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# Low grade Waste Heat Recovery for Optimized Energy Efficiencies and Enhanced Sustainability in Process Industries: A Comprehensive Review

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*Abstract*– **This article presents a review of various works focussed on identifying the scope of recovering low grade waste heat in process industry for improving energy efficiency. The review portrays various aspects of heat recovery and the methodologies and technologies being employed for its optimization. Waste heat recovery reduces the overall cost of production by reducing the energy cost. Indirect advantages are increased sustainability through increased life of fossil fuel reserves and the alleviation of burden of environmental and thermal pollution. This work also reviews the opportunities and challenges faced by developing countries in recovering low grade waste heat.**

*Keywords*– **Waste Heat Recovery, Thermal Efficiency, Exergy, Optimization and Cost**

## I. INTRODUCTION

In industries heat is used to perform various tasks. Waste heat is a by-product of the processes; it is dumped into the environment after getting the prime objective (output) of system. Heat lost is a thermodynamic obligation which cannot be avoided. Generally in any system, heat is generated by combustion of fuels. Waste heat is the energy contained by air, gases and liquids in waste streams/outlets. ‘Waste Heat Recovery’ (WHR) is applied for utilization of unused heat for various other heating or cooling purposes. It is not the quantity of heat but the quality which is worth considering in WHR. High temperature waste streams are ideal for heat recovery; but for low temperature waste streams some other factors are to be considered. Other factors include the flow rate of waste streams and economics of implementation. Some of the process industries such as textile and paper throw large amounts of low temperature waste heat into atmosphere in the form of waste hot water. As the world’s most of the energy requirements are met by fossil fuels, which are very scarce and their reserves are depleting very fast. It becomes a necessity for us to use energy wisely and with minimum wastage until. It has been estimated that approximately 26% of the industrial energy is wasted in the form of hot gases or liquid streams, which can be reduced by employing WHR systems. Doing this not only saves the energy but also reduces the adverse impact on environment. Any WHR potential depends upon the waste fluid properties such as temperature, flow rate and pressure. The size and cost of WHR system depends upon the waste heat recovery potential and type of usage. Researchers from all over the world have pointed out the opportunity of recovering the heat in various industries and have suggested and compared the means of heat recovery. Yasmine Ammar et. Al. [61] analyzed past and current drivers for heat recovery studies in various industries and defined high and low grade heat sources according to the viability of recovery within the processes. Both high grade heat capture and low grade heat recovery within the processes were reviewed with a focus on the potential for low grade heat capture. An effective heat capture demands organizational, financial, technical and economic barriers to be overcome and benefits from a holistic vision could be gained with stronger governmental policies and regulatory incentives. Present review focuses on the work done in recovery of waste heat in terms of available and projected technologies, their scope and challenges. The article is divided into six sections and their sub sections which systematically categorize the relevant researches according to their areas of concern. Section two accounts the researches done on thermodynamic cycles used for heat recovery whereas the section three discusses the various researches for the selection of working fluid for these cycles. Selection of working fluid plays a vital role in any thermodynamic cycle. Section four presents the brief thermodynamic analysis and researches involving the second law analysis. Section five details the researches from various industries where WHR is implemented followed by section six, which accounts for optimizing the heat recovery technically and financially and the methods in use and further scope for improvements.

## II. REVIEW OF THE THERMODYNAMIC CYCLES USED FOR WASTE HEAT RECOVERY

Waste heat can be recovered and reused directly for different uses such as space heating, preheating and air-conditioning by using vapor absorption technology. Utilization and recovery of waste heat demand utility points to be situated in the near vicinity of the waste heat source as long distance heat transfer is uneconomical and inefficient due to losses. Not all the industries have sufficient utilization points to use all of their waste heat and in most cases it is discharged directly into the atmosphere. A better alternative which is regularly sought after by researchers is generating electricity from waste heat. It gives manifold benefits as electricity can be transmitted to long distances with higher efficiencies. Thermodynamic cycles are used to convert waste heat into electric power. Despite the efficiencies of conversion are very low due to low temperatures but they still prove to be better over direct utilization of heat for heating purposes. Various researchers have compared the different thermodynamic cycles available for low temperature conversion and have tried to optimize the heat recovery for electricity generation. Researchers have found Organic Rankine , Kalina , Goswamy, trilateral flash and supercritical Rankine cycles appropriate for electricity generation from low temperature waste heat sources.

### *A) Organic Rankine Cycle (ORC)*

In the past decades interests has been shown in low-grade heat recovery by Organic Rankine Cycle (ORC). ORC is same as a typical Rankine Cycle but differs in terms of the type of working fluid. Which is here a low temperature boiling refrigerant. Fig. 1 represents a schematic of ORC.

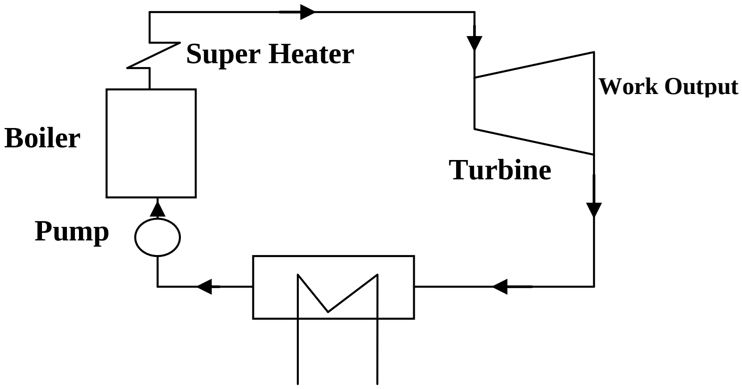

Fig.1. Schematic of an ORC

ORC is most commonly used cycle for low grade waste recovery. Tiangou Wang et. Al. [53] presented a review of various researches for providing an insight into possible system designs, thermodynamic principles and selection of working fluids to maintain the necessary system performance of ORC. It was found that Organic Rankine cycle can be efficiently used for WHR from exhaust**.** Hung et. Al. and Larjola [52], [26] analysed that upto 50% of exergy of exhaust gas can be recovered by Rankine cycle system. Sylvain Quoilin [51], [50] also focused on the thermodynamic and economic optimization of a small scale ORC in waste heat recovery applications and proposed a sizing model, capable of predicting the cycle performance with different working fluids and different component sizes. The working fluids considered were R245fa, R123, n-butane, n-pentane and R1234fa. Results indicated that, for the same fluid, the objective functions (economics profitability, thermodynamic efficiency) lead to different optimal working conditions in terms of evaporating temperature. Authors developed a dynamic model of a small-scale ORC and a simulation run was carried out. The simulation results showed that small-scale ORCs were well adapted to waste heat recovery with variable heat source flow rate and temperature. An overall waste heat recovery efficiency of 6.6% was obtained for the defined heat source. Some researchers have compared ORC with other cycles. Paola Bombarda et. Al. [37] conducted a comparison between the thermodynamic performances of Kalina cycle and ORC cycle. The maximum net electric power that can be produced exploiting the heat source constituted by the exhaust gases was calculated for the two thermodynamic cycles. The obtained powers were equal in value, but the Kalina cycle required a very high maximum pressure in order to obtain high thermodynamic performances. So, the adoption of Kalina cycle, at least for low power level and medium-high temperature thermal sources, was not justified. Adrienne B. Little [2] assessed thermally activated systems based on absorption cycles and organic Rankine cycles using refrigerant R245fa for work recovery and considered two cases one for smaller-scale and lower temperature applications using waste heat at 60 $^{o}$C, and the other for larger-scale and higher temperature waste heat at 120 $^{o}$C. Comparative assessments of these cycles on the basis of efficiencies were used for selection of waste heat recovery systems. The ORC and Maloneye Robertson cycles were designed here to have similar cycle sizes, and under this condition found that the ORC performed better than the Maloneye Robertson cycle. Kalyan K. Srinivasan et. Al. [24] examined the exhaust WHR potential of a high-efficiency, low emissions dual fuel low temperature combustion engine using an Organic Rankine Cycle and carried out the pinch point analysis and ORC evaporator and heat exchanger effectiveness. It was found that higher pinch point temperature differences uniformly yielded greater exergy destruction in the ORC evaporator and percentage of exhaust gas recirculation should be chosen carefully to ensure optimum values of exergy efficiency , incremental system cost, system reliability, exhaust emissions, and overall fuel conversion efficiencies. Among low-grade heat bottoming cycles, the ORC is the most commercially developed one. It is simpler and economically more feasible than the steam Rankine cycle.

### *B) Kalina Cycle*

The Kalina cycle (KC) uses a solution of two fluids with different boiling points as working fluid. The solution boils over a range of temperatures therefore more heat can be extracted from the source. The same applies on the condenser end. This results in higher efficiency with less complexity. The boiling point of the working solution can be adjusted by choosing an appropriate ratio between the components of the solution depending upon heat input temperature. Water and ammonia is the most widely used combination. Since it takes the full advantage of the temperature difference between the particular heat source and sink available, it has been tested by various researchers for recovering waste heat. Fig. 2. represents a schematic of Kaina cycle.

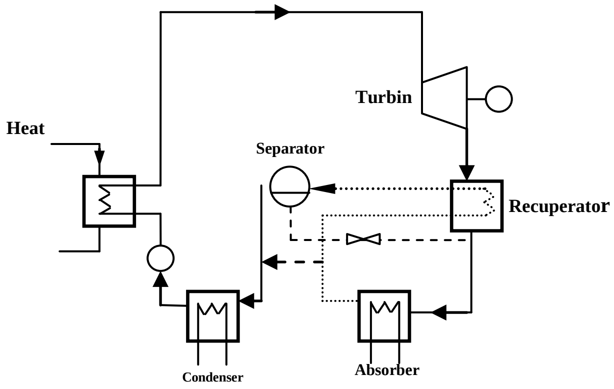

Fig. 2. Schematic of Kalina cycle

Xinxin Zhang et. al. [59] presented a review of the researches on the Kalina cycle alongwith its description. A comparison of the the Rankine and Kalina cycle and an energy and exergy analysis was attempted . Different correlations for calculating thermodynamic properties of ammonia–water mixture were screened and discussed. Mounir B. Ibrahim and Ronald M. Kovach [32 ] investigated A multi-component ($NB_3/H_2O$) Kalina-type cycle which utilized the exhaust from a gas turbine. The relationships between turbine-inlet flow and the seperator-inlet were studied and cycle was found to be 10–20% more efficient than a Rankine cycle with the same boundary conditions. Wencheng Fu et. al [56]studied the possibilities of generating electricity by low temperature geothermal energy resource of oilfield by using Kalina cycle and proposed a cascade utilization system including KC subsystem . A model of the KC subsystem was calculated numerically and validated. The KC subsystem was optimized by analyzing the thermal and exergetic efficiencies. The economic performance of the cascade utilization system was evaluated. The economic benefits were estimated to be 2 million dollars per year. A solar-driven Kalina cycle was examined by Jiangfeng Wang et. al. [22]. A thermal storage system was introduced to store the collected solar energy and to provide power when solar radiation is insufficient. A mathematical model was developed to simulate the solar-driven KC and a modified system efficiency was defined to evaluate the system performance. The optimized modified system efficiency was obtained to be 8.54%. Nasruddin et. al. [34] attempted to increase the efficiency of power plant by using the waste heat produced by power plant. KC was used to generate additional power from waste heat. The modelling application on energy system was used to study the basic design of thermal system. The study of this process was done by cycle Tempo 5.0 simulation software, to obtain the data of efficiency, energy and exergy that could be generated from the heat source. An ammonia-water mixture was used as a working fluid on KC system. In order to obtain the maximum power output and maximum efficiency, the system was optimized on the mass fraction of working fluid and also on the turbine output pressure. It was found that that the maximum efficiency and power output were achieved at 78% ammonia-water mixture. Ying ZHANG et. al. [62] presented an analysis Based on the first law of thermodynamics by adopting the Peng-Robinson equation (P-R equation) as the basic equation for the properties of ammonia-water mixtures. A program was developed to calculate the thermodynamic properties of ammoniawater mixtures and performance of Kalina cycle. The influences of key parameters on the cycle performance were analysed. The parameters taken were pressure and temperature at the inlet of the turbine, the back pressure of the turbine, the concentration of the working solution, the concentration of the basic solution and the cycle multiplication ratio. E. Thorin et. al. [12] analysed Power cycles with ammonia–water mixtures as working fluids. Higher thermal efficiencies were obtained than the traditional steam turbine Rankine cycle with water as the working fluid. Different correlations for the thermo-dynamic properties of ammonia–water mixtures were used in studies. The differences in thermal efficiencies were in the range 0.5 to 3.3%. The Kalina Cycle achieved better performance and smaller plant size than a steam Rankine plant with equal output. Order of superiority between the Kalina Cycle and the ORC is debatable. Ammonia is toxic and highly corrosive, which has to be taken into account in material selection. The Kalina Cycle has found some applications in waste heat and geothermal power plants.

### *C) Goswami Cycle*

It is a comparatively new cycle and still in research phase. It uses a binary mixture to produce power and refrigeration simultaneously. It is a combination of the Rankine cycle and a vapor absorption cycle. Its advantages are the production of power and cooling in the same cycle, the design flexibility, the efficient conversion of moderate temperature heat sources and the possibility of improved resource utilization. Ricardo Vasquez Padilla et al. [42] analysed the Goswami cycle combined with Rankine cycle and found that the maximum output net work was 85MW. The maximum theoretical effective first law efficiency were higher than the values obtained by the traditional Rankine cycle.

### *D) Trilateral Flash Cycle*

In trilateral flash cycle (TFC) expansion starts from the saturated liquid rather than a vapor phase. Boiling part is avoided here and the heat transfer from a heat source to a liquid working fluid is achieved with almost perfect temperature matching. Irreversibility is thereby minimized.

Stiedel et. al. [48], concluded that the potential power recovery can be 14 - 85% more than ORC or flash steam systems provided that the two-phase expansion process is efficient. Major limitation is lack of suitable two-phase expanders with high adiabatic efficiencies. Two-phase expanders were studied extensively during the 1970, among which a Lysholm screw expander in a twin screw machine proposed by Sprankle and further studied by Stiedel have adiabatic efficiencies of the order of 50%. However, studies conducted by Smith et al. [46] showed that it was possible to design and construct twin screw expanders for trilateral flash cycle application with predicted adiabatic efficiencies of the order of 80% or more. They realized the design, and test results of screw machines showing two-phase fluid expansion with adiabatic efficiencies of more than 70%. In spite of

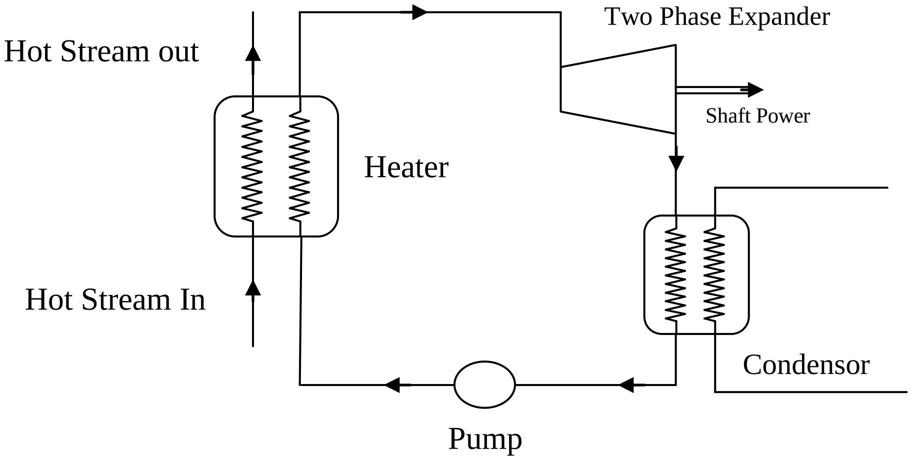

Fig. 3. Schematic of a Trilateral Flash Cycle

Table 1: Comparison of different cycles for waste heat recovery (Zamfirescu & Dincer [55])

| S.N | Type of Cycle | Working Fluid | Efficiency (η) % | Power output (P) kW | Heat Input (Q) kW |
|---|---|---|---|---|---|
| 1. | ORC | R141b | 10 | 13 | 132 |
| 2. | ORC | R123 | 9 | 17 | 179 |
| 3. | ORC | R245ca | 9 | 18 | 189 |
| 4. | ORC | R21 | 9 | 18 | 198 |
| 5. | Kalina | $NH_3$- $H_2O$ | 3 | 13 | 373 |
| 6. | TFC | $NH_3$- $H_2O$ | 8 | 38 | 477 |

advantages of theoretical TFC there is no trilateral flash cycle power plant reportedly in operation. However, some pilot demonstrations have been conducted by Smith, Stosic and Kovacevic [49]. Zamfirescu & Dincer [55] compared TFC, different ORCs and Kalina cycles, operating under the same temperature conditions in heat sink and source at the same flow rate and temperature at source inlet. Isentropic efficiency of turbine was assumed to be 70%. The cycle efficiencies (η), power outputs (P) and heat inputs (Q) are listed in Table 1.

### *E) Supercritical Rankine Cycle*

Fluids with low critical temperature and pressure can be compressed directly to their supercritical pressures and heated to their supercritical state before expansion to obtain a better thermal match with waste heat source. The heating in a supercritical Rankine cycle does not pass through a two-phase region like a conventional Rankine or Organic Rankine cycle thus has less irreversibility**.** Fig. 3 presents a schematic of Supercritical Rankine Cycle.

Chen et al. [60] presented a comparative study of the carbon dioxide supercritical power cycle and compared it with an organic Rankine cycle using R123 as the working fluid in a waste heat recovery application. It shows that a $CO_2$ supercritical power cycle has higher system efficiency than an ORC. The $CO_2$ cycle shows no pinch limitation in the heat exchanger. Zhang et al. [57] also conducted researches on the supercritical $CO_2$ power cycle. Experiments revealed that the power generation efficiency obtained was from 8.78% to 9.45% and the COP for the overall outputs from the cycle was from 0.548 and 0.406. Organic fluids like propane, isobutene, propylene, di-fluoromethane and R-245fa can be used for supercritical Rankine cycle. It was found that supercritical fluids can maximize the efficiency of the system. Supercritical critical Rankine Cycle has an advantage in thermal efficiency over other cycles and its working is also simple. Presently, There is no supercritical Rankine cycle power plant in operation.

## III. WORKING FLUIDS AND SELECTION

Much effort is being put in for using waste heat and other low temperature sources for producing electricity. The organic Rankine cycle (ORC), Kalina cycle and other cycles are available for conversion of low and medium temperature heat to electricity. A certain challenge is the choice of working fluids and of the particular design of the cycle. The process should have a high thermal efficiency and it should allow a high utilization of the available heat source. Moreover, the working fluid should fulfil safety criteria, it should be environmentally friendly, and allow low cost for the power plant. An important criteria for the choice of the working fluid is the temperature of the available waste heat source, which can range from low temperatures of about near 80 $^{o}$C to medium temperatures of about 350 $^{o}$C. For low temperature heat sources the use of organic fluids is advantageous because of the volume ratio of the working fluid at the turbine outlet and inlet. This can be smaller by an order of magnitude for organic fluids than for water and hence allows the use of simpler and cheaper turbines [43].

### *A) Types Of Working Fluids*

Amlaku Abie Lakew et. al. [4] studied the performance of different working fluids to recover low-temperature heat source. A simple Rankine cycle with subcritical configuration was considered. Aim of the authors was to screen working fluids based on power production capability and component (heat exchanger and turbine) size requirements. Working fluids considered were R134a, R123, R227ea, R245fa, R290, and n-pentane. Energy balance was carried out to predict operating conditions of the process. Outputs of energy balance were used as input for exergy analysis and components design. It was found that R227 gives highest power for heat source temperature range of 80-160 °C and R245fa produces the highest in the range of 160-200 °C. The Selection of working fluid depends on heat source type, temperature level and objective. The main objective can be to get the maximum power possible or smaller component sizes. R227ea produces the highest power for heat source temperature range considered here (80-160 °C). R24fa gives higher work output for temperature greater than 160 °C. There is an optimal evaporator pressure for maximum power. This pressure depends on heat source temperature and working fluid used. As heat source temperature increases, working fluids with high vapor pressure can operate at higher pressure and this will improve power output. Bahaa Saleh et. al. [6] perfomed screening of 31 working fluids for organic Rankine cycles. The fluids were alkanes, fluorinated alkanes, ethers and fluorinated ethers. The ORC cycles operate between 100 and 30 $^{o}$C for geothermal power plants at pressures mostly limited to 20 bar, but in some cases supercritical pressures are also considered. Authors presented thermal efficiencies for cycles of different types. Studies showed that the largest amount of heat can be recovered by a supercritical fluid and the least by a high-boiling subcritical fluid. P. J. Mago et. al. [35] presented second-law analysis of organic Rankine cycle (ORC) to convert waste energy to power from low-grade heat sources. The organic working fluids were selected to investigate the effect of the fluid boiling point temperature on the performance of ORC. The working fluids under investigation were R134a, R113, R245ca, R245fa, R123, iso-butane, and propane, with boiling points between 43$^{o}$C and 48$^{o}$C. A combined first- and second-law analysis was performed by varying some system operating parameters. Results demonstrated that ORC using R113 showed the maximum efficiency among the evaluated organic fluids for temperatures greater than 430 K. Refrigerants R123, R245ca, and R245fa show the best efficiencies for temperatures between 380 and 430 K; and for temperatures lower than 380 K iso-butane showed the best efficiency. It was also shown that the organic-fluid boiling point had a strong influence on the system thermal efficiency.

## IV. THERMODYNAMIC ANALYSIS

The amount of waste heat which can be recovered depends upon many factors such as temperature of waste stream, mass flow rate, pressure, type of fluid and heat exchanger used. Thermodynamic relations and theories can give a precise value of heat which can be recovered. Thermodynamic laws are very helpful in arriving at the optimum levels and decisions. Researches show the extensive application of second law of thermodynamics in waste heat recovery problems.

### *A) Available and Unavailable Energy*

As per second law of thermodynamics, it is not possible to convert all the heat absorbed by a system into work. If a certain quantity of energy Q as heat is received from a body at temperature T. The maximum work W which can be obtained by operating a Carnot engine using the body at T as the source and the ambient atmosphere at $T_0$ as the sink is given by:

$$W = Q_{\eta} = Q\left(1 - \frac{T_0}{T}\right) = Q - T_0|\Delta_s| \qquad (1)$$

Where Δs is the entropy of the body supplying the energy as heat. Fig. 4 represents the Carnot cycle and the available and unavailable energy.

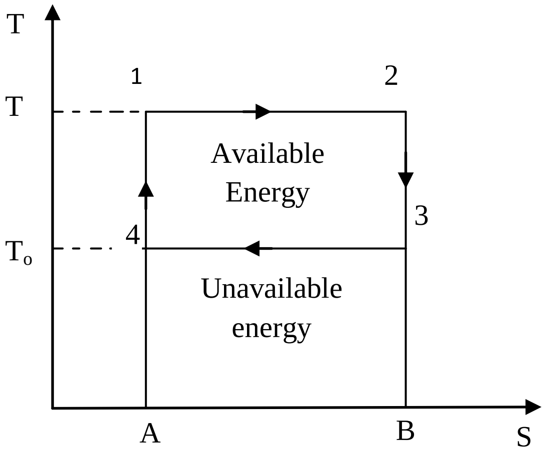

Fig. 4. Carnot Cycle

The area 1-2-3-4 represents the available energy. The area 4-3-B-A represents the energy, which is discarded to the ambient atmosphere, and this quantity of energy cannot be converted into work and is called Unavailable energy. If a finite body is used as a source. Let a large number of differential Carnot engines be used with the given body as the source. If the initial and final temperatures of the source are $T_1$ and $T_2$ respectively, the total work done or the available energy is given by:

$$W = \int dQ_\eta = \int_{T_1}^{T_2} dQ\left(1 - \frac{T_o}{T}\right) = Q - T_o \int_{T_1}^{T_2} \frac{dQ}{T} \qquad (2)$$

Loss in available energy:

$$= Q\left(1 - \frac{T_o}{T_1}\right) - Q\left(1 - \frac{T_o}{T_2}\right) = T_o\left(\frac{Q}{T_2} - \frac{Q}{T_1}\right) = T_o \Delta s_{uni} \qquad (3)$$

where $Ds_{uni}$ is the change in the entropy of the universe.

The availability of a given system may be defined as the maximum useful work that can be obtained in a process in which the system comes to equilibrium with the surroundings or attains the dead state.

### *B) Second Law Efficiency*

Thermodynamic efficiency or first law efficiency compares real processes to internally reversible process. It does not take into account the lost work associated with external irreversibilities due to heat transfer through a finite temperature difference. This is overcome by defining a new type of efficiency that is based on the comparison of real processes to a completely reversible process operating between the same two states as the real process. This new type of efficiency is called the second law efficiency. For processes that produce or consume work, such as turbines and compressors, the 2nd Law Efficiency is relatively easy to apply. However, it is difficult to apply the second law efficiency to processes that do not produce or consume shaft work. It can be defined as the ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same conditions.

$$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}} \qquad (4)$$

While calculating second-law efficiency, it is required to determine how much exergy or work potential is consumed for that process. Entire exergy supplied can be recovered in a reversible process, irreversibility for this process is zero. A zero second-law efficiency shows no recovery of exergy supplied to the system.

### *C) Exergy Analysis*

Exergy analysis is a proven tool for analysing the exergy destruction areas and the areas of heat loss, it thus highlights the major points of energy recovery. Researchers all over the world are attempting exergy based analyses for precisely defining and calculating exergy destructions and scope of heat recovery at various points in a process. E Mozes [13] calculated the efficiency of conventional textile processes by using cumulative exergy consumption (CExC) and performed studies to minimize the CExC. It is the exergy consumption of all production processes starting from the extraction of natural resources to final product. The author considered five variables which influence the washing process which were temperature, detergent quantity, washing time, agitation and water input. Other variables were assumed to be constant. In this work washing performance was related to detergent quantity and temperature ranging from $30^oC$-$80^oC$. Ahmet Gay [3] assessed the processing of textile fabrics at a jet dyeing machine using exergy analysis method. He concluded that an increase in process temperature, time and liquor ratio increases the energy destruction rates. It was noted that with an increase in fabric inlet temperature, the exergy destruction rate decreases. It was also recommended to use a heat recovery system to recover heat from waste water streams. This ensured a decrease in exergy destruction rate and results in a decreased steam consumption. D. Peinado [8] presented an energy and exergy analyses of a rotary dryer employed in a Hot Mix Asphalt (HMA) plant for heating and drying of the aggregates in the mixture to identify and evaluate the thermodynamic losses. Results showed the energy and exergy efficiencies of 0.89 and 0.18 respectively. The energy losses were mainly due to the flue gases. The exergy distribution indicated that the combustion and the heat transfer at different temperatures in the burner yield the highest exergy destruction in the process and the exergetic efficiency was very poor due to high irreversibilities. To overcome the great exergy destruction the authors proposed a cogeneration plant to take advantage of the temperature values needed for these plants. Al-Ghandoor [1] analyzed the energy and exergy utilizations in the U.S manufacturing sector by considering the energy and exergy flows. The average site energy and exergy efficiencies of the manufacturing sector were estimated as 63.5% and 38.8% respectively and the embodied energy and exergy efficiencies were estimated as 52.7% and 32.1% respectively. M.T Oladiran et. al. [30] also analysed the energy-utilization over a period of 10-years for the South African industrial sector, which consumes more primary energy than any other sector of the economy. The results indicated that exergy efficiency was considerably lower than energy efficiency in all the sub-sectors, particularly in mining and quarrying processes, for which the values were approximately 16% and 83%, respectively. The performance of exergy utilization in the industrial sector can be improved by introducing various conservation strategies. Results from this study may be used to compare exergy efficiencies of different countries. This work gives an insight of a holistic approach towards the exergy and energy utilizations of a country. R. saidur et. al. [40] analysed the concept of energy and exergy utilization by applying it to the boiler system. Most of the major industrial users use fossil fuels to generate steam. Industrial systems are generally different from each other but often have common major steam systems. Boiler efficiencies have a great influence on energy savings. It is important to maximize the heat transfer to the water and to minimize the losses. R. Saidur identified energy, exergy efficiency, energy losses and exergy destruction for a boiler and ways to reduce boiler energy consumption. M.G Rasul et. al. [29] presented a model for the thermal performance of a cement industry with an integrated view to improve the productivity of the plant. The model was developed on the basis of mass, energy and exergy balance and was applied to an existing Portland cement industry. The thermal energy conservation opportunities were identified. This study showed that by replacing industrial diesel oil (IDO) with waste heat recovery from kiln and cooler exhaust for drying of raw meal and fuel, and preheating of combustion air can save about $1.264 \cdot 10^5$ US dollars per Year. J-Y San [31] analyzed the second law performance of heat exchangers used for waste heat recovery and evaluated on the parameter “effectiveness”. In this work the author defined an exergy based evaluation factor for evaluating the second law performance of heat exchanger used in waste heat recovery process.. Xiaojun Shi et. al. [58] performed an experimental and theoretical investigation of the utilization of finned tube compact heat exchanger and concluded that A normalized correlation of convection-condensation heat transfer in fin-and-tube heat exchangers is derived by using the heat and mass transfer analogy models. V. Calabro [54] studied the energy consumption of simulated textile processes. An energy and exergy analysis was attempted. The energy used in dye house represents about 80% of the textile factory’s total energy consumption. A low efficiency of operation results in losses. Dye baths are usually discharged at a temperature of 80-90$^o$C with an efficiency of less than 15%. Author suggested some cycles for recovering dyes and chemicals. For each cycle, energy and exergy analysis was done been developed for evaluating the energy efficiency. In both the cycles the hot water permeated was used. The experiments on concentrations of salts and dyes solutions by RO gave good results.

## V. HEAT RECOVERY IN INDUSTRIES

In industries waste heat losses arise from equipment inefficiencies and thermodynamic limitations. Efforts can be made in designing more energy efficient equipments with better heat transfer and lower exhaust temperatures. The laws of thermodynamics place a lower limit on the temperature of exhaust streams. Higher waste stream temperatures result in loss of energy and as high as 40% of the energy input to the equipments is lost. Industrial waste heat can be recovered via a number of methods. The recovered heat can either be “reused” within the same process or transferred to some other process. Ways of reusing heat include using combustion exhaust gases to preheat combustion air or feed-water in industrial boilers this results in reduced amount of energy required to heat the water to its final temperature. Alternately, the heat can be transferred to another process, a heat exchanger is used to transfer this heat. In this way, the recovered heat can replace fossil energy that would have otherwise been used. Waste heat can also be used to produce electricity, which can be easily utilized at any point of choice and with minimum efforts.

### *A) Heat Recovery in Textile, Paper and Cement Industry*

Textile, Cement and paper industries are some of industries which come under the category of energy intensive industries. All of them have great opportunities for WHR. Researchers have attempted for it and found encouraging results.

S.N. Gaeta [44] developed a process to recover energy from effluents of textile dye-house by using spiral wound membrane modules specifically designed for this application. The shortage of water and increasing cost of chemicals and energy has pushed this technology. These products were recovered by using the same technology, it also controlled the pollution caused by the effluents. R. Budin et.al. [39] calculated the energy savings through the condensate recovery and heat recovery from boiler flue gases . The polyester production process analysis showed that condensate returning from the reactor to the steam boiler raises inlet temperature, giving a reduced fuel requirement of about 8%. Also, boiler flue gas with a sufficiently high outlet temperature for boiler feed water and Combustion air preheating resulted in further fuel savings. The process saved 8.44% energy with economizer and 6.25% with a combustion air preheater. R. Tul Grul and O Gulata [41] found drying one of the most energy-intensive operations in textile processes and dryers exhaust large amounts of warm and moist air into environment. An analysis was carried out on heat-recovery systems which utilize the heat produced in the drying process. A heat recovery system was designed and employed on the convection-type drying machine and significant energy savings were achieved. G. Manfrida [16] accounted the types of energy losses encountered in various textile processes such as washing, drying, dyeing and bleaching. He discussed a much efficient pressurized condensate recovery system against the traditional system where a great amount of flash steam is lost to the environment. A multiple pumps system was suggested for different pressures without any collection tank. Although the Service cost of pumps increased slightly but overall efficiency was increased by 12%. The new method for condensate recovery reduced the exergy losses by 12%. Forrest Meggers et. al. [15] presented a new concept for recovering waste heat from the wastewater of dye-house by evaluating heat recovery immediately after process. This allowed exploitation of higher temperatures found at the points of warm water usage. Heat pumps were integrated in the system to utilize this heat. In a typical cement plant, 25% of the total energy used is electricity, 75% is thermal energy, and about 35-40% of the total process heat is lost through waste heat streams. Approximately 26% of the heat input to the system is lost by dust, clinker discharge, radiation from the kiln and pre- heater surfaces, and convection from the kiln and pre-heaters. Ziya Sogut et. Al. [64]examined heat recovery from rotary kiln for a cement plant in Turkey. An exergy analysis was carried out on the operational data of the plant. Results indicated the presence of 217.31 GJ of waste heat, which is 51% of the overall heat of the process. A mathematical model was developed for a new heat recovery exchanger for the plant. It was determined that 5% of the waste heat can be utilized with the heat recovery exchanger. The useful heat recovered partially satisfied heating demands of 678 dwellings in the vicinity through district heating system. This system expected to decrease domestic-coal and natural gas consumption by 51.55% and 62.62% respectively. $CO_2$ emissions were also reduced. Energy consumption share of the cement sector in the industrial field is between 12% and 15%. In terms of total energy consumption of countries, this share changes between 2% and 6%. Utilizing the energy through these approaches ensures least financial, environmental and social costs. Thus, it is urgent that the studies of energy recycling should be conducted in the cement sector as well as other sectors where energy losses are high. P. Saneipoor et. Al.[36] examined the performance of a new Marnoch Heat Engine (MHE) that recovers waste heat from a cement plant. Two MHE units with compressed air as the working fluid were installed to recover waste heat. The units operated with three pairs of shell and tube heat exchangers. The recovered heat was converted to electricity through the MHE system and used internally within the cement plant. A predictive model and it's results were presented and discussed. The new heat recovery system increased the efficiency of the cement plant and lowered the $CO_2$ emissions from the clinker production process.. High WHR opportunities lie in paper industry, Leena Sivil & Pekka Ahtila [27] demonstrated the heat recovery potential in paper industry with a case study of three operating paper machines and suggested some retrofit methodologies. The analysis revealed savings of 110 GWh/a in process heat with profitable investments. The investments carried out have resulted in 12% lower fuel use and 24% lower $CO_2$ emissions. The results implied that all operating paper machines should be similarly examined.

Many researchers emphasized on joint WHR and the recovery across the plants rather than considering individual processes and single plant. This resulted in formulation of various policies and strategies for optimized heat recovery and utilization. Sibel Ozodon et. al. [45] evaluated the energy utilization efficiencies of Turkish food, textile and cement sectors by using energy and exergy analysis . The work characterized the annual energy uses in the above sectors and tried to include all major end uses such as process heat, space heating, water heating, motive power & illumination. The paper dealt with the analysis of survey findings, evaluating them & extrapolating them to find the distribution of energy requirement for different sectors. The survey findings indicated that the electrical energy utilization for process, space and water heating was negligible. Energy and exergy efficiencies were calculated for each sector as a weighted average of different end uses. A comparison of energy usage was prepared between the survey results & countries like UK & USA. It was found that the percentage usage of electricity is more in UK & US textile Industry as compared to developing countries. The reasons assigned is the better utilization efficiencies of electricity and higher space heating requirements. A greater recovery potential lies with developing countries. Song Hwa Chae et. al. [47] drew attention towards the development of an eco-industrial park (EIP) which seeks the mutual benefit to the economy and environment. In order to find energy strategies in an EIP, a framework was proposed to investigate waste heat of an industrial complex. A mathematical model was developed to synthesize a waste heat utilization network, including nearby companies and communities. The total energy cost and the amount of waste heat of the region was reduced by more than 88% and 82% respectively. Grethe et. al. [19] described the project CREATIV which is a research initiative for industry energy efficiency focusing on utilisation of surplus heat and efficient heating and cooling. In CREATIV, international research groups work together with key vendors of energy efficiency equipment and an industry consortium including the areas metallurgy, pulp and paper, food and fishery, and commercial refrigeration supermarkets. The main research topics are electricity production from low temperature heat sources in supercritical $CO_2$ cycles, energy efficient end-user technology. A lot of concepts and systems are in use for individual processes and multiple processes, such as pinch analysis but very little work is done to reduce the energy consumption by improving the energy recovery between multiple plants. Efforts are being done to optimize the heat recovery by finding the utilization points in nearby plants and using waste heat across the plants, Mirko. Z. et. al. [31] aimed at increasing energy efficiency by recovering waste heat between different processing plants and proposed a method for WHR at industrial zone level by determining the recovery potential and network design across multiple plants. Further the author described the main constrains and barriers such as safety, reliability of operations, optimal utilization of capital investments. A strategic approach was given to estimate the WHR potential and optimal reuse. A Lower emissions and better energy efficiency was achieved by this approach.

Issues related to technical problems and difficulties in implementing and operating the waste heat recovery measures are also addressed by researchers. Forrest Meggers et. Al. [15] pointed out the problem of corrosion of the heat exchanger which occurs during latent heat recovery caused by the strongly acidic condensate. Authors conducted studies to investigate a titanium heat exchanger with excellent corrosion resistance for waste heat recovery with the condensation arranged in a gas fired water heater. Different arrangements of the tubes were investigated. Final results indicate that the thermal efficiency of the gas fired water heater with a latent heat recovery (LHR) heat exchanger was enhanced by about 10% compared with conventional instantaneous water heaters. The thermal efficiency of the water heater was enhanced upto 93%. Ismail teke et. al. [20] in his work took the problem of choosing the most appropriate heat exchanger for WHR and developed a model for calculating the area required for maximum net gain. Georges Descombes and Serge Boudigues [17] presented some studies of cogeneration applications using gas turbines and thermal engines. A detailed study of thermodynamic modelling cycles was done and the potential of 10 % improvement of the energy efficiency was found.

### *B) Challenges to Low Grade Waste Heat Recovery*

In developing countries low grade waste heat recovery faces following challenges:

- Recovering heat in the low temperature zone makes sense only if the plant has a use for low temperature recovered heat. Other potential end uses may include domestic water heating, space heating, and low temperature process heating. Low temperature power generation technologies are also emerging slowly.

- Corrosion of the heat exchanger surface: As water vapor contained in the exhaust gas cools, some of it will condense and deposit corrosive solids and liquids on the heat exchange surface. To avoid this it is generally required to using advanced materials, or frequently replacing components of the heat exchanger, which is often uneconomical.
- Large heat exchange surface area is required for heat transfer: Heat transfer rates are a function of the thermal conductivity of the heat exchange material, the temperature difference between the two fluid streams, and the surface area of the heat exchanger. Since low temperature waste heat will involve a smaller temperature gradient between two fluid streams, larger surface areas are required for heat transfer. This limits the economics of heat exchangers.
- Adequate technologies are available to recover low-temperature waste heat. Which include deep economizers, indirect contact condensation recovery, direct contact condensation recovery, and transport membrane condensers. Commercialization has been limited due to high costs and because facilities lack an end-use for the recovered heat. When facilities lack an end-use for waste heat, other methods are to be worked out , including heat pumps and low-temperature power generation. These technologies are also frequently limited by economic constraints.
- Unaware Managements: In many industries managements are interested in production only and ensuring a smooth production and are least interested in any heat recovery measures. As the investment cost of heat recovery measures is high.

## VI. OPTIMIZING THE HEAT RECOVERY

Recovering the heat optimally is of very much concern in heat recovery procedures. It can be done at different levels with varying outputs and results. Many researchers have tried to optimize the thermodynamic cycles on the basis of the refrigerant and have worked for the best refrigerant; some others took the cycle as a whole and tried a best combination of all parameters for optimized results. Some of them have worked on optimizing the whole process as well as works are available which have attempted optimization of whole of the plant for waste heat recovery. Sylvain Quoilin [38] points out that most of the research focuses mainly on the optimization of the cycle efficiency or output power with respect to the cycle configuration and of the available working fluids. Other criteria such as turbine availability for the selected conditions or size of the components have rarely been taken into account. Every methodology applied strives to increase the gains in terms of heat recovery units and thus an increased profit for the plant as a whole. Common optimization techniques applied by the researchers are Genetic Algorithms, Pinch Technology and Artificial Neural networks. Application of other optimization techniques such as Taguchi's methods, linear programming and graph theory is rarely found in waste heat recovery problems. These methods can prove to be very instrumental in optimizing the recovered heat.

### *A) Optimization Methods*

Anita Kovac Kralj et. al. [5] applied Energy integration between several processes, providing more economical and profitable operation. The method for waste heat integration of several processes was analysed to reduce energy consumption. Authors applied the simultaneous integration method within the production plant. Optimized overall heat recovery was obtained by optimizing individual devices for heat recovery. Di Liu et. al. [10] also emphasized on the efficient use of energy by improving efficiencies of individual devices and thus optimizing the system efficiency for exploiting the low grade energy. Leonardo Pierobon et. al. [28] aimed at optimizing the design of organic Rankine cycle run on low grade waste heat by employing the multi-objective optimization with the genetic algorithm. Three objective functions considered were thermal efficiency, total volume of the system and net present value. The optimization variables chosen were the working fluid, the turbine inlet pressure and temperature, the condensing temperature, the pinch points and the fluid velocities in the heat exchangers. Results suggested that acetone and cyclopentane were two optimal working fluids. Thermal efficiency and net present value were higher for cyclopentane. The technique can be utilized in waste heat recovery applications where a compromise between performance, compactness and economic revenue is required. Donghong Wei et. al. [11] optimized the performance of ORC by taking the system as a whole and optimizing the performance using HFC-245fa (1,1,1,3,3-pentafluoropropane) as working fluid driven by exhaust heat. The thermodynamic performances of an ORC system were analyzed. The results showed that maximizing the usage of exhaust heat improved the system output, net power and efficiency. Enhua Wang et. al. [14] evaluated the performance of five different ORCs by preparing Genetic algorithm. Five different configurations include a simple ORC, an ORC with an internal heat exchanger (IHE), an ORC with an open feed organic fluid heater (OFOH), an ORC with a closed feed organic fluid heater (CFOH), and an ORC with a reheater. Analysis indicated that the ORC with IHE performed best and the ORCs with OFOH and CFOH were sub optimal and the simple ORC and that with preheater were not optimized. The effect of expander inlet pressure, the condenser outlet temperature and the expander isentropic efficiency performances were also analyzed. Yiping Dai et. al. [63]**.** Examined the effects of thermodynamic parameters on the ORC performance. The parameters for each working fluid were optimized with exergy efficiency as an objective function by means of the genetic algorithm. The optimum performance of cycles with different working fluids was compared and analyzed under the same waste heat condition. The results showed that the cycles with organic working fluids were much better than the cycle with water in converting low grade waste heat to useful work. The cycle with R236EA had the highest exergy efficiency, and adding an internal heat exchanger into the ORC system could not improve the performance under the given waste heat condition. Jiangfeng Wang et. Al. [23] conducted Parametric and exergy analysis to examine the effects of thermodynamic parameters on the cycle performance. The thermodynamic parameters were optimized with exergy efficiency as an objective function by means of genetic algorithm (GA) under the given waste heat condition. An artificial neural network (ANN) with the multi-layer feed-forward network type and back-propagation training was used to achieve the parametric optimal design.

### *B) Cost Analysis*

Cost of implementation of any heat recovery device varies widely from one application to another and a precise information is required to calculate the actual cost. In most of cases this information is not readily available on a generalized basis. A workable cost is the total cost of all heat exchangers as this contributes to the major cost of any heat recovery application. Researches done for cost estimation provide many indicators, one such indicator for the estimation of the cost of power plant is given by criteria of APR , which considers the ratio of total heat transfer area to the total net power as an objective function. Some researches [7], [25], [9] also highlight the use of levelized energy cost (LEC) for optimization. LEC of the project is calculated from the capital expenditures of the power unit , the operational expenses in the power production and several financial parameters. The capital expenditures are calculated by summing up the power unit cost model. Which is based on the major components (expander, heat exchangers, condenser, and pumps) cost functions. These major costs are summed up, and multiplied by a fixed coefficient to account for the installation cost (including freight, sales tax, building materials and labor). The operating cost is calculated by summing up the equipment maintenance cost and the labor cost. The equipment maintenance cost is taken as a fraction of the capital expenditure for the power unit. The labor cost is estimated based on a method used in the GETEM [18] cost model. LEC is the ratio of system cost to the total net power output. It is found that the LEC reduces as the temperature of waste stream increases. LEC calculations are used on a relative basis to compare the benefits of one advanced cycle-working fluid combination to another. Uncertainties on the power unit components cost functions and cost estimates do not allow taking the calculated levelized cost of electricity alone as an absolute number or a measure to assess the economic viability of a geothermal project. It however offers a valuable tool for a quick, yet comprehensive, estimation of the levelized cost of electricity to assess the attractiveness of advanced working fluids.

### *C) Economic Optimization*

Waste heat recovery investment decisions are subjected to a large variety of investment appraisals. A distinction is between static and dynamic investment appraisals. Some static investment appraisals are the comparative cost method, the average return method and the simple payback period . The method of accumulation of an annuity, the net present value method and the internal rate of return method are representative of the dynamic investment appraisal. Mostly used methods in energy conservation and waste heat recovery measures are simple payback period, Net present value and Internal rate of return. Nafey AS and Sharaf MA [33] calculated the capital recovery cost (CRF) by using the following relation.

$$CRF = \frac{i(1+i)^{LTeq}}{(1+i)^{LTeq}-1} \qquad (5)$$

Where i is the interest rate and $LT_{eq}$ is the equipment life time in years. Any WHR investment consists of an initial outlay (and possible other outlays in the future) followed by receipts in terms of savings. Cash flows at time t could be positive or negative and either discrete c(t) or continuous ρ(t).The net present value at interest rate i is denoted as NPV(i).

$$NPV(i) = \sum c_t v^t + \int_0^t \rho(t) v^t \, dt \qquad (6)$$

WHR investment is profitable when NPV is positive. NPV is used by the researchers to compare the profitability of two or more alternative projects. The internal rate of return (IRR) of a project is the annualized yield obtained over the project's lifetime. It is calculated by solving the equation for the value of rate. The IRR gives the % return on each unit of money invested in the project.

## VII. CONCLUSIONS

Recovering Waste heat is the need of the day for the industries of developing countries. Extent of literature available shows a continuously increasing interest of researchers, managements and engineers in recovering the heat. Many big industrial plants have already realized the importance of heat recovery and they are effectively utilizing it in one or other way . Efforts are being done to improve the recovery efficiencies by using the latest technological advancements and optimization methods. Most of the researches in the field try to improve the recovery efficiencies by considering the thermodynamic and technical aspects. Improving the recovery cycles by changing one parameter at a time for getting maximum output by considering the other variables constants. Very less work has been attempted on applying the newer optimization tools such as Artificial neural networks, Fuzzy Logic and Genetic Algorithms. Some of the parametric optimization methods such as Taguchi's Method and Graph theory if applied to these problems may also provide promising results.

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