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WASTE HEAT RECOVERY TECHNOLOGIES: PATHWAY TO SUSTAINABLE ENERGY DEVELOPMENT

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ABSTRACT

The aim of this study was to review the significant of waste heat recovery technologies as means of achieving sustainable energy development. Most developing nations of the World are faced with the enormous release of industrial waste heat of low temperature grade to the environment. Unlike material waste that is clearly visible, waste heat can be difficult to identify and evaluate both in terms of quantity and quality. Hence, understanding the availability of waste heat, and the ability to recover it, offer great opportunity to reduce energy costs and associated environmental impacts. Utilizing low-grade energy from waste heat sources is considered to offer a significant contribution to improving overall energy efficiency in the energy-intensive industrial sectors. The concept of industrial waste heat is explained, potential sources of waste heat from industries are identified, and the technologies available for waste heat recovery are presented in this study. From the review study, it is shown that about 72% of the global primary energy consumption is lost after conversion, while 63% of the considered waste heat streams arise at a temperature below 100 °C in which electricity generation has the largest share followed by transportation and manufacturing industry. The results of this study reveals that considerable amount of waste heat can be technically and economically recovered through sustainable technologies with prospective capacity for the much desired sustainable energy development. Specifically, in-depth utilization of waste heat resources can effectively moderate the rate of depletion of the fossil fuels and sufficiently reduce toxic emissions to within acceptable limits that are compatible to the projected time of full deployment of renewable energy (RE) source.

Keywords: *Sustainable Energy, Sustainable Technology, Waste Heat Recovery, Low Grade Energy, Sustainable Development, Emissions*

INTRODUCTION

Energy is a prime necessity of life which determines the quality of life of the citizens, the political power of a government, and the level of industrial, technological and socioeconomic development of the nation. Globally, industrial and economic developments are strongly associated with increasing use of fossil fueled-combustion systems [1]. Industrial sector covers about a third of world energy consumption, which reportedly increased by 61% between 1971 and 2004 [2], risen more than 40% between 1990 and 2008 [3], and is expected to grow by 34% between 2014 and 2035 [4].

Despite the typically low conversion efficiencies for thermal processes involving the limited resources, the growing industrial sector is rather mainly covered by fossil fuels solely incited by economic considerations, especially coal which is relatively abundant and cheaper [5] but contributes 36% of carbon dioxide (CO_2) pollution annually to the environment [6]. Recent reports show that world energy consumption from fossil fuels (Natural gas, oil, and coal) in 2016 and 2015 are 13,276.3 and 13,105.0 million tonnes oil equivalent which respectively represent 85.5 and 86.0 % of the total annual energy consumptions for each year [7; 8]. Similar report showed that annual waste heat dissipation into the atmosphere solely from US manufacturing sector is estimated at $3x10^{13}$ kWh [9]. It is common knowledge that carbon dioxide is responsible for global warming and has however been established that global CO_2 emissions is primarily a reflection of the world's fossil energy consumption [10].

Likewise, the power sector has equally been identified as a key sector promoting the increase utilization of fossil fuels but with great carbon dioxide mitigation potential since its emissions are centralized and much easier to

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control than the industrial sector with distributed emissions11]. Globally, coal is the leading electricity source at present providing around 40% of total electricity generation, followed by natural gas at approximately 22%, oil at only 4% while the rest is supplied by other energy sources, including nuclear and renewable technologies [12]. Unarguably, the path travelled so far in transforming global, regional and national economies is fossil-based development 13] hence, economic development is traditionally interrelated with increasing energy use and growth of greenhouse gas (GHG) emissions ([14]. Sequently, International Energy Agency (IEA) projection based on the current trend of energy consumption and efficiency shows that the rise in temperature is expected to hit 6 °C by 2050 with devastating consequences [15].

Study shows that 91% of the global 548 x10^{18} J of energy production is derived from non-renewable resources [16] of which recent assessments revealed that 72% of the global primary energy content of the fossil fuels is lost after conversion in waste heat streams of various temperatures of the [2; 17]. This unsustainable pattern of energy utilization inherently implies that a bigger share of 395 x10^{18} J in low grade energy form is wastefully discharged into the atmosphere in various waste heat streams annually, while at the same time depositing excessive and avoidable amount of toxic emissions into the environment. This in essence indicates overexploitation of the limited resources as well as excessive degradation of the environment from thermal and toxic pollutions. Factually, most developing nations of the World are faced with the enormous release of exploitable waste heat of low temperature grade to the environment that can be utilized to improve global energy efficiency and energy consumption for sustainable development but it remains largely untapped and unaccounted for in most nations of the world [18].

With the continuing exponential growth in population coupled with depletion of limited natural resources, waste heat recovery technologies provide an attractive option that promotes energy savings and conservation of natural resources from further depletion and as well offer considerable reduction in the environmental effect of fossil fuels combustion. Unlike material waste that is clearly visible, waste heat can be difficult to identify and evaluate both in terms of quantity and quality. Hence, understanding the availability of waste heat, and the ability to recover it, offer great opportunity to reduce energy costs and associated environmental impacts. Utilizing low-grade energy from waste heat sources is considered to offer a significant contribution to improving overall energy efficiency in the energy-intensive industrial sectors, power plants or transportation sector. Several studies have been conducted on existing and advanced technologies to realize the opportunity of low-grade waste heat recovery. Hussam et al. [19] carried out a comprehensive review of waste heat recovery methodologies and state of the art technologies used for industrial processes. Legros et al. [20] provided a complete state of the art review of the main technologies to recover waste heat energy in the exhaust gases of a light duty vehicle engine. The study pointed out major drawbacks of those technologies and several relevant performance indicators were compared: efficiency, cost, technical maturity, packaging and weight to power ratio. In their work, Alessandro et al. [21], presented a decision support tool to compute the compatibility of waste heat source(s) and sink(s), that is, the exergy balance and temporal availability, along with economic and environmental benefits of available heat exchanger technologies to propose a streamlined and optimised heat recovery strategy. Result of the study demonstrated substantial improvement in plant energy efficiency together with reduction in the payback time for heat recovery. Elliot et al. [22] developed a waste heat energy recovery framework to provide industrial sectors with a four step methodology in assessing production activities in facilities: evaluating the potential of waste heat source(s) and sink(s) in terms of exergy balance and temporal availability, selecting appropriate heat recovery technologies and decision support based on economic benefits. Langan and O'Toole [2] assessed the cost effectiveness of a new technology for recovery of low grade heat – Exergyn Drive (an innovative, new engine cycle that operates on hot water). For the first time, this low-grade waste-heat recovery technology delivered attractive payback periods less than 3 years and returns on investment without the need for additional incentives. In their study, Clemens et al. [23] estimated the global waste heat potential. The study presented a novel top-down approach for the estimation of waste heat potential of the most common sectors of end use including electricity generation on a global scale. The study also considered with the temperature distribution of this unused energy. Results of the study showed that 72% of the global primary energy consumption is lost after conversion while 63% of the considered waste heat streams arise at a temperature below 100 °C in which electricity generation has the largest share followed by transportation and industry. Shengwei et al. [24], proposed an improved system to efficiently utilize the low-temperature waste heat from the flue gas of coal-fired power plants based on heat cascade theory. An in-depth analysis of the energy saving characteristics of the improved waste heat utilization system (WHUS) conducted in a typical 1000 MW unit showed net power output increased by 19.51 MW, exergy efficiency improved to 45.46%, and net annual revenue reached USD 4.741 million.

Alison et al. [25] presented a theoretical study of organic Rankine cycles (ORCs) powered by three different waste heat source. The study aimed at further understanding the influence of the T – H profile of the heat source fluid on the optimal cycle configuration, and to identify general design principles for ORCs over a range of energy scales. Simeon et al. [26] assessed the possibility of fitting an organic Rankine cycle (ORC) system in a commercial agricultural tractor to recover waste heat from a 300-kW brake power heavy-duty diesel engine. A maximum fuel consumption reduction of 10.6% was obtained using methanol and recovering heat from tail-pipe and exhaust gas recirculation (EGR). Fakeye and Oyedepo [27] conducted a comprehensive review of working fluids selection for different applications. The study helps in identifying the possible most suitable organic fluids for various ORC applications depending on the operating conditions. Karimi et al. [28] reviewed performance and optimization of different thermodynamic cycles (*Organic Rankine cycle, Kalina cycle and Goswami cycle)* used for combined power plant using low grade heat sources. In the study, comparison of different cycles was carried out so as to identify the best cycle to convert various low grade heat sources into electrical power under various conditions using different methodologies. Arash et al. [29] carried out thermodynamic modeling and optimization to compare the performance of organic Rankine cycle (ORC) and Kalina cycle (KC) as a bottoming cycle for waste heat recovery from CGAM cogeneration system. A comprehensive comparison between Kalina and ORC revealed that the ORC has significant privileges for waste heat recovery in the case study. Zare and Mahmoudi [30] presented a comparative thermodynamic analysis and optimization for waste heat recovery from a standalone Gas Turbine-Modular Helium Reactor (GT-MHR) employing organic Rankine cycle (ORC) and Kalina cycle (KC). The results showed that, employing ORC is more appropriate than KC for GT-MHR waste heat recovery. The first and second law efficiencies of the combined GT-MHR/ORC are higher than those of the combined GT-MHR/KC. In addition, the helium mass flow rate in the combined GT-MHR/ORC is significantly lower than that in the combined GT-MHR/KC. Moreover, the high-pressure level of the ORC is extremely lower than that of the KC under optimized conditions.

This paper aimed at review waste heat resources and potential and to ascertain waste heat recovery (WHR) technologies as pathway to sustainable energy development. The paper also provides an overview of existing waste heat recovery technologies and discusses several barriers which currently prevent their wide-spread implementation.

THE CONCEPT OF INDUSTRIAL WASTE HEAT

Waste heat can be described as the heat stored in a substance which is rejected from a process at a temperature greater than the ambient temperature of the plant whose source has a sufficient portion that may be economically recovered and re-used [31]. The two factors which are basically responsible for generating waste heat are equipment inefficiencies and thermodynamic limitations on equipment and processes. The various sources of waste heat generated as a result of the two factors from various industrial processes involving kilns, furnaces, ovens, power plant turbines, combustion engines, etc. and as well at field locations such as landfills, mining sites and compressor stations accounts for between 20 to 50% of industrial energy input [32; 33].

Waste Heat Resources and Potential

Effective utilization of lost energy in industry is important economically and environmentally all over the world. Designing efficient and cost effective systems that also meet lower capital and running costs and environmental conditions are the foremost challenges that engineers face. In the world, with finite natural resources and large energy demands, it becomes ever increasingly important to understand the mechanisms that degrade energy and resources and to develop systematic approaches for improving systems and, thus, also reducing the impact on the environment [34].

Based on the present status of energy consumption in industries, one of the best ways for companies to reduce their energy consumption without the need for costly and vast equipment, or facility overhauls is through the implementation of waste heat recovery (WHR) technologies [35]. These offer the industrial sector an incredible opportunity to save energy and improve efficiency. According to the estimates by the American Department of Energy (DOE), between 20-50% of industrial energy input is presently lost as waste heat in the form of hot exhaust gases, cooling water, or from equipment surfaces and heated products [36; 37].

Each waste heat stream possesses distinctive quantity, quality and exergy whose potential for WHR can be assessed for recovery opportunity. Table 1 presents groups of exploitable waste heat sources being classified into three based on the temperature range as the temperature is the determinant of the quality and efficiency of the recovery potential as well as a significant factor in screening for a suitable recovery technology [38]. Three types of methods have been identified in estimating the waste heat potential of a heat source namely: the theoretical (or physical) potential, the technical potential, and the economically feasible potential [32; 39, 40].

Table 1. Classification of the quality of energy depending on temperature

Quality	Temperature range (ºC)
High	650 and above
Medium	232 – 649
Low	232 and lower

The theoretical potential only determines the amount of heat above the ambient temperature that can be harnessed from the heat carrier while the technical potential considers the minimum allowable temperature, possibility of extracting and using heat, heat losses and the choice of technology. The economically feasible or techno-economic potential is more comprehensive approach as it considers economic implications and financial parameters along with the technical potential. It is necessary to determine the appropriate type when considering WHR technology option to adopt. The overall potential of WHR is generally assessed to range between 32% and 80% depending on the temperature level when the temperature is greater than 150ºC [41]. In addition, [42] presented that the resulting waste heat potential solely from exhaust gases in European industrial region ranges between 5 and 30% of the energy demand of the region while preliminary results from Panayiotou et al. [43] put recoverable waste heat potential in European industry at 370.41TWh per annum.

Waste Heat Recovery and Utilization

Waste heat is usually the energy associated with waste streams of air, exhaust gases, and/or liquids that leave the boundaries of an industrial facility and enter the environment. Recovering the waste heat can be conducted through various waste heat recovery technologies to provide valuable energy sources and reduce the overall energy consumption [44]. Dissipation of waste heat from industrial processes and operation of power plants may be inevitable but the various waste heat streams generated could be exploited as input for heating, cooling or power systems. Waste heat recovery in industry covers methods of collection and re-use of the lost heat of industrial processes that can then be used to provide useful energy and reduce the overall energy consumption. Technologies for industrial waste heat utilization can be categorized as passive or active technologies as shown in Figure 1. This depends on whether the heat is being recycled directly at the same or at lower temperature level or whether it is transformed to another form of energy or to upgraded to a higher temperature [39].

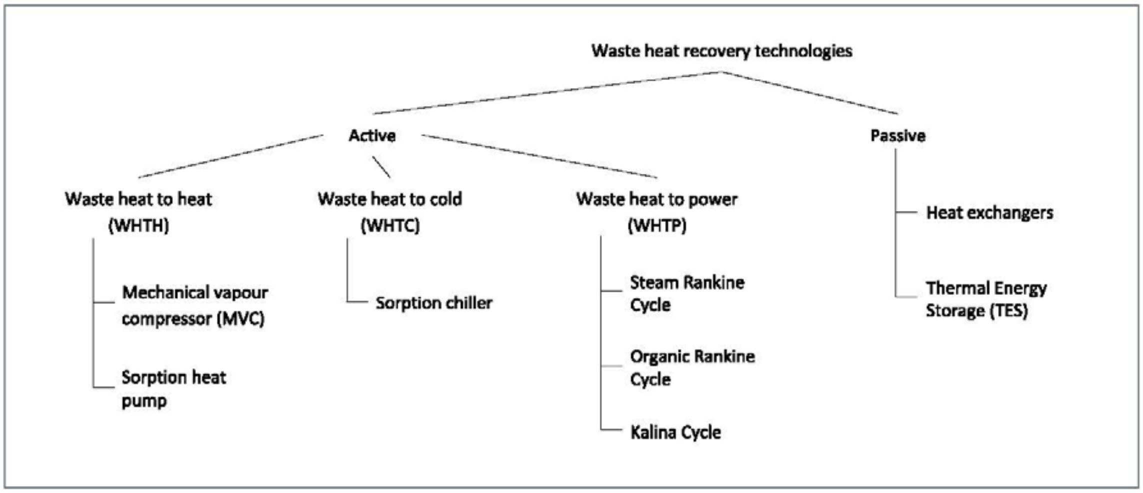

Figure 1. Categorization of waste heat recovery technologies

It is however, often more economical to reuse the waste heat as energy input in an on-site heating or cooling process [32] but they are disadvantaged by problems associated with storage and transmission distance and thereby is rarely adopted except when distance and purpose are suitable for off-site use [45]. Otherwise, a waste heat-to-power (WHP) system may be an economically attractive option especially when the heat source temperature is above 150ºC ([30] because of their unique advantage of diverse cycles that can adapt to various medium-low heat sources to generate more electricity. Meanwhile, upgrading heat is sometimes more economical depending on the temperature difference to be achieved and the relative costs of fuel and electricity. For a heat load slightly higher than the temperature of the waste heat source, the heat can sometimes be more efficiently provided by a heat pump than from burning additional fossil fuels [46]. Table 2 shows exhaust temperature of some on-site industrial application of WHR.

Table 2. Exhaust temperature for some on-site industrial applications

Manufacture of some basic metals	**Temperature (ºC)**
Iron & steel making	1450-1550
Steel electric arc furnace	1370-1650
Nickel refining furnace	1370-1650
Aluminium reverberatory furnace	1100-1200
Cooper refining furnace	760-820
Manufacture of non-metallic minerals	
Cement sintering	1450
Glass melting furnace	1300-1540
Calcining of limestone in the kiln	900
Calcination of magnesia	600-800
Cement kiln	450-620
Clinker cooler waste air	177-232
Kiln system exhaust/preheater	382-816
Manufacture of non-metallic minerals	
Furnace black process	1200-1900
Ammonia catalyst reaction	510
Paint and varnish depolymerization	288-343
Plastic and rubber	90-200

Waste Heat-to-Heat Technologies

Waste heat-to-heat is a means of utilizing the waste heat in form of heat either at a lower temperature or slightly upgraded temperature. A waste heat recovery technology produces heat or power by utilizing the heat energy lost to the surroundings from thermal processes, at no additional fuel input [38]. Hence by being able to understand the availability of waste heat energy, and the ability to recover it, there is an opportunity to reduce industrial energy consumptions and costs and associated environmental impacts. The recovery of WHE energy in industry is potentially more economically viable than the installation of renewable energy technologies and other mechanisms for reducing overall energy consumption across a facility. Because of the often low-tech solution required to harness the energy, the approach is generally accessible for most companies and payback times can be relatively short (of the order of two years) [22]. Technologies for waste heat-to-heat utilization are presented as follows:

Gas Turbine Regenerator

Gas turbine Regenerators or Recuperators use high temperature flue gases to preheat the air-fuel mixture entering the combustion chamber in a process called recuperation. It is an energy efficient ancillary in gas turbines that utilizes the waste heat that otherwise could be employed in bottoming cycles. Heat recovery steam generator could then be integrated after regeneration, as shown in Figure 2, to further harness heat from the exhaust gas and utilized in a conventional steam Rankine cycle to generate up to 50% more electricity at no additional fuel input in the combined cycle plant. Different regenerative cycle architectures were investigated by Ramakrishnan and Edwards[47] and was established to improve efficiency up to 68% for partial intercooled compression configuration. This makes the plant more ecofriendly and also improves the reliability, efficiency and cost effectiveness of the plant as well.

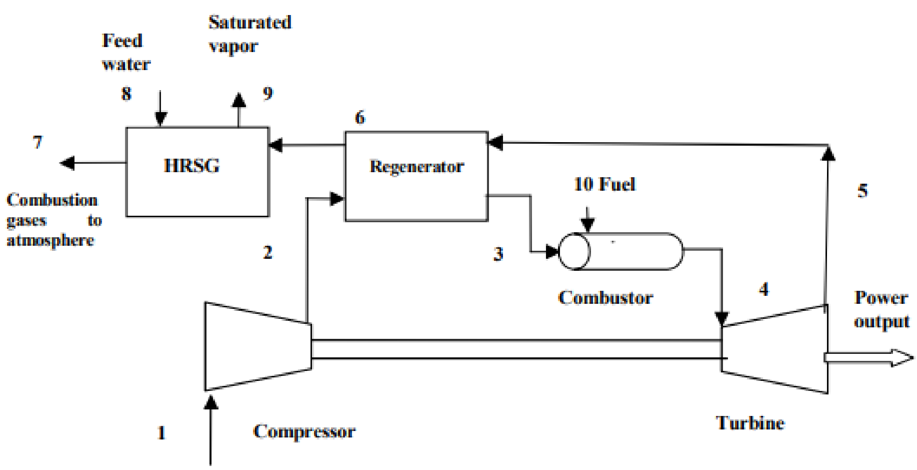

Figure 2. Schematic of gas turbine cogeneration with regeneration

Heat Pumps and Heat Transformers

These are thermal machines that transfer heat from region of low temperature to a higher temperature region by either vapour compression or absorption process using low temperature-boiling organic working fluids in order to raise low grade heat (source) to a suitably high, more useable temperature (sink) [47]. Heat pumps are particularly suited for refrigeration operations while heat transformers are primarily for recycling and upgrading of low-grade heat to a high temperature, high quality usable energy. Heat pumps and heat transformers of the absorption types are promising in industrial applications when a combined heating and cooling capacities are required. A single-stage heat transformer (SSHT) and single stage heat pump (SSHP) can be used for waste heat recovery at intermediate temperatures when it is necessary to increase the temperature not more than 50°C but when the required temperature upgrade is greater than 50°C, double stage heat transformer (DSHT) and double absorption heat transformer (DAHT) are suitable [48]. Figures 3 and 4 show schematic diagrams of single stage heat transformer (SSHT)[49] and Single-Stage Absorption Heat Transformer (SSAHT), respectively.

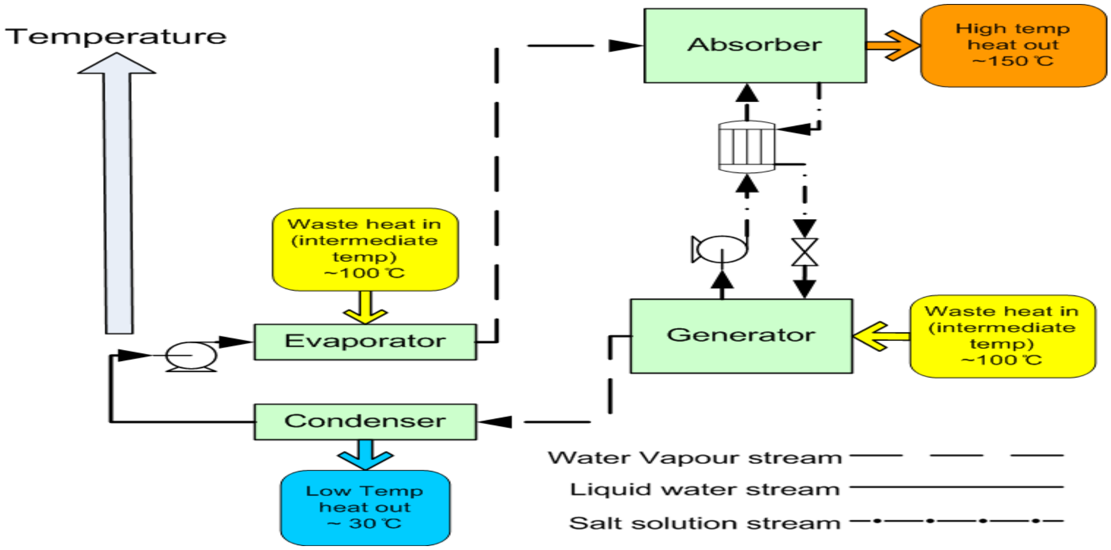

Figure 3. A schematic diagram of a single stage heat transformer (SSHT)

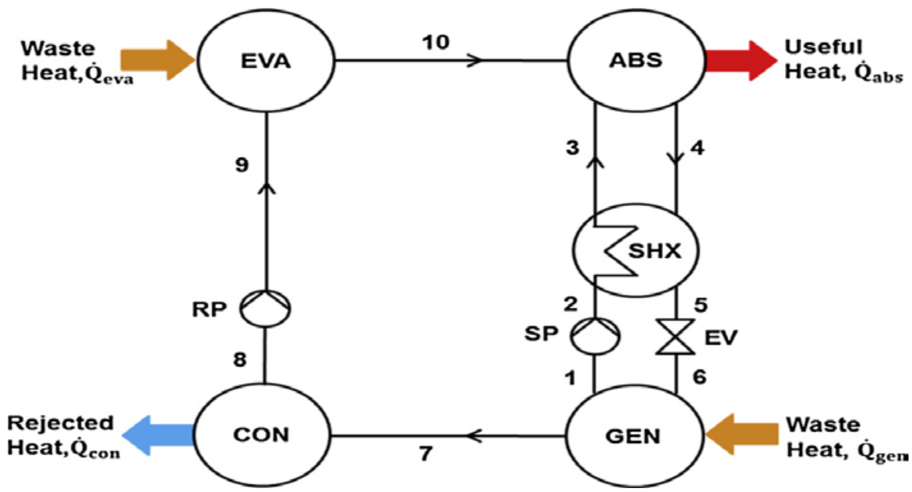

Figure 4. A schematic diagram of a Single-Stage Absorption Heat Transformer (SSAHT) cycle [From Bianchi et al., [48], with permission from Elsevier]

ABS: Absorber, GEN: Generator, CON: Condenser, EVA: Evaporator, RP: Refrigerant Pump, SP: Solution Pump, SHX: Solution Exchanger

Heat Pipe

Heat pipes are becoming increasingly popular as passive heat transfer technologies due to their high efficiency. A heat pipe is a structure with very high thermal conductivity that enables the transportation of heat whilst maintaining almost uniform temperature along its heated and cooled sections. In general, heat pipes are passive thermal transfer devices able to transport large amounts of heat over relatively long distances, with no moving parts, using phase-change processes and vapour diffusion [50].

Heat pipes are made up of 3 basic components- a working fluid and a tubular vacuum-sealed container inherently lined with capillary wick structure. Thermal energy that is applied to the external surface causes instantaneous evaporation of the working fluid near the surface (Evaporator side), after which the vapour migrates to the alternate end of the pipe (condenser side) by capillary action to release the latent energy.

The use of heat pipes for waste heat recovery is an excellent way to save energy and prevent global warming. A heat pipe heat exchanger (HPHE) is utilized as an efficient air-to-air heat recovery device in both commercial and industrial applications. The HPHE is the best choice, with virtually no cross-leakage between the exhaust gas and supply air. It possesses many advantages, such as its heat recovery effectiveness, compactness, lack of moving parts, light weight, relative economy, small pressure drop on the air side, complete separation of hot and cold fluids, and reliability. The HPHE has been applied extensively in many industries (e.g., energy engineering, chemical engineering and metallurgical engineering) as waste heat recovery systems. One of the most important applications of HPHEs is the recovery of the heat from exhaust gases in a furnace stack [51].

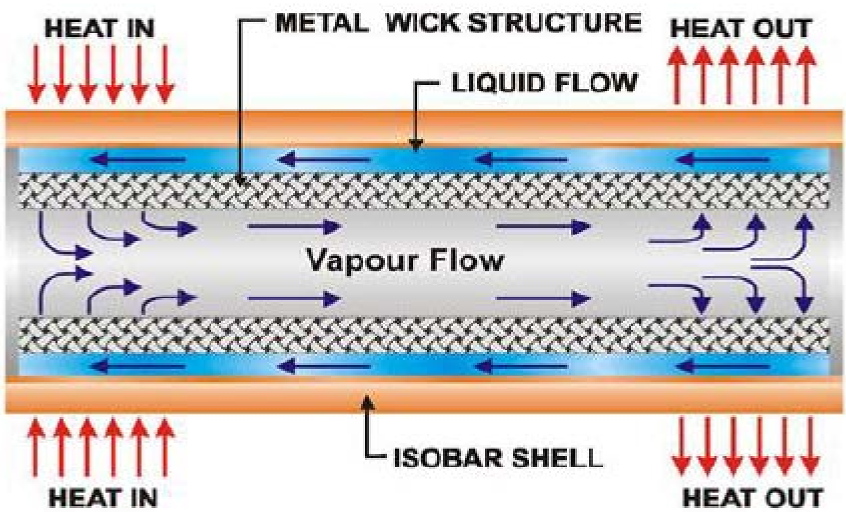

Figure 5. Heat pipe working cycle [From Chandrakishor [52], with permission from IJERT]

Thermal Wheels

A thermal wheel (rotary heat exchanger, or rotary air-to-air enthalpy wheel, or heat recovery wheel) is a type of energy recovery heat exchanger positioned within the supply and exhaust air streams of an air-handling system or in the exhaust gases of an industrial process, in order to recover the heat energy [53].

Thermal wheels are honeycomb matrix spinning wheels made of high thermal conductivity materials that permit fast discharge of heat from hot air stream and fast absorption of heat to the cold air stream without the two air streams mixing when the wheel is slowly rotated. The honeycomb matrix provides large surface areas of the high thermal conductivity material to the air streams for better heat transfer. Thermal wheels have major application in heating, ventilation, and air conditioning (HVAC). Figure 6 shows the schematic diagram of thermal wheel (rotary wheel).

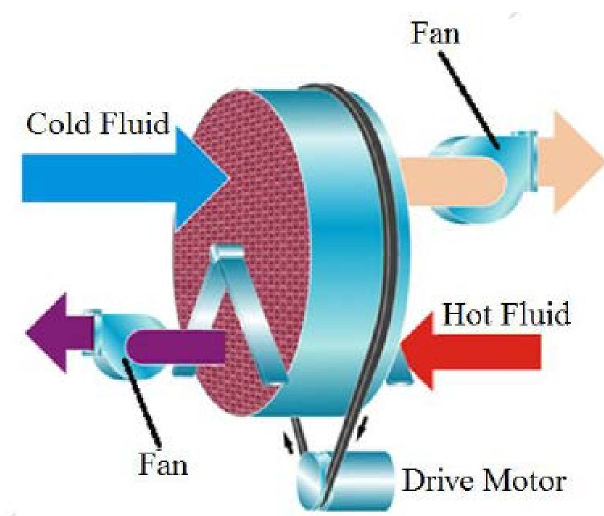

Figure 6. Schematic diagram of thermal wheel [From Xu et al, [53], with permission from MDPI]

Condensing Boilers

They are usually coupled with high efficient recuperators to extract additional heat from flue gas streams by reducing the exit temperature below the dew point consequently condensing the stream constituents. They are particularly valuable when using high hydrogen content fuels such as biomass and municipal wastes but with less application in industries compared to domestic use [54].

Waste Heat-to-Cooling (WHC) Technology

Waste heat-to-cooling is a technique of using a heat exchanger to reclaim energy from the exhaust of combustion engines used for powering electrical generators and using the regained heat for vapour absorption technology (Figure 7) for space cooling such as air conditioning or refrigeration of adjacent facilities. The electrical energy output from electrical generators is only about 30% of the fuel energy content meaning about 70% of the fuel energy is dissipated in the exhaust gases. Mostly, off-grid electrical generators having efficiencies lower than 30% are used to power residential, office, commercial buildings in most developing nations which consume about 30 to 50% of the electricity generated. Hence, using the waste heat to meet one of the biggest sources of energy demand is a significant savings in energy and cost, promotes the reliability of the generator, makes it more economical and environmental friendly as well as conserve the depleting resource. Thus, a significant amount of savings in energy and cost can be achieved, annually, from waste heat-to cooling.

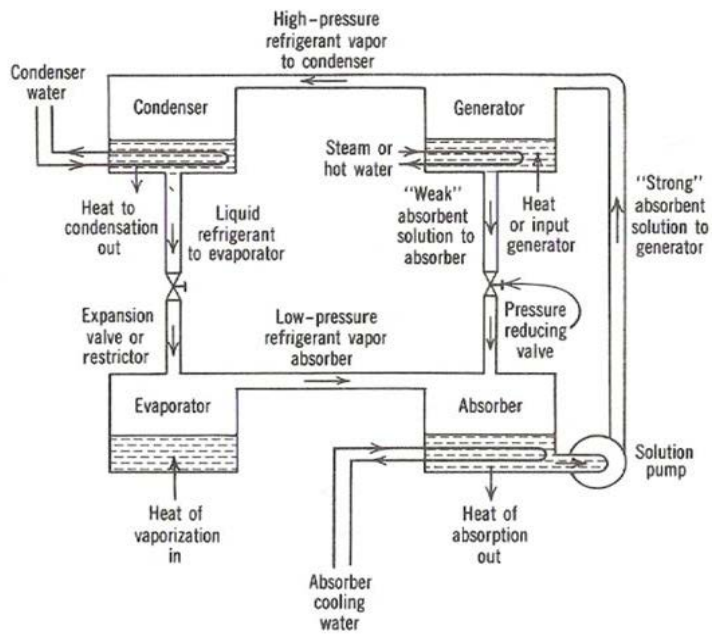

Figure 7. Basic absorption refrigeration cycle

Thermodynamic Cycles used for Waste Heat Recovery Technologies

The recovery of energy from waste heat is a modern method for energy conversion that came from most industrial and technological processes [55]. Through the use of thermodynamic cycles, heat recovery from waste sources can be directly assesse to obtain electrical energy and improve energy efficiency of a process. The thermodynamic cycles for waste heat recovery technologies make use of organic refrigerants with high molecular mass that allows energy recovery of waste heat streams that are moderate in temperature to be converted into electrical power by conventional steam cycles.

There are four thermodynamic cycles popularly used for waste heat recovery. These include: Trilateral Flash cycle (TFC), Transcritical CO_2 cycle (T-CO_2), Kalina cycle (KC), and Organic Rankine cycle (ORC). In comparison, the Kalina cycle systems are complex, bulky, corrosion-prone, and hence expensive; Transcritical CO_2 power cycles are disadvantaged by the inappropriateness of multi-phase expansion and the complexity of cooling below ambient temperature; while Trilateral Flash cycle's problematic two-phase expansion limits its practical applications.

Organic Rankine cycles (ORCs) are however, characteristically simple-structured, highly reliable, easy to maintain, modify and effectively adapt to various heat sources [56; 57] and may be operated in subcritical or transcritical cycles. The WHR cycles and technologies are described below:

The Kalina Cycle

The Kalina cycle was proposed by Kalina in the early 1980s as a breed of thermodynamic power cycles with a binary working fluid mixture of ammonia and water [58]. Kalina cycles are considered suitable for temperatures between 93ºC and 538ºC are particularly advantaged with better heat absorption in the evaporator and dissipation in the condenser unit compared to ORC and hence are 15 - 25% more efficient than ORC systems [59]. Kalina cycle however, has to maintain unnecessarily high temperature to achieve such heat transfer.

Besides the corrosive potency of the working fluid, Kalina cycle requires additional accessories such an absorber and separator and the turbine needs to be multistage in design or have high rotational speed [60]. All these makes Kalina cycle more complex, expensive and bulkier compared to ORC. Data from practical cycles and simulations under identical conditions of ambient temperature and cooling systems indicates a difference in performance of 3% in favor of Kalina cycle but the Organic Rankine Cycle is very much less complex and require less maintenance [61].

The Transcritical CO_2 Power Cycle

The Transcritical CO_2 power cycles have capacity to generate more power with better efficiencies than ORC but a major hindrance to its application is that at transcritical stage, the properties of the working fluid are not distinctively liquid or gas and as such lack suitable expanders which are multi-phase compatible and unaffected by the small liquid droplets and associated erosion in multi-phase flow. From literature, initial selection of carbon dioxide for investigation as the working fluid for transcritical cycle was primarily based on: first, its low critical pressure which is only a third that of water, allowing lesser operating pressures; second, its stability and inert nature within the operating temperature range of interest, third, there was sufficient information on the properties of carbon dioxide, hence cycle analysis was based on fairly credible data, and lastly, carbon dioxide is richly available, non-toxic and relatively cheap [62].

However, the low critical temperature of carbon dioxide of 31.1°C is a drawback on condensation process as the CO_2 has to be cooled below the critical point, preferably to around 20.8°C, in order to condense. Cooling below the ambient temperature presents practical design complications of the cooling system. Therefore, alternative organic working fluids are widely considered to realize the supercritical Rankine cycle [61].

Trilateral Flash Cycle (TFC)

Trilateral Flash Cycle, TFC is a thermodynamic cycle basically consisting of same components as the Rankine-cycle system but the low boiling point liquid is only heated up at constant pressure to its boiling point (saturated liquid condition) after which it performs a flash expansion through a convergent-divergent (CD) nozzle to deliver power [63]. If the expansion process terminates in the wet region, it is represented in the T-s diagram approximately by a triangle and hence called trilateral cycle. The exhaust mixture from the turbine condenses back to liquid and pumped back to the heat exchanger to repeat the cycle.

Avoiding boiling is beneficial for better temperature matching and reducing irreversibility but the big setback for the technology is the lack of appropriate expanders that can effectively operate with a two phases flow and a high adiabatic efficiency. TFC can extract heat from sources where it is almost impossible for Carnot cycles produce power [64] and have therefore variously been investigated and found prospective technology for further development for low grade temperature sources below 100ºC [58]. However, there is no practical TLC power plant in operation but only a few demonstration units.

Organic Rankine Cycle (ORC)

The ORC is a heat-to-power conversion technology that has been in use since 19th century making use of low-grade temperature sources between 80 to 300°C but the temperature range is now widening due to development of new applications [65]. According to Shu et al., [66] there is possibility of combined thermoelectric generator (TEG) and ORC for WHR from the exhaust of an internal combustion engine. The theoretical analysis however indicates a significant improvement on system performance when the TEG and internal heat exchanger are combined with ORC bottoming.

ORC is a mature, suitable, and commercially available technology in realizing greenhouse gas emission reductions and conservation of the excessively depleting fossil fuel reserve by improving the efficiency of energy use by utilizing low-power and low-temperature heat source. Waste heat sources available for recovery from various industrial processes are capable of effectively powering ORC systems that can deliver output energy scales ranging from about 10 kW to 10MW [67]. However, Wang et al., [68] stated that ORC technology is uneconomical for any application when the heat source temperature is lower than 100ºC.

ORCs are the most prevalent low-grade waste heat recovery cycles popularly used because of their simplicity and readily available components [69]. The advantages of ORC over a steam Rankine cycle become especially evident for low-grade heat sources when appropriate working fluids and operating conditions are selected [70]. According to Abadi et al. [71], ORCs applications are advantageous over the steam Rankine cycle at the lower temperatures because the thermal efficiency of ORCs becomes economically feasible by using low-boiling Organic fluids to recover waste heat at temperatures below 300˚C, especially when used as bottoming cycles for low-temperature waste heat recovery in process industries, enhance the efficiency improvement in a power station generating less than 20 MW, and to recuperate heat from geothermal sources. Another preferential advantage of ORC systems is utilization of organic working fluids that typically require single stage expanders which are simpler and more cost effective as regards capital costs and maintenance [72].

Waste Heat-to-Power (WHP) Technologies

Waste heat-to-power (WHP) is a major application of WHR. The most popular and currently researched WHP technologies that have been proposed for industrial WHR applications are Thermoelectric Generators (TEGs).

Thermoelectric Generators (TEGs)

TEGs are made of Thermoelectric modules (TEM) comprising of n and p-type semiconductors in form thermocouples that are electrically connected in series and thermally connected in parallel. They are used for heat conversion to electricity based on the Seeback effect. One module consists of several hundreds of thermocouples. TEMs are available for a wide range of temperatures up to 1000ºC and above. At over 1000ºC the efficiency is lower than 20% and below 10% at 400ºC [73].

TEGs have good prospects in WHR because of promising attributes such as very simple assembly with no moving parts, hence subject to no noise or vibration, solid state operation without any form of chemical reactions or toxic residuals, which in the overall ensure long life span of reliable, low maintenance operations. They also offer the advantage of small sizes but are however expensive. Producing and promoting uniform performance standards and metrics for measuring thermoelectric materials and devices has been identified as an important factor for broad adoption of thermoelectric electric generators for waste heat recovery units in industrial and manufacturing facilities.

Comparative Studies on the Power Cycles Employed for WHR

Table 3 shows brief comparative studies of few recent studies on the four examined power cycles on their suitability and technical applications for WHP.

Table 3. Comparative studies on the power cycles

S/N	Author(s)	Work	Findings/Remarks
1	Varga & Polotai [74]	Compared the effectiveness of ORC and Kalina cycles for WHR applications.	Recuperator enhanced the achievable power delivered and the efficiency of the ORC at the expense of higher heat exchanger area while increase in ammonia content enhanced the power output and efficiency of the Kalina cycle at the expense of the excessive high pressure. Kalina cycle delivered the higher turbine power, efficiency, and CO_2 reduction potential but no clear merit was established between the alternatives at the levels of the study.
2	Wang et al., [75]	Developed a simulation model to compare the performances of ORC and Kalina cycle for WHR from multi-stream heat sources divided into straight, concave and convex waste heat composite curve	Kalina cycle showed better performance for straight and concave waste heat while ORC is preferable for convex waste heat.
3	Bombarda et al., [76]	Compared thermodynamics performances of Kalina cycle and ORC for waste heat-to-power conversion from diesel engines	Kalina cycle produced higher power output but equal amount of useful power at ten times the maximum pressure in the ORC
4	Lai & Fischer, [77]	Optimized and compared exergy efficiency for power generation for TFC using water, ORC, and conventional steam Rankine cycle	TFC generally exhibited higher power production efficiency but larger volume flows at turbine exit. Alkanes are more suitable than water for working fluids in TFC than water.
5	Fischer, [78]	Made a comparison of optimized TFC systems employing water as the working fluid and optimized ORC systems with pure organic.	Results indicated that the exergy efficiency for power production is larger by 14 to 29% for the TLC systems than for the ORC systems but the flow rates at the exit of the expander are however larger for the TLC than for the ORC by a multiple of 2.8 to as much as 70 for the different cases studied.
6	Li et al., [79]	The authors conducted a thermo-economic analysis and comparison T-CO_2 and an ORC using 4 pure fluids for low temperature geothermal source ranging from 90◦C to 120◦C.	Results indicated that the regenerator essentially enhances the thermodynamic performance of the two power cycles but the maximum net power delivered by regenerative T-CO_2 is only slightly higher than the basic cycle. Additionally, T-CO_2 exhibited a better economic performance than ORC in terms of cost per net power output and under certain turbine inlet pressures.
7	Chen et al., [72]	Investigated the performance of Transcritical CO_2 power in comparison with transcritical ORC using R23	R32 demonstrated higher thermal conductivity and better condensation process than CO_2. Energy and exergy analyses of the 2 transcritical cycles indicated that the R32-based transcritical Rankine cycle can achieve 12.6 to 18.7% higher thermal efficiency while operating at much lower pressures.

Table 3. Comparative studies on the power cycles (Cont.)

S/N	Author(s)	Work	Findings/Remarks
8	Fiaschi et al., [80]	Carried out performances of 3 cycles namely Kalina cycle, Transcritical CO_2 cycle and ORC (ORC utilizing different working fluids) for power generation from two geothermal sources of 212°C and 120°C temperature streams.	KC shows the best performance, being able to produce 22–42% more net power than the ORC and 24 to 34% lower cost of electricity than ORC with different pure working fluids.
9	Yue et al., [81]	Investigated the comparative performance of Kalina cycle using zeotropic mixtures of NH_3–H_2O and the transcritical ORC using alkanes-based working fluids subject to identical operating conditions	Transcritical ORC displayed better performance on the overall heat recovery efficiency, lower operation pressure and simpler system components configuration over Kalina cycles but however was accomplished with much higher expansion ratio in the transcritical ORC and therefore would require complex multi-stage turbine design and big turbine size.

Review of Industrial WHR Applications

The summary of some industrial applications and studies on WHR systems is presented in Table 4.

Table 4. Brief summary of industrial applications and studies on WHR systems

S/N	Author(s)	Application & Research	Results/Recommendations
1	Reis & Gallo, [82]	WHP and waste heat-to-cooling for Floating production storage and off-loading (FPSO) Considered the basic and regenerative ORC for recovery of waste heat from gas turbines in the FPSO platform in order to meet the demand for heat from hot water and as well maximize the electricity production	It was established that WHR was capable of sufficiently meeting the heat demand and as well contribute as much as 21% of the electricity demand on the FSPO platform. The overall efficiency and the utilization factor of the system were enhance by 10.8% and 19.2%, respectively, leading to about 22.5% reduction in both the fuel consumption and CO_2 emissions over the lifetime of the FPSO. Economic analysis showed possibility of US$12.55 million return on investment.
2	Varga & Palotai, [84]	WHP for Chemical industry Compared the suitability of various configurations of ORC and Kalina cycle for recovering waste heat streams from an air cooler for cooling hydrocarbon from 130ºC to 70ºC and discharging 12.1MW heat into the environment.	Results indicated that the heat energy recovered were 8-8.6MW for ORC and 8.2- 8.3MW for Kalina cycle. CO_2 saving potentials were 2200, 2260 and 2600 t/y for BORC, RORC, and Kalina cycle respectively. They could not reach a clear decision on the alternatives at the present level of details of the study. Necessitated detailed design and also to extend the methodology to other process industry.

Table 4. Brief Summary of industrial applications and studies on WHR systems (Cont.)

S/N	Author(s)	Application & Research	Results/Recommendations
3	Huang & Li, [6]	WHP for Coal-fired power plant. Proposed an improved energy saving system for a plant that can generate a net additional from a typical 1000MW coal-fired power plant in China.	Economizer is conventionally placed downstream of the air preheater in exhaust gas duct. Instead, air preheating is achieved by waste heat from boiler and turbine exhaust High energy flue gas can therefore be used for feed water heating reducing the amount of high water steam extraction, leading to more power generation. Exergy efficiency increased to from 44.80% to 45.46%, net power output increased by more than 3 times (5.83MW to 19.51MW), and net annual revenue from USD 1.244 to USD 4.741 million. Techno-economic analysis is much in favour of the improved WHR system.
4	Panayiotou et al., [43]	The authors outlined the prospects and the potential for industrial heat recovery in the European Union. Identified and quantified primary energy consumption in the major industrial sectors and their related waste heat streams and temperature levels.	Industrial processes consumes 26% of EU primary energy demand (275 Mtoe/yr), mostly fueled by fossil fuels. Results showed the availability of a rather significant potential amounting to 370.41 TWh (Waste heat) or 173.99 TWH Their next phase is to perform a more detailed and more comprehensive analysis that will extend the results presented in the work.
5	Singh & Pedersen, [38]	Reviewed WHR technologies for maritime applications. 1. Rankine cycle Steam/conventional Rankine cycle (SRC) Organic Rankine cycle (ORC) Super-critical Rankine cycle (SCRC) 2. Kalina cycle (KC) 3. Exhaust gas turbine system Hybrid turbocharger Mechanical turbo-compound system Hydraulic turbo-compound system Electrical turbo-compound system 4. Thermoelectric generation systems	Stated that 50% of total energy supplied to power the vessels which are mostly diesel engine are lost as thermal pollutant (100-500ºC) between 2007-2012 It accounts for 2.8 % of GHG equivalent to1 billion tons of GHG annually, along with 15% NO_X and 13% SO_X annual global emissions. Appropriate WHR system that can exploit the residual wasted heat for generating mechanical/electrical power that can be further used for propulsion and auxiliary services at no extra fuel costs and zero associated CO_2 emissions.
6	Peris et al., [83]	WHP for Ceramic industry The authors investigated an experimental application of an ORC (using thermal loop) in a ceramic industry for low grade WHR.	A final energy production above 115 MWh was obtained, saving about 237 MWh of primary energy and cutting down 31 t/y of CO_2 emission to the atmosphere. The payback was 4.63 years.

Table 4. Brief summary of industrial applications and studies on WHR systems (Cont.)

S/N	Author(s)	Application & Research	Results/Recommendations
7	Thermax, [84]	Waste heat-to-cooling for Food Products & Beverages processing industry in Nigeria Thermax Profetherm installed a 660 TR (2317 kW) exhaust gas driven absorption chillers for Cadbury, a Beverage Processing company, Nigeria. The absorption chiller provides process cooling and air conditioning from a 3.7 MW gas-fired engine.	The installation achieves 2400 tons CO_2 reduction yearly which is said to be equivalent to planting of 129,514 trees per annum, It also provides considerable savings in energy consumption and in operational costs.
8	Brueckner et al., [42]	The authors presented and categorized waste heat potentials of different regions in Europe according to the *study scale*, *data collection* and *chosen approach.*	Because different countries have different data bases, there is no possibility of a direct comparison of the different methods but in general, the resulting waste heat potential was concluded to range between 5 and 30% of the energy demand of the industrial sector of a region. The author suggested a clear distinction between theoretical, technical and economic potentials of WHR and decried lack of data as a huge hindrance to the qualification and utilization of waste heat in industry.
9	Tan et al., [85]	WHP & Carbon Capture and Storage (CCS) in Cement Plant Investigated 3 options of waste heat utilization in the plant, namely: 1, power generation from high temperature and low temperature steam in the suspension preheater and air quenching cooler respectively, 2, CCS 3, power generation combined with CCS	They are all effective means of waste heat utilization but carbon credit determine the optimal option and best economic performance.

Table 4. Brief summary of industrial applications and studies on WHR systems (Cont.)

S/N	Author(s)	Application & Research	Results/Recommendations
10	Berthou & Bory, [86]	Evaluated the quantity of waste heat in the manufacturing industry in France for year 2009. Heat availability was based on 3 × 8 hrs a day work by most of the industry, although equipment do not operate at full loads all the time. Heat storage facilities are often required.	Industry consumes 423 TWh which represents 25% of national energy consumption. Waste heat from industry with the largest potential was assessed at 100 TWh for a temperature range between 40 and 250ºC. From roughly 70 % (300 TWh) of energy consumed, assessments showed that 109 TWh of waste heat could be technically Recommended 3 methods of low-temperature utilization as appropriate: 1.Reduce waste heat at the source by improving the process, 2. Reuse waste heat inside the factory into the same or different energy uses with heat exchangers and storage or raised via a heat pump, 3. Reuse outside the factory for district heating, to produce electricity with an ORC or to couple with a factory using low temperature for its process such as food, fine chemical and paper.
11	Mckenna & Norman, [87]	The authors classified heat users in UK into broad temperature groups, quantified heat usage and wastage at different temperatures by way of energetic and exergetic analysis methods. They went further to estimate the technical potential for heat recovery based on current technologies.	Around 60% of industry and 90% of energy-intensive sectors were covered and the total annual heat use for these sectors was estimated at 650 PJ. Technically feasible annual savings in the region was put at 36–71 PJ.
12	Li [88]	WHP for Gas turbine power plants & Waste incineration plants, Waste cold from LNG regasification process in Singapore to meet the cooling energy demand which is mostly met by electrically driven devices. Business-As-Usual (BAU) and District Cooling (DC) scenarios were developed and modeled for the year 2030 and 2050 to assess the potential and investigate the impact of district cooling on the energy system of Singapore.	Results indicated that CO_2 emissions could be reduced by 11.5% and 9.9% in years 2030 and 2050 compared to the BAU scenario. Primary energy demand could also be reduced by 12.2% and 10.2%, while total socio-economic costs could be 4.6% and 3.8% lower.

Economic and Environmental Benefits of Waste Heat Recovery (WHR)

Many major industrial processes are highly energy intensive and the ability to recover waste heat for power generation can give a significant advantage in terms of reduced energy usage and emission GHGs to the environment. In addition, effective energy recovery systems support the general drive for sustainability and improved energy-efficiency [89].

The two-arm benefit obtainable from WHR are economic and environment benefits. The economic benefits of waste heat recovery borders on the significant improvement on energy utilization efficiency of power and industrial process plants which yields appreciable cost savings on fuel while the environmental benefits anchors more on significant reduction in the depletion rate of the finite resource, and as well in thermal, CO_2 and other toxic pollutants to within tolerable limits and hence, promoting sustainability. Hence, waste heat is a resource exploitable by a number of available sustainable technologies. Slight increasing in efficiencies of high capacity plants such as industrial and power plants have a remarkable impact on emissions reductions and on fuel consumption. It was reported that efficiency improvement of +0.1% for large combustion power plants results in 1,000 to 1,500 tons of reduced CO_2 emissions per year [90]. Typical benefits of implementation of some WHR technologies are outlined in Table 5.

Table 5. Benefits of implementation of selected WHR technologies

S/N	Application	Fuel Reduction (%)	Performance Enhancement
1	Cogeneration using ORC, Kalina Cycle or transcritical CO_2 cycle [91]	15-35	Up to 80% electrical efficiency
2	Combined cycle heat recovery generator in regenerative Gas turbine power plant [63]	Not available	More than 65%
3	CO_2 sequestration	At no additional fuel	More ecofriendly
4	Desalination system for steam power plants [18]	Up to 1844kh/h on a 47MW steam turbine	Not applicable
5	Regenerative combined TEG-ORC system [66]	Not available	Efficiency increases from 41 to 45.71%

Barriers to Development & Implementation of Waste Heat Recovery Systems

Despite the huge potentials for WHR technologies, barriers to effective industrial implementation of WHP systems was identified by Elson & Hampson [32] include technical issues, business considerations, and regulatory issues, which are often interrelated to each other and hence require different tradeoffs regarding either the profitability or efficiency of WHR options [41]. These barriers include:

Techno economic barriers

- Fluctuating and/or intermittent nature of the waste heat source.
- Peculiarity of each waste heat source- temperature, contaminants, etc.
- Lack of relevant information and data
- Lack of sufficient technical skill and experience on the technologies globally
- Cost and complexity for incorporating WHR system to existing process controls
- Location of end users of the energy (on-site or off-site)
- Competition with renewable energy (RE) options

Business barriers

- Reluctance on making investments that do not raise production and revenues
- Perceived high risk and uncertainty of the project
- Long payback periods and expectations of too high rate of return

- Securing financing for WHP projects
- Lack of awareness on the prospects and benefits of the technologies

Policy and regulatory barriers

- Lack of viable incentives for WHR technologies
- Lack of internalization of relevant global policies by individual nations

Economic considerations relating to cost of equipment and the forecasted energy savings are hence the primary determinant of the possibility of effective WHP applications. However, regulations and policies have a significant effect on project economics. The main hindrance to the advancement of industrial waste heat utilization for power generation and process industries is the lack of adequate experience with prospecting, design and operation of the diverse plants in the industries with potential resources [92], especially in developing countries.

Possible Solutions to Development and Utilization of WHR Systems

The possible solutions to the development and utilization of WHR system in pursuit of global sustainable energy development are highlighted below:

- Increased research on development and application of WHR systems
- Creating incentives and loan facilitation for WHR systems implementation
- Internalization of policies that will enforce global best practices on efficient use of energy in industrial and power sectors in all nations
- Creating global public awareness and confidence in sustainable technologies
- Technology transfer from advance nations to developing nations

Waste Heat Recovery Technologies and Sustainable Energy Development

Different words have been used in defining sustainable energy in different literatures which sometimes tends to compromise or overstretch the concept of sustainability. Sustainability certainly implies “must be maintained long enough without disruption or weakening and must be practicable” but not necessarily without ever ending. Hence, Vidadili et al., [93] proposed a definition of sustainable energy as “production, conservation and use of energy sources in ways that promote or at least are suitable with long-term human well-being and ecological balance.” The concept of sustainability is thus an equitable, trilateral relationship between energy, environment and economy.

Factually, the energy sector is presently characterized by high uncertainty on the feasible direction in both the short and long term run sequence to the fast depletion rate with the associated ecological hazards of the utilization of the limited fossil sources, the technological and economic barriers of the RE sources, couple with the hypothesis of shale gas being a promising bridge to RE sources to prolong the lifespan of the finite energy sources [94]. However, the level of development of RE sources constitutes only 14 % of the total world energy demand [91] and grows at an average of 2.6%/yr [95], the transition to such facilities have been shown to be insufficiently to meet the projections of future energy demands. Moreover, convincing arguments require that more than 50% of the existing non-renewable energy reserves, especially coal, the cheapest and most abundant of all fossils will have to be left untapped to combat climate change [16].

The topical climate change agreement in Paris however demands that global temperature rise for this century is kept well below 2ºC, preferably 1.5ºC but for this to be achieved, based on world population projections, there has to be a significant reduction in fossil fuel consumption before mid-century if global warming is to be limited to less than 2°C [16]. In order to achieve the goals, the United Nation 2015 population projections will require 37-fold of RE contribution of the 2014 level of $13x10^{18}$J by 2028, and based on the quantitative projected peak of non-renewable energy resources, will require 75 to 81 times by 2100 regardless of even the climate goals.

Nevertheless, the Paris agreement inherently identified sustainable technology as a key pathway to aggressively decarbonize the energy economy, especially for the generation of environmentally-friendly electrical energy and went further to initiate a framework to support developing nations and the most vulnerable nations to pursue the goals for a sustainable environment. Therefore, attaining a reliable, sustainable and low-carbon path especially for the industrial and power sectors is critical to sustainable energy development.

China is the biggest consumer of energy and emitter of CO_2 in the world [96], and the CO_2 emissions of China are still increasing fast [97]. Despite the current global resolve to transit to RE sources, the economy of China which is the fastest growing economy in the world, put at average of 7% annually, is powered by less expensive fossil fuel-coal [98]. Amri, [99] in a research explored the interconnection between economic growth and energy consumption in Algeria which is a nation with substantial fossil fuel reserves, between the period of 1980 and 2012. The research indicated that only the non-renewable energy sort and capital could initiate significant economic growth while RE demonstrated only a trivial effect.

Some nations that produce fossil fuel such as Pakistan and Nigeria presently depend largely on the resource to meet their energy needs and of which the current trend of unsustainable deployment of the resources would rapidly exhaust the known reserves of such countries in few years [100]. Some of the critical questions raised by Cash & McCormack [101] on the choice of the path to the clean energy future were on how fast enough and equitable the transition to the full deployment of RE sources and hence suggested a path in line with the focus of this study. With the current rate of development and deployment of RE energy sources in the world, it is however unlikely to leave about 50% of non-renewable energy sources unexploited, especially by developing nations but rather many nations would choose the path to effectively utilize sustainable technologies to prolong the lifecycle of the resources with the possibility of discovery of more reserves and unpredictable technological innovation like fracking (for shale gas extraction) on the other hand. Global proved oil reserves however rose in 2016 by 0.9% and are expected to last 50.6 years of global production at the 2016 levels [7, 102].

WHR technologies are effective sustainable technologies which have gained remarkable interest in recent years with widespread acceptance and some attaining commercial applications. It is an especially attractive option of effectively increasing the overall efficiency of thermal and process plants, reducing cost and consumption of fuel, as well as the toxic emissions to tolerable limits as to meet sustainable energy development goals [103 – 104]. Waste heat resources are currently being underutilized globally with Canada taking the lead in waste heat utilization. Table 6 shows industrial waste heat per energy consumed by the industry along with energy consumed by the country.

Table 6. Industrial waste heat per energy consumed by the industry and industrial waste heat per energy consumed by the industry ratios

Selected Country	Industrial Waste Heat per Energy Consumed by Industry (%)	Industrial Waste Heat per Energy Consumed by the Country (%)
Japan	1.0	0.4
Latvia	3.0	0.6
US	4.0-4.2	1.5
Sweden	5.5-18.4	2.0-6.7
UK	5.5-21.3	1.1-4.2
Slovenia	7.3	1.9
Korea	8.0	4.7
EU	9.1-22.2	2.3-5.6
Estonia	11.9	2.5
Denmark	12.9	2.0
Luxembourg	13.6	2.2
Norway	15.4	5.7
Ireland	16.3	2.6
Finland	16.9	7.4
Czech Republic	17.4	6.0
Germany	18.8-20.7	5.2-5.8
France	19.9-26.0	5.0-6.5
Austria	20.4	6.4

Table 6. Industrial waste heat per energy consumed by the industry and industrial waste heat per energy consumed by the industry ratios (Cont.)

Selected Country	Industrial Waste Heat per Energy Consumed by Industry (%)	Industrial Waste Heat per Energy Consumed by the Country (%)
Bulgaria	21.0	6.0
Hungary	22.2	3.9
Spain	23.1	6.0
Poland	23.1	5.4
Portugal	23.4	7.0
Italy	24.2	6.0
Belgium	24.5	7.5
Romania	26.0	8.0
Netherlands	26.7	7.1
Slovak Republic	27.7	10.5
Greece	38.2	7.0
Turkey	46.9	17.4
Cyprus	47.8	5.0
Lithuania	55.7	10.4
Canada	71.0	26.4

CONCLUSION

In this study, various WHR technologies have been considered and found where applicable to be the most suitable option to achieve sustainable energy development through more efficient use of fossil based fuels. As established, in-depth utilization of the waste heat resources through deployment of appropriate technologies can result in substantial economic and environmental benefits resulting from decrease in the primary energy demand, CO_2 emissions reduction, and economic gains.

It is evidently clear that there are abundant resources of fossil fuels as well as the waste heat resources generated from them that can be effectively utilized to meet the energy demand of the world at no detriment to sustainable development till the militating factors limiting the full exploitation of renewable energy resources is achievable in all regions of the world. The major challenges are more of business considerations and regulatory issues than technical issues. As a result, there is the urgent need to put policies in place that will encourage favourable business considerations. In such a manner, this will lead to more exploitation of WHR that will increasingly lead to sustainable development. Based on the advantages that WHR systems operate at no additional fuel input, require minimal maintenance and from literature reviewed, their payback period is always less than seven years, it is essential to carry out a comprehensive research into the proposed optimum energy utilization of some selected nations in every region of the world in order to estimate the expected lifespan of the proven reserves of the limited fossil resources and as well, the stability of the ecosystem. This would further substantiate the need for the full deployment of the various relevant WHR technologies for sustainable development.

REFERENCES

[1] Lee, C. E., Yu, B., & Lee, S An analysis of the thermodynamic efficiency for exhaust gas recirculation-condensed water recirculation-waste heat recovery condensing boilers (EGR-CWR-WHR CB). Energy, 86, 2015; 267–275. https://doi.org/10.1016/j.energy.2015.04.042

[2] Langan, M., & O'Toole, K A new technology for cost effective low grade waste heat recovery. Energy Procedia, 2017; 123, 188–195. https://doi.org/10.1016/j.egypro.2017.07.261

[3] Lecompte, S., Huisseune, H., van den Broek, M., De Schampheleire, S., & De Paepe, M. Part load based thermo-economic optimization of the Organic Rankine Cycle (ORC) applied to a combined heat and power (CHP) system. Applied Energy, 2013; 111, 871–881. https://doi.org/10.1016/j.apenergy.2013.06.043

[4] Dong, B., Xu, G., Li, T., Luo, X., & Quan, Y. Parametric analysis of organic Rankine cycle based on a radial turbine for low-grade waste heat recovery. Applied Thermal Engineering, 2017; 126, 470–479. https://doi.org/10.1016/j.applthermaleng.2017.07.046
[5] Quoilin, S. Sustainable energy conversion through the use of Organic Rankine Cycles for waste heat recovery and solar applications, 2011; 1–183. Retrieved from http://orbi.ulg.ac.be/handle/2268/96436
[6] Huang, F., Zheng, J., Baleynaud, J. M., & Lu, J. Heat recovery potentials and technologies in industrial zones. Journal of the Energy Institute, 2017; 90(6), 951–961. https://doi.org/10.1016/j.joei.2016.07.012
[7] BP. BP Statistical Review of World Energy 2017. British Petroleum, 2017; (66), 1–52. Retrieved from http://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-full-report.pdf
[8] World Energy Resources (WER) | 2016; https://doi.org/http://www.worldenergy.org/wp-content/uploads/2013/09/Complete_WER_2013_Survey.pdf
[9] U.S. Department of Energy, & Energy, U. S. D. of. 2012. Low-Grade Waste Steam to Power Absorption Chillers, Steap Tip Sheet #14.
[10] Olivier, J. G. J., Muntean, M., & Peters, J. A. H. W. Trends in global CO2 emissions: 2015 report. PBL Netherlands Environmental Assessment Agency & European Commission’s Joint Research Centre (JRC), 2015; 1–78.
[11] Chen, S., Guo, Z., Liu, P., & Li, Z. Advances in clean and low-carbon power generation planning. Computers and Chemical Engineering, 2018; 0, 1–10. https://doi.org/10.1016/j.compchemeng.2018.02.012
[12] Ritchie, H and Roser, M Fossil Fuels. Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/fossil-fuels [Online Resource], 2018
[13] Cash, D. W., & McCormack, J. W. Choices on the road to the clean energy future. Energy Research and Social Science, 2017; 1–3. https://doi.org/10.1016/j.erss.2017.10.035
[14] Sathaye, J., Lucon, O., & Rahman, A. Renewable energy in the context of sustainable development. IPCC Special Report on, 2011; 707–790. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Renewable+Energy+in+the+Context+of+Sustainable+Development#0
[15] Rahbar, K., Mahmoud, S., Al-Dadah, R. K., Moazami, N., & Ashmore, D. Feasibility study of power generation through waste heat recovery of wood burning stove using the ORC technology. Sustainable Cities and Society, 2017;.. https://doi.org/10.1016/j.scs.2017.09.013
[16] Warner, K. J., & Jones, G. A. A population-induced renewable energy timeline in nine world regions. Energy Policy, 2017; 101, 65–76. https://doi.org/10.1016/j.enpol.2016.11.031
[17] Mohr, S. H., Wang, J., Ellem, G., Ward, J., & Giurco, D. Projection of world fossil fuels by country. Fuel, 2015; 141, 120–135. https://doi.org/10.1016/j.fuel.2014.10.030
[18] Miró, L., Gasia, J., & Cabeza, L. F. Thermal energy storage (TES) for industrial waste heat (IWH) recovery : A review, 2016; 179, 284–301, https://doi.org/10.1016/j.apenergy.2016.06.147
[19] Hussam J, Navid K, Sulaiman A, Bertrand D, Amisha C and Savvas A. T. Waste heat recovery technologies and applications, Thermal Science and Engineering Progress, 2018; 6, 268 – 289
[20] Legros A, Guillaume L, Diny M, Zaïdi H and Lemort V. ‘Comparison and Impact of Waste Heat Recovery Technologies on Passenger Car Fuel Consumption in a Normalized Driving Cycle’, Energies, 2014; 7, 5273-5290; doi:10.3390/en7085273
[21] Alessandro S, Yang L, Elliot W, Shahin R and Claudio B ‘A decision support system for waste heat recovery in manufacturing’, CIRP Annals - Manufacturing Technology, 2016; 65: 21–24
[22] Elliot W, Yang L and Alessandro S ‘Industrial waste heat recovery: A systematic approach’, Sustainable Energy Technologies and Assessments, 2018; 29:50 – 59
[23] Clemens F, Ibrahim K. M, Robert P and Bernd M (2016), ‘Estimating the global waste heat potential’, Renewable and Sustainable Energy Reviews, 2016; 57:1568–1579
[24] Shengwei H, Chengzhou L , Tianyu T, Peng F, Gang X and Yongping Y ‘An Improved System for Utilizing Low-Temperature Waste Heat of Flue Gas from Coal-Fired Power Plants’, Entropy, 2017; 19, 423: 1 – 17.
[25] Alison A, Arganthae B and Simon H Organic Rankine cycles in waste heat recovery: a comparative study’, International Journal of Low-Carbon Technologies, 2013; 8, i9–i18
[26] Simone L, Constantine N. M, Ioannis V and Rodolfo T ‘A thermodynamic feasibility study of an Organic Rankine Cycle (ORC) for heavy-duty diesel engine waste heat recovery in off-highway applications’, International Journal of Energy Environment and Engineering, 2017; 8:81– 98
[27] Fakeye, B.A and Oyedepo, S.O ‘A Review of Working Fluids for Organic Rankine Cycle (ORC) Applications’, IOP Conf. Series: Materials Science and Engineering, 2018; 413 (2018) 012019 doi:10.1088/1757-

899X/413/1/012019

[28] Karimi, M.N, Dutta, A, Kaushik, A, Bansal, H and Haque, S.Z 'A Review of Organic Rankine, Kalina and Goswami Cycle', International Journal of Engineering Technology, Management and Applied Sciences, 2015; 3, 90 – 105, www.ijetmas.com

[29] Arash N, Hossein N, Faramarz R and Mortaza Y, 'A comparative thermodynamic analysis of ORC and Kalina cycles for waste heat recovery: A case study for CGAM cogeneration system', Case Studies in Thermal Engineering, 2017; 9: 1–13

[30] Zare, V and Mahmoudi, S.M.S, 'A thermodynamic comparison between organic Rankine and Kalina cycles for waste heat recovery from the Gas Turbine-Modular Helium Reactor', Energy, 2015; 79: 398 – 406

[31] Upathumchard, U. Waste Heat Recovery Options in a Large Gas- Turbine Combined Power Plant Waste Heat Recovery Options in a Large Gas-Turbine Combined Power Plant, 2014.

[32] Elson, A., & Hampson, A. Waste Heat to Power Market Assessment, 2015.

[33] Kandathil, A. K. A Guide to working fluid selection for Organic Rankine Cycle ORC generators. Genixx, HEATCATCHER. Retrieved from http://www.heatcatcher.com/guide-working-fluid-selection-organic-rankine-cycle-orc-generators/ , 2016

[34] Pulat, E, Etemoglu, A.B and Can, M, 'Waste-heat recovery potential in Turkish textile industry: Case study for city of Bursa', Renewable and Sustainable Energy Reviews, 2009; 13: 663–672

[35] O'Rielly, K and Jeswiet, J (2015), 'Improving Industrial Energy Efficiency through the Implementation of Waste Heat Recovery Systems', Transactions of the Canadian Society for Mechanical Engineering, 2015; 39, 1: 125 – 136

[36] Campana, F., Bianchi, M., Branchini, L., De Pascale, A., Peretto, A., Baresi, M., Fermi, A., Rosetti, N., Vescovo, R. "ORC waste heat recovery in European energy intensive industries: Energy & GHG savings", Energy Conversion and Management, 2013; 76, 244 – 252.

[37] Xu, Z.Y, Mao, H.C, Liu, D.S and Wang, R.Z 'Waste heat recovery of power plant with large scale serial absorption heat pumps', Energy, 2018; 165: 1097 – 1105

[38] Singh, D.V and Pedersen, E (2016), 'A review of waste heat recovery technologies for maritime applications', Energy Conversion and Management, 2016; 111: 315–328

[39] Brückner, S., Liu, S., Miró, L., Radspieler, M., Cabeza, L. F., & Lävemann, E. Industrial waste heat recovery technologies : An economic analysis of heat transformation technologies, 2015; 151, 157–167. https://doi.org/10.1016/j.apenergy.2015.01.147

[40] Fakeye A.B, Feasibility Study of Power Conversion of Exhaust Waste Heat Recovery from Gas Turbine Power Plant Using Organic Rankine Cycles (ORC), M.Eng Dissertation, Department of Mechanical Engineering, Covenant University, 2018; pp 147

[41] Kurle, D., Schulze, C., Herrmann, C., & Thiede, S. Unlocking waste heat potentials in manufacturing, 2016; 48, 289–294. https://doi.org/10.1016/j.procir.2016.03.107

[42] Brueckner, S., Miró, L., Cabeza, L. F., Pehnt, M., & Laevemann, E. Methods to estimate the industrial waste heat potential of regions – A categorization and literature review, 2014; 38, 164–171. https://doi.org/10.1016/j.rser.2014.04.078

[43] Panayiotou, P., Bianchi, G., Georgiou, G., Aresti, L., Argyrou, M., Agathokleous, R., … Christodoulides, P. Preliminary assessment of waste potential District heat in major European industries Assessing the feasibility of using the heat demand-outdoor , Lazaros forecast temperature function for a district heat demand, 2017; https://doi.org/10.1016/j.egypro.2017.07.263

[44] Hussam J, Navid K, Sulaiman A, Bertrand D, Amisha C, Savvas A. T 'Waste heat recovery technologies and applications', Thermal Science and Engineering Progress, 2018; 6: 268 – 289

[45] Zhang, X., Wu, L., Wang, X., & Ju, G. Comparative study of waste heat steam SRC, ORC and S-ORC power generation systems in medium-low temperature. Applied Thermal Engineering, 2016;106, 1427–1439. https://doi.org/10.1016/j.applthermaleng.2016.06.108

[46] Incorporated, B.. Waste Heat Recovery: Technology Opportunities in the US Industry. Waste Heat Recovery: Technology Opportunities in the US Industry, 2008; 1–112. https://doi.org/10.1017/CBO9781107415324.004

[47] Date, A., Alam, F., Khaghani, A., & Akbarzadeh, A. Investigate the potential of using trilateral flash cycle for combined desalination and power generation integrated with salinity gradient solar ponds. Procedia Engineering, 2012;49, 42–49. https://doi.org/10.1016/j.proeng.2012.10.110

[48] Bianchi, G., Mcginty, R., Oliver, D., Brightman, D., Zaher, O., Tassou, S. A. and Jouhara, H.. Development and analysis of a packaged Trilateral Flash Cycle system for low grade heat to power conversion applications. Thermal Science and Engineering Progress, 2017; 4, 113–121. https://doi.org/10.1016/j.tsep.2017.09.009

[49] Donnellan, P, Development of a triple stage heat transformer for the recycling of low temperature heat energy,

PhD Thesis, National University of Ireland, Cork, 2014; pp 260
[50] Jouhara, H, Chauhan, A, Nannou, T, Almahmoud, S, Delpech, B and Wrobel, L.C, 'Heat pipe based systems - Advances and applications', Energy 2017; 128:729 – 754
[51] Srimuang, W and Amatachaya, P, 'A review of the applications of heat pipe heat exchangers for heat recovery', Renewable and Sustainable Energy Reviews, 2012; 16: 4303– 4315
[52] Chandrakishor L. L, A Critical Review - Optimization of Heat Pipe, International Journal of Engineering Research & Technology (IJERT), IC-QUEST - 2016 Conference Proceedings (Special Issue – 2016), 2016; 4, 30, pp 1 – 7.
[53] Xu, Q, Riffat, S and Zhang, S (2019), Review of Heat Recovery Technologies for Building Applications, Energies, 12, 1285; 1 – 22, doi:10.3390/en12071285
[54] Thornley, P., and Walsh, C. Addressing the barriers to utilisation of low grade heat from the thermal process industries, 2010
[55] Ramakrishnan, S., and Edwards, C. F. Maximum-efficiency architectures for heat- and work-regenerative gas turbine engines. Energy, 2016; 100, 115–128. https://doi.org/10.1016/j.energy.2016.01.044
[56] Bao, J., and Zhao, L. A review of working fluid and expander selections for organic Rankine cycle. Renewable and Sustainable Energy Reviews, 2013; 24, 325–342. https://doi.org/10.1016/j.rser.2013.03.040
[57] Feng, Y., Hung, T. C., Zhang, Y., Li, B., Yang, J., & Shi, Y. Performance comparison of low-grade ORCs (organic Rankine cycles) using R245fa, pentane and their mixtures based on the thermoeconomic multi-objective optimization and decision makings. Energy, 2015; 93, 2018–2029. https://doi.org/10.1016/j.energy.2015.10.065
[58] Zoltan Varga, B. P. Comparison of low temperature waste heat recovery methods Zolt a, 2017; 137, 1286–1292. https://doi.org/10.1016/j.energy.2017.07.003
[59] Zeb, K., Ali, S. M., Khan, B., Mehmood, C. A., Tareen, N., Din, W., … Haider, A. A survey on waste heat recovery: Electric power generation and potential prospects within Pakistan. Renewable and Sustainable Energy Reviews, 75(July 2016), 2017; 1142–1155. https://doi.org/10.1016/j.rser.2016.11.096
[60] Division, S. S and Beach, N. The Supercritical Thermodynamic Power Cycle, 1968.
[61] Dhar, H., Kumar, S., & Kumar, R. A review on organic waste to energy systems in India. Bioresource Technology, 2017;. https://doi.org/10.1016/j.biortech.2017.08.159
[62] Langan, M and O'Toole, K, 'A new technology for cost effective low grade waste heat recovery', 1st International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF 2017, 19-20 April 2017, Berkshire, UK, Energy Procedia, 2017; 123: 188–195
[63] Iqbal, M. A., Ahmadi, M., Melhem, F., Rana, S., Akbarzadeh, A., & Date, A.. Power Generation from Low Grade Heat Using Trilateral Flash Cycle. Energy Procedia, 2017; 110, 492–497. https://doi.org/10.1016/j.egypro.2017.03.174
[64] Iglesias, S., Ferreiro, R., Carbia, J., & Iglesias, D. Critical review of the first-law efficiency in different power combined cycle architectures. Energy Conversion and Management, 2017; 148, 844–859. https://doi.org/10.1016/j.enconman.2017.06.037
[65] Landelle, A., Tauveron, N., Revellin, R., Haberschill, P., & Colasson, S.. Experimental Investigation of a Transcritical Organic Rankine Cycle with Scroll Expander for Low—Temperature Waste Heat Recovery. Energy Procedia, 2017;129, 810–817. https://doi.org/10.1016/j.egypro.2017.09.142
[66] Shu, G., Zhao, J., Tian, H., Liang, X., and Wei, H.. Parametric and exergetic analysis of waste heat recovery system based on thermoelectric generator and organic rankine cycle utilizing R123. Energy, 2012; 45(1), 806–816. https://doi.org/10.1016/j.energy.2012.07.010
[67] Auld, A., Berson, A., and Hogg, S. Organic rankine cycles in waste heat recovery: A comparative study. International Journal of Low-Carbon Technologies, 2013;8, 9–18. https://doi.org/10.1093/ijlct/ctt033
[68] Wang, Z. Q., Zhou, N. J., Guo, J., and Wang, X. Y.. Fluid selection and parametric optimization of organic Rankine cycle using low temperature waste heat. Energy, 2012; 40(1), 107–115. https://doi.org/10.1016/j.energy.2012.02.022
[69] Ziviani, D., Beyene, A., and Venturini, M.. Advances and challenges in ORC systems modeling for low grade thermal energy recovery. Applied Energy, 2014; 121, 79–95. https://doi.org/10.1016/j.apenergy.2014.01.074
[70] Jones, G. A., and Warner, K. J..The 21st century population-energy-climate nexus. Energy Policy, 2016;93, 206–212. https://doi.org/10.1016/j.enpol.2016.02.044
[71] Abadi, M, Payam H, Behrooz Khezri, A. R. Investigation Of Using Different Fluids For Using In Gas Turbine-Rankine Cycle, 2014; 1(2), 74–81.
[72] Chen, H., Yogi Goswami, D., Rahman, M. M., & Stefanakos, E. K. Energetic and exergetic analysis of CO2- and R32-based transcritical Rankine cycles for low-grade heat conversion. Applied Energy, 82011; 8(8), 2802–

2808. https://doi.org/10.1016/j.apenergy.2011.01.029
[73] Bendig, M. Integration of Organic Rankine Cycles for Waste Heat Recovery in Industrial Processes PAR, 2015; 6536.
[74] Varga, Z., & Palotai, B. Comparison of low temperature waste heat recovery methods. Energy, 2017;. https://doi.org/10.1016/j.energy.2017.07.003
[75] Wang, Y., Tang, Q., Wang, M., & Feng, X.. Thermodynamic performance comparison between ORC and Kalina cycles for multi-stream waste heat recovery. Energy Conversion and Management, 2017;143, 482–492 https://doi.org/10.1016/j.enconman.2017.04.026
[76] Bombarda, P., Invernizzi, C. M., & Pietra, C. Heat recovery from Diesel engines: A thermodynamic comparison between Kalina and ORC cycles. Applied Thermal Engineering, 2010; 30(2–3), 212–219. https://doi.org/10.1016/j.applthermaleng.2009.08.006
[77] Lai, N. A., & Fischer, J. Efficiencies of power flash cycles. Energy, 2012; 44(1), 1017–1027. https://doi.org/10.1016/j.energy.2012.04.046
[78] Fischer, J. Comparison of trilateral cycles and organic Rankine cycles. Energy, 2011; 36(10), 6208–6219. https://doi.org/10.1016/j.energy.2011.07.041
[79] Li, M., Wang, J., Li, S., Wang, X., He, W., & Dai, Y.. Thermo-economic analysis and comparison of a CO2 transcritical power cycle and an organic Rankine cycle. Geothermics, 2014; 50, 101–111. https://doi.org/10.1016/j.geothermics.2013.09.005
[80] Fiaschi, D., Manfrida, G., Rogai, E., & Talluri, L. Exergoeconomic analysis and comparison between ORC and Kalina cycles to exploit low and medium-high temperature heat from two different geothermal sites. Energy Conversion and Management, 2017;154, 503–516. https://doi.org/10.1016/j.enconman.2017.11.034
[81] Yue, C., Han, D., Pu, W., & He, W. Comparative analysis of a bottoming transcritical ORC and a Kalina cycle for engine exhaust heat recovery. Energy Conversion and Management, 2015;89, 764–774. https://doi.org/10.1016/j.enconman.2014.10.029
[82] Reis, M. M. L., and Gallo, W. L. R. Study of waste heat recovery potential and optimization of the power production by an organic Rankine cycle in an FPSO unit. Energy Conversion and Management, 157, 2018; 409–422. https://doi.org/10.1016/j.enconman.2017.12.015
[83] Peris, B., Navarro-Esbrí, J., Molés, F., & Mota-Babiloni, A. Experimental study of an ORC (organic Rankine cycle) for low grade waste heat recovery in a ceramic industry. Energy, 2015; 85, 534–542. https://doi.org/10.1016/j.energy.2015.03.065
[84] Thermax. Waste heat recovery for chocolate cooling at a leading confectionery company, 2015
[85] Tan, Y., Li, X., Zhao, L., Li, H., Yan, J., & Yu, Z.. Study on Utilization of Waste Heat in Cement Plant. Energy Procedia, 2014; 61, 455–458. https://doi.org/10.1016/j.egypro.2014.11.1147
[86] Berthou, M., & Bory, D.. Overview of waste heat in the industry in France, 2012; 453–459.
[87] Mckenna, R. C., & Norman, J. B.. Spatial modelling of industrial heat loads and recovery potentials in the UK, 2010; 38, 5878–5891. https://doi.org/10.1016/j.enpol.2010.05.042
[88] Li, Y.. Analysis of Low Temperature Organic Rankine Cycles for Solar Applications Analysis of Low Temperature Organic Rankine Cycles for Solar Applications. Thesis and Dissertations, (1113), Lehigh University, 2013
[89] Thomas K, Lasse R. C, Fredrik H and Anish M, ‘Energy and exergy analysis of the Kalina cycle for use in concentrated solar power plants with direct steam generation’, Energy Procedia, 2014; 57: 361 – 370
[90] Ekama, G. A., Sötemann, S. W., Wentzel, M. C., Ekama, G. A., & Eurelectric.. Efficiency in Electricity Generation. Water Research, 2003; 32(3), 297–306. https://doi.org/10.1016/j.watres.2009.01.036
[91] Demirbas, A.. Waste Energy for Life Cycle Assessment. 2016; https://doi.org/10.1007/978-3-319-40551-3
[92] Jung, H. C., Krumdieck, S., & Vranjes, T. Feasibility assessment of refinery waste heat-to-power conversion using an organic Rankine cycle. Energy Conversion and Management, 2014; 77, 396–407. https://doi.org/10.1016/j.enconman.2013.09.057
[93] Vidadili, N., Suleymanov, E., Bulut, C., & Mahmudlu, C.. Transition to renewable energy and sustainable energy development in. Renewable and Sustainable Energy Reviews, 2017;80, 1153–1161. https://doi.org/10.1016/j.rser.2017.05.168
[94] Furlan, C., & Mortarino, C.. Forecasting the impact of renewable energies in competition with non-renewable sources. Renewable and Sustainable Energy Reviews, 2018; 81, 1879–1886. https://doi.org/10.1016/j.rser.2017.05.284
[95] EIA. World energy demand and economic outlook EIA’s handling of non-U.S. policies in the International Energy Outlook. U.S. Energy Information Administration, 2016:, 7–17. Retrieved from http://www.eia.gov/forecasts/ieo/world.cfm

[96] Cipollone, R., Bianchi, G., Di Bartolomeo, M., Di Battista, D., & Fatigati, F.. Low grade thermal recovery based on trilateral flash cycles using recent pure fluids and mixtures. Energy Procedia, 2017;123, 289–296. https://doi.org/10.1016/j.egypro.2017.07.246

[97] Zhang, D., Ma, L., Liu, P., Zhang, L., & Li, Z. (2012). A multi-period superstructure optimisation model for the optimal planning of China's power sector considering carbon dioxide mitigation. Discussion on China's carbon mitigation policy based on the model. Energy Policy, 41, 173–183. https://doi.org/10.1016/j.enpol.2011.10.031

[98] Chen, Y.. Factors influencing renewable energy consumption in China: An empirical analysis based on provincial panel data. Journal of Cleaner Production, 2018;174, 605–615. https://doi.org/10.1016/j.jclepro.2017.11.011

[99] Amri, F.. The relationship amongst energy consumption (renewable and non- renewable), and GDP in Algeria, 2017;. https://doi.org/10.1016/j.rser.2017.03.029

[100] Aized, T., Shahid, M., Bhatti, A. A., Saleem, M., & Anandarajah, G.. Energy security and renewable energy policy analysis of Pakistan. Renewable and Sustainable Energy Reviews, 2016; 84, 155–169. https://doi.org/10.1016/j.rser.2017.05.254

[101] Miró, L., Brueckner, S., Mckenna, R., & Cabeza, L. F.. Methodologies to estimate industrial waste heat potential by transferring key figures : A case study for Spain, 2016;169, 866–873. https://doi.org/10.1016/j.apenergy.2016.02.089

[102] Miró, L., Brückner, S., & Cabeza, L. F. Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries. Renewable and Sustainable Energy Reviews, 2015; 51, 847–855. https://doi.org/10.1016/j.rser.2015.06.035

[103] Ozdemir, E and Kilic, M, Thermodynamic Analysis of Basic and Regenerative Organic Rankine Cycles Using Dry Fluids from Waste Heat Recovery, Journal of Thermal Engineering, 2018; 4, 5, pp. 2381 – 2393

[104] KAYA I, KARAKURT, A.S and UST, Y, Investigation of Waste Heat Energy in a Marine Engine with Transcritical Organic Rankine Cycle, Journal of Thermal Engineering, 2020; 6, 3, pp. 282 - 296