, solar pond and modular solar power plants have been proven to be a viable energy source, however, it is not currently widely implemented. Binary geothermal combined heat and power (CHP) and biomass represent the most commonly used energy source whereas low-grade waste heat recycling (WHR) is growing rapidly as it demonstrates a huge potential within the energy and power industry

3.2 Kalina Cycle

The evolved version of the Organic Rankine Cycle is the Kalina Cycle which utilises the ammonia-water mixture as its working fluid and is the more advanced version of the thermodynamic power cycle.

Recovery of low-grade waste heat is carried out through various units integrated into a process system. A simplified Kalina cycle system is shown in *Figure 1* (Zhang, et al., 2012) This system works by the heat source causing the ammonia-water working fluid to change phase into a vapour that is fed into the turbine. The vapour is expanded at the turbine generating power. The vapour from the turbine is diluted with a weak ammonia-water fluid and lastly condensed in an absorber by cooling water producing a saturated ammonia-water liquid. This liquid is separated into a weak ammonia-water and rich ammonia-water fluid. The desired concentration of ammonia in the rich and weak fluid is 70% and 30% respectively. The resulting rich liquid is sent back to the heat source restarting the whole cycle (Zhang, et al., 2012)

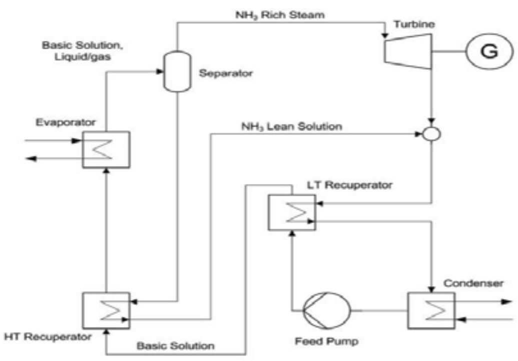
Varma and Srinivas (2017) state that the working fluid is a zeotropic mixture and so the main benefit is due to its varying boiling and condensing temperatures. Ogriseck (2009) further discusses the advantages of the ammonia-water working fluid signifying that due to ammonia's low boiling point, recovery of low-grade heat is more efficient when compared with steam. In addition to this, ammonia is cheap, safe for industrial processes and readily available. However, disadvantages from Law, et al. (2012) suggest that the complexity of this cycle will lead to greater maintenance cost and a higher capital cost when compared to the Organic Rankine cycle.

Through technology progression, different Kalina Cycle systems (KCS) have emerged and therefore offer more than the original KCS 1 design. Zhang, et al. (2012) and Hettiarachchi, et al. (2007) identified different Kalina cycle systems and their application. The authors state examples such as KCS 4 developed for cogeneration application, KCS 2 for low temperature geothermal and KCS 8 as a bottoming cycle. Similarities between the systems are that they usually operate with ammonia-water working fluids in aiding plant performance. Law, et al. (2012) states that the Kalina cycle has not been implemented into any major processes with less than five case studies being published. The author gives examples of such plants which include the use in geothermal power plants and low-grade waste heat recovery.

The research was performed by Ogriseck (2009) on the integration of the Kalina cycle in a combined heat and power plant. The data suggested that if integrated, the cycle will offer a net efficiency of between 12.3% and 17.1%. Furthermore, the gross electricity power is between 320 and 440kW for a 2.3MW of heat input and so the efficiency is between 13.5% and 18.8%. Law, et al. (2012) in their article 'Opportunities for low-grade heat recovery in the UK food processing industry' addresses uncertainties from reports that the Kalina cycle can offer an increase in power output of up to 20% but practice as little as 3%. Khankari and Karmaker (2016) in their article 'Power Generation from Coal Mill Rejection Using Kalina Cycle' discusses data from a report which compares the Kalina cycle with the Rankine cycle in which under the same conditions, the Kalina cycle can reach a 10% to 30% greater thermal efficiency than the Rankine Cycle.

In terms of capital cost and assuming 8000 operating hours per annum, Ogriseck (2009) evaluated for a small plant with a power output of 400kW the cost is between 2000 – 3000 EUR/kW in which the payback period is 7.9-18.5 years. The payback period can be reduced to 3 years if the capital cost was 1000 EUR/kW. For Coal Mill rejection, Khankari and Karmaker (2016) calculated a maximum payback period of 5.5 years.

Due to the lack of implementation in actual sites, the Kalina cycle has yet to be seen on an industrial scale and therefore, it is not a tried and tested technology. However, the potential of the Kalina cycle suggests this is the technology of the near future.



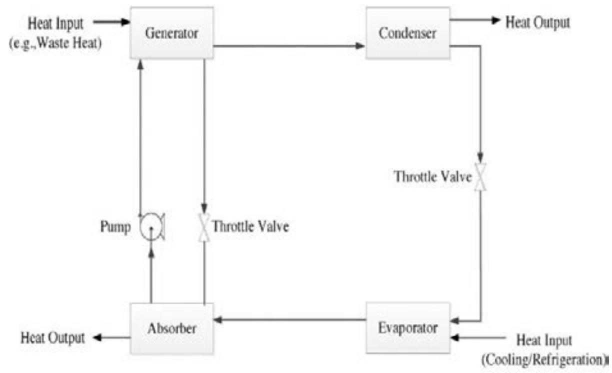


Figure 1 - Schematic diagram of a simple Kalina Cycle Figure 2 - Schematic diagram of a simple Absorption process (Ogriseck, 2009) Refrigeration process (Wang, et al., 2017)

3.3 Absorption Refrigeration

Refrigeration is a thermodynamic process that involves the transfer of heat from the heat source to the heat sink. The typical, vapor compression refrigeration system (VCRS) was set forth by American engineer Oliver Evans in 1805 (Sellers Jr., 1886). VCRS is widely used in many applications ranging from industrial cooling to domestic chilling and air conditioning.

The elementary VCRS consists of five major components: a refrigerant, a throttle valve or expander, an evaporator, a compressor, and a condenser. The refrigerant, typically ammonia, initially existing as a liquid, would be expanded by a throttling valve causing a pressure drop. This liquid would flow through an evaporating unit which would absorb heat from the heat source resulting in the desired refrigeration effect. The formed vapour passes through a powered compressor increasing both the temperature and pressure of the refrigerant. Finally, the vapour flows through a condensing unit which would reject heat to the heat source typically at ambient conditions. This is the elementary VCRS cycle implemented to produce the desired cooling effect. (Wang, et al., 2017)

VARS is primarily driven by the laws of physics and chemistry rather than mechanical laws. In comparison, the VARS cycle consists of an expander, an evaporator and a condenser, but in contrast, the powered condenser is replaced by an absorber, a generator or boiler, another expansion device, and a pump (in some variations, a solution heat exchange (SHE) is utilised). The absorber receives the outlet refrigerant as vapour from the evaporator and this reaction, using the absorbent, rejects heat from the system; a strong, rich solution is formed and pumped to the generator resulting in a pressure increase. Heat, sometimes in the form of lowgrade waste heat, is added to the generator in which gaseous refrigerant is sent to the condenser and a weak solution is recirculated back into the absorber after it is expanded through a throttle valve (Wang, et al., 2017).

In common practices of VCRS, high energy costs due to the use of electricity powering the compressor, are traded through the absorption system which utilises low-grade heat. Despite pumps requiring power, they are more efficient at raising the pressure of liquids as opposed to compressors raising the pressure of vapours; therefore, less power is required. Consequently, VARS bears high heating as opposed to high power requirements. Nevertheless, VARS heating duty is not high and so utilising low-grade heat is a suitable application. (Kwak, et al., 2017)

The performance of VARS is heavily based on the coefficient of performance (COP) and the exergy (total minus unavailable energy) efficiency. Models have been simulated which discovered the COP increases with increasing generator and evaporator temperature but decreases with increasing absorber and condenser temperature. "The biggest exergy loss occurs when air is the heat source while hot water gives the smallest loss." (Wang, et al., 2017). As a result, the objective function of the maximum exergy is determined by selecting the most optimum heat source which is dependent on system performance and irreversibility.

Moreover, an economic analysis was conducted by Kwak, et al. (2017) which compared three other technologies in addition to VARS. The minimum total annualised costs were calculated from fuel, electricity, cooling water and capital costs. For VARS, the key parameters were "generator inlet and outlet temperatures" and the constraints were the "amount of low-grade heat with sufficiently high temperatures and minimum temperature approach in the heat exchanger". Using Sour Peng-Robinson property package to model VARS and comparing with a standard propane VCRs, the case study showed that although VARS has advantages in lower fuel cost and higher energy efficiency, it is less profitable due to higher capital cost – at the worst-case scenario during realistic summer temperatures, this is 8.2% costlier. However, if the cooling duty increases, the energy-saving could outweigh the capital costs; this is dependent on each site in which simulation would be required.

A case study into replacing propane chillers with VARS in the oil and gas industry with relation to LNG recovery was conducted. The study concluded that "recovering waste heat from a 9 MW electricity generation process could provide 5.2 MW waste heat produced additional cooling to the LNG plant and save 1.9 MW of electricity consumption" (Kalinowski, et al., 2009). Furthermore, Salmi, et al. (2017) suggested that absorption refrigeration applies to a wide range of businesses such as marine applications; as well as combining with other technologies that as the combined ejector/Rankine cycle (Tchanche, et al., 2011).

3.4 Absorption Refrigeration Using CO_2 as a Refrigerant

In 1987 after significant research into the depletion of the ozone layer, especially over Antarctica, it was decided by the united nations environment programme that the use of chlorofluorocarbons would come under regulation and be phased out, both when used in aerosols and refrigeration cycles. Hydrofluorocarbons were used thereafter, however, a major problem that arises is the relatively high carbon footprint that these compounds have (Secretariat for The Vienna Convention for the protection of the ozone layer & The Montreal Protocol on Substances the Deplete the Ozone, 1987).

Carbon dioxide is now a very popular choice for a refrigerant since it is considered carbon neutral (being found naturally in the atmosphere) and is also considerably cheaper than other available gases such as R134a. Traditionally when looking for a refrigerant there are common characteristics that are desired such as having a smaller vapour density so that the compressor can be both physically smaller and requires less work to be put into the system and also having a high enthalpy of vaporisation to ensure a greater heat absorption during the evaporations part of the cycle. Transcritical refers to the carbon dioxide existing at its critical point at some point within the system (pressure of 74 bar and temperature of 30^{o}C [CO_2 Transcritical refrigeration cycles]) and at this point the CO_2 displays many of the properties necessary. The reason for its emergence is the drop-in production cost of the high pressure rated parts necessary for this system. (Meng, 2017; Pieve, 2017)

Apart from the aforementioned advantages of using supercritical $CO_{2,}$ it is non-corrosive, has low toxicity, low flammability and very high molecular stability. There are however disadvantages such as the special equipment needed to withstand the high pressure and the overall system sensitivity to water contamination This problem, in particular, is highlighted since there are fewer regulations in place and therefore companies are less inclined to carry out regular leak detection exercises. This system is also unsuitable for areas with high ambient temperatures such as the Middle East and South Asia as this will cause the system to operate almost exclusively above critical conditions. (The Emerson climate Technologies, 2015)

3.5 Heat Pump

Various types of heat pumps have been used to recover and utilise low-grade waste heat in many processes. One of the advantages of the heat pump is that it could convert waste heat into a useful high-temperature energy source by increasing the temperature and reducing the amount of cooling water needed for the process. In addition to this, the amount of CO_2 emitted by the plant is expected to decrease by using the heat pump. Heat pumps could be divided into four types: Absorption heat pump (AHP), Compression heat pump (CHP), Hybrid compression-absorption heat pump (CAHP) and Cascaded compression absorption heat pump (CCAHP). (Farshi, et al., 2018) The comparison and analysis of three types of heat pumps excluding AHP, which was described in the previous section, are described in the following passages.

CHP system consists of four components; compressor, evaporator, condenser and expansion valve. The working principle of CHP is increasing the pressure of vapour by using the compressor. In the condenser, high- pressure vapour from the compressor is used as a hot utility or heating source for a process (Kwak, et al., 2014; Ommen, et al., 2015). In terms of CAHP, it is the combination of vapour compression heat pump and absorption heat pump and consists of six components: compressor, expansion valve, absorber, desorber, solution pump and heat exchanger. There are two pressure levels between absorber and desorber. In the desorber, evaporated refrigerant is drawn into the compressor by external heat from waste heat. The weak solution is pressurised by a solution pump and flows to the absorber via a heat exchanger. In the absorber, high-pressure refrigerant vapour and weak solution are recombined and refrigerant vapour is condensed. CCAHP is newly introduced in a recent study by Farshi, et al. (2017). This system consists of two CAHP subsystems with different pressure levels connected by the cascaded heat exchanger. *Table 1* illustrates the advantages and disadvantages of the different types of heat pumps.

Table 1 - Advantages and disadvantages of different types of heat pumps (Morawetz, 1989; Zhang, et al., 2016; Farshi, et al., 2017)

Type	Advantage	Disadvantage
CHP	• Relatively low capital cost	• Limited temperature lift • Temperature mismatches • Inflexible operating ranges • Low coefficient of performance
CAHP	• Safe when heat source with high temperature is offered	• High compression ratio • High discharge temperature
CCAHP	• Small maximum pressure • High-temperature lift	• Relatively high capital cost

CHP is the most widely used heat pump as it meets the industrial requirement at various temperature ranges. Industrial applications of heat pump can be seen in the study of Zhang, et al., (2016). According to this study, vapour compression pumps are utilised for printing and dyeing. Furthermore, they identified that applying a heat pump to the process can reduce the operating cost by 47% compared to without. In addition to this, the payback period is 1.84 years. Sun, et al., (2014) in their article suggested the application of a heat pump for district heating. The efficiency of heat utilisation could be improved significantly by integrating the heat pump with other system and creating a hybrid heat pump, solar hybrid heat pump, for example (Chua, et al., 2010). Overall, these cases demonstrate that heat pumps have a positive impact on recovering waste heat and improving energy utilisation efficiency.

3.6 Heat Transformer

Due to the low temperature of low-grade waste heat, many companies find it difficult to utilise low-quality heat sources. Consequently, many industrial plants have inevitably wasted their money on a large amount of heat being disposed into the environment. Absorption heat transformer can save up heat by increasing the temperature of the heat source and recycle the heat back in the system and supply other chemical processes (Sözen and Yücesu, 2007). The absorption cycle consists of four main compartments; generator, condenser, absorber, and evaporator. The medium-temperature waste heat is used to feed the generator for separating the refrigerant from the absorbent which typically is LiBr and water, respectively. The refrigerant is cooled down and condensed in the condenser releasing its latent heat to the coolant. The refrigerant then enters the absorber. The medium-temperature vapour is then upgraded to higher-temperature vapour from the heat of absorption discharged in the absorber (Donnellan, et al., 2015).

To achieve optimal thermodynamic performance, parametric analysis has been carried out according to alternate cycle configurations and operating conditions. For single-stage heat transformer (SSHT), increasing evaporator temperature and absorber temperature will result in a higher performance of heat production, however, the performance drops when increasing condenser temperature (Horuz and Kurt, 2009; Sekar and Saravanan, 2011). For advanced heat transformer, even though the thermodynamic performance is relatively low compared to SSHT performance, the gross temperature lift is significantly higher than those from SSHT which benefits some chemical processes that require high-temperature streams (Donnellan, et al., 2015).

Despite the cycle configurations, working fluids also play an important role in enhancing thermodynamic performance. Several working fluids such as NH_3-H_2O, NaOH-H_2O, and $CaCl_2$ have been investigated to find an alternative instead of using LiBr-H_2O which has high corrosivity. Nevertheless, LiBr- H_2O provides the best thermodynamic properties regardless of its negative effect (Donnellan, et al., 2015). For industrial applications, the integrated design of both absorption heat transformers and heat recycling from auxiliary condenser developed a higher COP when used with generator, evaporator and both generator and evaporator. The results showed a performance growth of 110.3%, 61.5% and 79.3% respectively (Huicochea and Siqueiros, 2010). Mostofizadeh and Kulick (1998) have shown that by testing a 100kW SSHT installed pilot plant and performed economic analysis, 20kW of electricity is needed and the payback period is predicted to be 2.36 years.

Absorption heat transformer can recover heat energy up to 50% with a low operating cost. The absorption cycle run with only small electrical energy consumption which makes this technology an attractive option to many industries (Sözen and Yücesu, 2007). However, there are only limited companies worldwide using the technology, the feasibility of practical operation remains unclear without any further study of absorption heat transformer application in actual processes.

3.7 Boiler Feed Water Pre-Heating

The utilization of the waste heat in any process to preheat feed water from ambient temperature before it enters the steam generator (boiler) is one of the common methods used in low-grade heat recovery and it is considered the simplest method among several others. According to Kapil et al., (2012), increasing the feedwater temperature from 25°C to 101°C by low-grade heat resource can contribute to a reduction in the cost of fuel consumed by the boiler from 93.08 M$/yr to 80.57 M$/yr. The main equipment associated with the preheating process is the heat exchanger which transfers heat from the heat source to the heat sink. Therefore, the amount of heat transfer plays a significant role in boiler fuel consumption. However, one major drawback of this method is the additional area for the heat exchanger and a higher capital cost (Kwak et al., 2014). According to Law et al., (2012), the waste heat resource may be available in gas or liquid streams. For this, two different types of heat exchangers are commonly used, such as gas-liquid heat exchangers and liquid-liquid heat exchangers.

Gas-liquid heat exchangers such as tubular heat exchanger are widely used in processes for the recovery of low-grade heat. However, the economiser is considered a more widespread option as it is applicable for domestic as well as industrial use. A common application for this heat exchanger is using flue gas to preheat the boiler feed water as the flue gas transfers heat through finned tubes. However, a modification in heat exchanger design is required to deal with the vapour condensation to increase its efficiency. Suitable materials selection is required to prevent corrosion due to the acid formed in the condensate. The heat pipe is another type of economiser but not common when compared with the tubular heat exchanger. Also, a spray condenser is another type of heat exchanger that is used for heavily fouled gas. Principally, this heat exchanger depends on water being sprayed into a gas stream with high humidity and as a result of that, hot water is produced. A good application for this type of heat exchanger is recovering heat from outlet streams that contain air, steam and solids such as spray dryer exhausts (Law, et al., 2012).

Liquid-liquid heat exchangers are another type of equipment that is used to recover low-grade waste heat. Shell and tube heat exchanger and plate heat exchanger are the most common types of liquid-liquid heat exchangers. Among the major advantages of this heat exchanger is a plating efficiency of 95% and requires a smaller area. One major drawback of this approach is that the limitation of the operation condition ranges up to 200°C and 25 bar and it is also susceptible to fouling. To increase the operating conditions to 900°C and 300 bar, the plates would initially have to be brazed and welded, however, this would increase the capital and maintenance cost. Another type of liquid-liquid heat exchanged that can be used for slurries is the scraped surface heat exchanger (Law, et al., 2012).

4 Conclusion

To recover low-grade waste heat from processes, there must be sound understanding and knowledge behind the technologies responsible for making this available to utilise. Boiler feed water heating is one of the simplest and common technologies, requiring only the water feed to be heated to implement heat recovery. However, the main problem is the limitation in the conditions (it can operate at 200^{o}C and 25 bar). The Organic Rankine cycle is primarily used to recover low-grade heat and generate electricity from it. Using an organic working fluid, this system has been implemented into a wide variety of processes suggesting its reliability in the industry. The Kalina cycle was developed from the Rankine cycle, containing very similar units. The potential for this cycle is great however due to a lack of real case studies, suggests reluctances in the industry. Conventional refrigeration implements the VCRS to be used in applications from industrial cooling to air conditioning, which has high power requirements. In recovering low-grade waste heat, VARS has been implemented which originally was based on engines; this has evolved, adapted and implemented into many process sites and power plants. VARS has a low heating duty and therefore more equipped for heat recovery. The main drawback is the high capital cost, around 8.2% costlier, hence is only effective if the cooling duty of a process increases. The heat pump works by converting low-grade heat into high temperatures and reducing the requirements for cooling water in a process. CHP and AHP are the most common and widely used in the industry. To complement the weakness of them, CAHP and CCAHP are introduced. The main disadvantage of a heat pump can be the high capital costs and limited temperature range for some systems. Heat transformers increase the temperature of the heat source and recycle the heat back into the system. The operating cost is low and can recover up to 50% of the heat. However, this technology is not widely used in industry and therefore the feasibility is uncertain. The seven technologies detailed have explored various options in waste heat utilisation as well reduction in CO_2 emissions, overall costs and improvement in the process efficiency suggesting promising options for a reduced energy future.

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