Symbols used

Nomenclature

1.	*E* is the waste heat loss	Btu/hr
2.	m is the waste stream mass flow rate	lb/hr
3.	h(t) is the waste stream specific enthalpy	Btu/lb
4.	Q is the heat transfer rate	Btu/hr
5.	U is the heat transfer coefficient	W
6.	A is the surface area for heat exchange	m^2
7.	ΔT is the temperature difference between two streams	°C
8.	Q Heat possessed by body	KJ/s
9.	m mass flow rate	kg/s
10.	C specific heat	KJ/kg.k
11.	V Volume flow rate	m^3/h
12.	Heat transfer efficiency	η

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Figure no. Figure details

Abstract

In this study a survey of the various type industrial waste heat source and technologies to utilize waste heat is presented. Initially, a description of various types of waste heat processes and there classification is provided. This is followed by various waste heat equipments including recuperators, regenerators, passive preheaters and waste heat boilers and waste heat utilization technologies. Typical applications of the various types waste heat recovery technologies are presented in order to show to the reader the extent of their applicability. This includes a case study of power generation using waste heat in cement plant and its thermal analysis. As can be seen industrial waste heat recovery systems can be used for a wide range of applications and provide significant benefits, therefore, they should be used whenever possible as system requirement.

1.0 Introduction

Industrial waste heat refers to energy that is generated in industrial processes without being put to use. Sources of waste heat include hot combustion gases discharged to the atmosphere, heated exiting industrial processes, and heat transfer from hot equipment surfaces. The exact quantity of industrial waste heat is poorly quantified, but various studies have estimated that as much as 20 to 50% of industrial energy consumption is ultimately discharged as waste heat. While some waste heat losses from industrial processes are inevitable, facilities can reduce these losses by improving equipment efficiency or installing waste heat recovery technologies. Waste heat recovery entails capturing and reusing the waste heat in industrial processes for heating or for generating mechanical or electrical work. Example uses for waste heat include generating electricity, preheating combustion air, preheating furnace loads, absorption cooling, and space heating.

Heat recovery technologies frequently reduce the operating costs for facilities by increasing their energy productivity. Many recovery technologies are already well developed and technically proven; however, there are numerous applications where heat is not recovered due to a combination of market and technical barriers. Various sources indicate that there may be significant opportunities for improving industrial energy efficiency through waste heat recovery. A comprehensive investigation of waste heat losses, recovery practices, and barriers is required in order to better identify heat recovery opportunities and technology needs. Such an analysis can aid decision makers in identifying research priorities for promoting industrial energy efficiency.

1.1 What is Waste Heat Recovery?

Waste heat losses arise both from equipment inefficiencies and from thermodynamic limitations on equipment and processes. For example, consider reverberatory furnaces frequently used in aluminium melting operations. Exhaust gases immediately leaving the furnace can have temperatures as high as 2,200-2,400° F [1,200-1,300°C]. Consequently, these gases have high heat content, carrying away as much as 60% of furnace energy inputs. Efforts can be made to design more energy efficient reverberatory furnaces with better heat transfer and lower exhaust temperatures; however, the laws of thermodynamics place a lower limit on the temperature of exhaust gases. Since heat exchange involves energy transfer from a high temperature source to a lower temperature sink, the combustion gas temperature must always exceed the molten aluminium temperature in order to facilitate aluminium melting. The gas temperature in the furnace will never decrease below the temperature of the molten aluminium, since this would violate the second law of thermodynamics. Therefore, the minimum possible temperature of combustion gases immediately exiting an aluminium reverberatory furnace corresponds to the aluminium pouring point temperature 1,200-1,380° F [650-750°C]. In this scenario, at least 40% of the energy input to the furnace is still lost as waste heat (Appendix A: Documentation of 4Waste Heat Estimates).

Recovering industrial waste heat can be achieved via numerous methods. The heat can either be “reused” within the same process or transferred to another process. Ways of reusing heat locally include using combustion exhaust gases to preheat combustion air or feedwater in industrial boilers. By preheating the feedwater before it enters the boiler, the amount of energy required to heat the water to its final temperature is reduced. Alternately, the heat can be transferred to another process; for example, a heat exchanger could be used to transfer heat from combustion exhaust gases to hot air needed for a drying oven. In this manner, the recovered heat can replace fossil energy that would have otherwise been used in the oven. Such methods for recovering waste heat can help facilities significantly reduce their fossil fuel consumption, as well as reduce associated operating costs and pollutant emissions. Typical sources of waste heat and recovery options are listed in Table 1.

Table 1- Waste heat sources and its uses

Waste Heat Sources	Uses for Waste Heat
Combustion Exhausts: Cement kiln Glass melting furnace Aluminum reverberatory furnace Boiler • Process offgases: Steel electric arc furnace Aluminum reverberatory furnace • Cooling water from: Furnaces, Air compressors, Internal combustion engines • Conductive, convective, and radiative losses from equipment: HallHèroult cells • Conductive, convective, and radiative losses from heated products: Hot cokes, Blast furnace slags	• Combustion air preheating • Boiler feedwater preheating • Load preheating • Power generation • team generation for use in: power generation, mechanical power, process steam • Pace heating • Water preheating • Transfer to liquid or gaseous process streams

Another advantage of waste heat recovery is that it can reduce capacity requirements for facilities' thermal conversion devices, leading to reductions in capital costs. For example, consider the case of combustion exhaust gases used to heat building air for space heat. In addition to replacing purchased fuels, the recovered waste heat can potentially eliminate the need for additional space heating equipment, thereby reducing capital and overhead costs[1].

In addition to the economic benefits of waste heat recovery for the facility, waste heat recovery is a Greenhouse gas free source of energy. Developed countries like U.S., Japan etc industrial sector consumes about 32 x 10_{15} Btu/yr, or one third of the energy consumed in these countries. It is likewise responsible for about one third of energy related greenhouse gas emissions[2].Reducing the Nation's fossil fuel demand will result in accompanying reductions in greenhouse gas emissions.

2.0 Literature review

For the study of this report and case study voluminous literature is been referred and studied. For this study I have gone through various papers and publications few of them are mentioned here. The research papers mainly include work related to waste heat recovery, there classification, technologies etc.

Cementhai Energy Conservation Co., Ltd.
Siam Cement (Thung Song) Waste Heat Power Generation Project (TS46 Project)

It is expected that the project would deliver multiple benefits in respect of sustainable development including:

Environmental benefits

- Reduction of greenhouse gas emission through the avoided electricity generation by other gridconnected power plant;
- Reduction of dust and particulate matters from the installation of de-dusting chamber;
- Reduction of the water used to cool down the waste heat before venting;
- Reduction in usage of non-renewable energy, ie fossil fuel for grid electricity generation;

Social benefits

- Involvement of local communities through public participation meeting, in which people accepted the project;
- Increased employment by employing 9 full time staff to operate the system;

Economic benefits

- Reduction in the dependency fossil fuel for electricity generation while at the same time enhancing energy security by increasing diversity of supply;
- Promoting the best practices of waste management in the cement industry;
- Generating incomes to the local community through additional local employment;
- Enhancing competitiveness of cement industry which is currently facing a lot of
- competitive pressure in the global market;
- Demonstrating the use of CDM as an incentive for bringing about an energy efficiency project;

Technology transfer

- Promoting technological excellence in the waste heat recovery project; and
- The power plant staff will receive necessary training on the management of the power plant.

Waste Heat Recovery for the Cement Sector: commissioned by IFC, a member of the World Bank Group found that:

Total worldwide cement consumption reached 3,312 Mt in 2010, up 10.4 percent over the previous year. Global consumption continued to climb, rising to 3,585 Mt in 2011 and an estimated 3,738 Mt in 2012 (increases of 8.3 percent and 4.2 percent respectively) (ICR 2013). Estimated consumption for 2013 is over 3,900 Mt.

There is a strong potential for WHR in Asia and Latin America. Opportunities in selected countries in Africa and Middle East are also profound. While WHR viability will vary in each specific cement plant, the general enabling factors are favorable in East and South Asian countries and in Latin America. In Africa and Middle East there is a mixed combination of enabling factors, most of all political stability and industrial electricity tariffs.

This report provides a comprehensive framework and necessary market information for the analysis of WHR opportunities in eleven country markets in Africa, South and East Asia, Middle East and Latin America. A review of the status of the cement industry and prospects for WHR development in a select group of countries was undertaken to identify emerging markets where WHR power generation may have significant growth potential and strong market drivers. The countries were selected based on the robustness of their respective cement industries and cement markets, relative prospects for near and mid-term growth in their economies and cement consumption, and market factors that would drive consideration of WHR such as power reliability concerns, industrial electricity tariffs and/or environmental and sustainability initiatives.

Growing trends in process off gas and waste heat recovery in captive power generation research paper by: Professor S.Umamaheswari

Classifies various waste heat sources in high, medium and low temperature heat sources.

DESIGN OF WASTE HEAT RECOVERY SYSTEM research paper by
Dr. Shabina Khanam, NIT Raurkela

Explained about various heat recovery equipments

- Heat Exchangers
- Recuperator
- Regenerator
- Furnace Regenerator
- Rotary Regenerator/Heat Wheel
- Passive Air Preheaters
- Regenerative/Recuperative Burners
- Finned Tube Heat Exchangers/Economizers
- Waste Heat Boilers

Waste Heat Recovery:
Technology and Opportunities in U.S. Industry report Prepared by U.S. Department of energy

Technologies of waste heat recovery

Steam Rankine Cycle

The most frequently used system for power generation from waste heat involves using the heat to generate steam, which then drives a steam turbine. A schematic of waste heat recovery with a Rankine cycle is shown in Figure 10. The traditional steam Rankine cycle is the most efficient option for waste heat recovery from exhaust streams with temperatures above about 650-700° F [340-370° C][9].At lower waste heat temperatures, steam cycles become less cost effective, since low pressure steam will require bulkier equipment. Moreover, low temperature waste heat may not provide sufficient energy to superheat the steam, which is a requirement for preventing steam condensation and erosion of the turbine blades.

Therefore, low temperature heat recovery applications are better suited for the organic Rankine Cycle or Kalina cycle, which use fluids with lower boiling point temperatures compared to steam.

Organic Rankine Cycle

The Organic Rankine Cycle (ORC) operates similar to the steam Rankine cycle, but uses an organic working fluid instead of steam. Options include silicon oil, propane, haloalkanes (e.g., “freons”), isopentane, isobutane, pxylene, and toluene, which have a lower boiling point and higher vapor pressure than water. This allows the Rankine cycle to operate with significantly lower waste heat temperatures— sometimes as low as 150oF [66oC].

Kalina Cycle

The Kalina cycle is a variation of the Rankine cycle, using a mixture of ammonia and water as the working fluid. A key difference between single fluid cycles and cycles that use binary fluids is the temperature profile during boiling and condensation. For single fluid cycles (e.g., steam or organic Rankine), the temperature remains constant during boiling. As heat is transferred to the working medium (e.g., water), the water temperature slowly increases to boiling temperature, at which point the temperature remains constant until all the water has evaporated. In contrast, a binary mixture of water and ammonia (each of which has a different boiling point) will increase its temperature during evaporation. This allows better thermal matching with the waste heat source and with the cooling medium in the condenser. Consequently, these systems achieve significantly greater energy efficiency.

Direct Electrical Conversion Devices

Whereas traditional power cycles involve using heat to create mechanical energy and ultimately electrical energy, new technologies are being developed that can generate electricity directly from heat. These include thermoelectric, thermionic, and piezoelectric devices. There is no evidence that these systems have been tested in industrial waste heat recovery applications, although a few have undergone some prototype testing in applications such as heat recovery in automotive vehicles.

Thermoelectric Generation

Thermoelectric (TE) materials are semiconductor solids that allow direct generation of electricity when subject to a temperature differential. These systems are based on a phenomenon known as the Seebeck effect: when two different semiconductor materials are subject to a heat source and heat sink, a voltage is created between the two semiconductors.

Piezoelectric Power Generation

Piezoelectric Power Generation (PEPG) is an option for converting low temperature waste heat (200300 °F or [100150° C]) to electrical energy[20]. Piezoelectric devices convert mechanical energy in the form of ambient vibrations to electrical energy. A piezoelectric thin film membrane can take advantage of oscillatory gas expansion to create a voltage output. A recent study[21] identified several technical challenges associated with PEPG technologies:

- low efficiency: PEPG technology is only about 1% efficient; difficulties remain in obtaining high enough oscillatory frequencies; current devices operate at around 100 Hz, and frequencies closer to 1,000 Hz are needed,
- high internal impedance,
- complex oscillatory fluid dynamics within the liquid/vapour chamber,
- need for long term reliability and durability, and
- high costs

Thermionic Generation

In these systems, a temperature difference drives the flow of electrons through a vacuum from a metal to a metal oxide surface. One key disadvantage of these systems is that they are limited to applications with high temperatures above 1,800°F [1,000°C]. However, some development has enabled their use at about 210-570° F [100-300°C][24].

Thermo Photo Voltaic (TPV) Generator

TPV Generators can be used to convert radiant energy into electricity. These systems involve a heat source, an emitter, a radiation filter, and a PV cell (like those used in solar panels). As the emitter is heated, it emits electromagnetic radiation. The PV cell converts this radiation to electrical energy.

3.0 Factors Affecting Waste Heat Recovery Feasibility

Evaluating the feasibility of waste heat recovery requires characterizing the waste heat source and the stream to which the heat will be transferred. Important waste stream parameters that must be determined include:

- Heat quantity,
- Heat temperature/quality,
- Composition,
- Minimum allowed temperature, and
- Operating economics.

These parameters allow for analysis of the quality and quantity of the stream and also provide insight into possible materials/design limitations. For example, corrosion of heat transfer media is of considerable concern in waste heat recovery, even when the quality and quantity of the stream is acceptable[3]. The following provide an overview of important concepts that determine waste heat recovery feasibility.

3.1 Heat Quantity

The quantity, or heat content, is a measure of how much energy is contained in a waste heat stream, while quality is a measure of the usefulness of the waste heat. The quantity of waste heat contained in a waste stream is a function of both the temperature and the mass flow rate of the stream:

$E = mh(t)$………………..Equation (1)

Where E is the waste heat loss (Btu/hr);
m is the waste stream mass flow rate (lb/hr); and
h(t) is the waste stream specific enthalpy (Btu/lb) as a function of temperature.

Enthalpy is not an absolute term, but must be measured against a reference state (for example, the enthalpy of a substance at room temperature and atmospheric pressure). In this report, the enthalpy of waste heat streams is calculated at atmospheric pressure and two reference temperatures: 77°F [25°C] and 300°F [150°C]. A reference of 77°F [25°C] was used to provide a basis for estimating the maximum heat attainable if a gas is cooled to ambient temperature. The second reference temperature of 300°F [150°C] is more representative of current industrial practices since the majority of industrial heat recovery systems do not cool gases below this value (see Section 2.4 Minimum Allowable Temperature).

Although the quantity of waste heat available is an important parameter, it is not alone an effective measure of waste heat recovery opportunity. It is also important to specify the waste heat quality, as determined by its temperature.

3.2 Waste Heat Temperature/Quality

The waste heat temperature is a key factor determining waste heat recovery feasibility. Waste heat temperatures can vary significantly, with cooling water returns having low temperatures around 100 200° F [40 90° C] and glass melting furnaces having flue temperatures above 2,400°F [1,320°C]. In order to enable heat transfer and recovery, it is necessary that the waste heat source temperature is higher than the heat sink temperature. Moreover, the magnitude of the temperature difference between the heat source and sink is an important determinant of waste heat's utility or "quality". The source and sink temperature difference influences a) the rate at which heat is transferred per unit surface area of heat exchanger, and b) the maximum theoretical efficiency of converting thermal from the heat source to another form of energy (i.e., mechanical or electrical). Finally, the temperature range has important ramifications for the selection of materials in heat exchanger designs[4].

Waste heat recovery opportunities are categorized in this report by dividing temperature ranges into low, medium, and high quality of waste heat sources as follows:

High: 1,200oF [649°C] and higher
Medium: 450oF [232°C] to 1,200°F [650°C]
Low: 450oF [232°C] and lower9

Typical sources of low, medium, and high temperature waste heat are listed in Table 4, along with related recovery advantages, barriers, and applicable technologies.

3.2.1 Heat Exchanger Area Requirements

The temperature of waste heat influences the rate of heat transfer between a heat source and heat sink, which significantly influences recovery feasibility[3]. The expression for heat transfer can be generalized by the following equation:
$Q = UA\Delta T$ (W or Btu/s)……………. Equation (2)

Where Q is the heat transfer rate;
U is the heat transfer coefficient;
A is the surface area for heat exchange; and
ΔT is the temperature difference between two streams.
Since heat transfer is a function of U, area, and ΔT, a small ΔT will require a larger heat transfer.

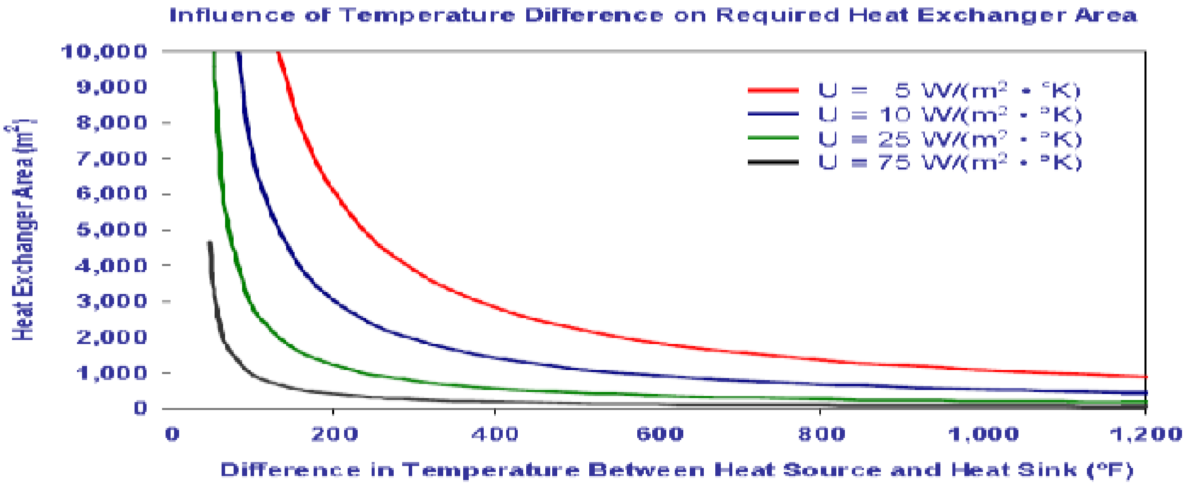


Figure 1- Influence of temprature difference on heat exchanger area

This figure graphs the surface area (m2) required for recovering 10million Btu/hr from a gaseous exhaust stream with a mass flow rate of 5 million lbs/hr by transfer to liquid water flowing at 1 ft3/s. Calculated from Equation 2 using estimated log mean temperature difference for ΔT.

3.2.2 Temperature and Material Selection

The temperature of the waste heat source also has important ramifications for material selection in heat exchangers and recovery systems. Corrosion and oxidation reactions, like all chemical reactions, are accelerated dramatically by temperature increases. If the waste heat source contains corrosive substances, the heat recovery surfaces can quickly become damaged. In addition, carbon steel at temperatures above 800°F [425oC] and stainless steel above 1,200°F [650oC] begins to oxidize. Therefore, advanced alloys or composite materials must be used at higher temperatures. Metallic materials are usually not used at temperatures above 1,600°F [871oC]. Alternatives include either bleeding dilution air into the exhaust gases to lower the exhaust temperature, or using ceramic materials that can better withstand the high temperature. In the case of air bleeding, the quantity of heat contained in the exhaust stream remains constant, but the quality is reduced due to the temperature drop.

3.3 Waste Stream Composition

Although chemical compositions do not directly influence the quality or quantity of the available heat (unless it has some fuel value), the composition of the stream affects the recovery process and material selection. The composition and phase of waste heat streams will determine factors such as thermal conductivity and heat capacity, which will impact heat exchanger effectiveness. Meanwhile, the process specific chemical makeup of off gases will have an important impact on heat exchanger designs, material constraints, and costs. Heat transfer rates in heat exchangers are dependent on the composition and phase of waste heat streams, as well as influenced by the deposition of any fouling substances on the heat exchanger. Denser fluids have higher heat transfer coefficients, which enables higher heat transfer rates per unit area for a given temperature difference

Table 1- General Range of Heat Transfer Coefficients for Sensible Heat Transfer in Tubular Exchangers

Fluid conditions	Heat Transfer coefficient (W/m^2 .°k)
Water, liquid	5x 10^3 to $1x10^4$
Light organics, liquid	$1.5x10^3$ to $2x10^3$
Gas (P=1,000kpa)	$2.5x10^2$ to $4x10^2$
Gas (=100-200kpa)	8x10 to $1.2x10^2$

Another key consideration is the interaction between chemicals in the exhaust stream and heat exchanger materials. Fouling is a common problem in heat exchange, and can substantially reduce heat exchanger effectiveness or cause system failure. Deposition of substances on the heat exchanger surface can reduce heat transfer rates as well as inhibit fluid flow in the exchanger. In other cases, it will degrade the heat exchanger such that it can no longer be used. Methods for addressing fouling are numerous and include filtering contaminated streams, constructing the exchanger with advanced materials, increasing heat exchanger surface areas, and designing the heat exchanger for easy access and cleaning. Nevertheless, the problem of fouling remains a significant challenge in thermal science. A 1992 study by Pacific Northwest National Laboratories examined 231patents dealing with fouling. The significant patent activity and continued antidotal reports indicate that fouling remains an unresolved problem; moreover, a large portion of the research is reactive, involving methods for easily cleaning fouling, rather than methods for preventing fouling[5].

3.4 Minimum Allowable Temperature

The minimum allowable temperature for waste streams is often closely connected with material corrosion problems. Depending on the fuel used, combustion related flue gases contain varying concentrations of carbon dioxide, water vapor, NOX, SOX, unoxidized organics, and minerals. If exhaust gases are cooled below the dew point temperature, the water vapor in the gas will condense and deposit corrosive substances on the heat exchanger surface. Heat exchangers designed from low cost materials will quickly fail due to chemical attack. Therefore, heat exchangers are generally designed to maintain exhaust temperatures above the condensation point. The minimum temperature for preventing corrosion depends on the composition of the fuel. For example, exhaust gases from natural gas might be cooled as low as ~250°F [~120°C], while exhaust gases from coal or fuel oils with higher sulfur contents may be limited to ~300 °F [~150oC] to ~350°F [~175°C]. Minimum exhaust temperatures may also be constrained by process related chemicals in the exhaust stream; for example, sulfates in exhaust gases from glass melting furnaces will deposit on heat exchanger surfaces at temperatures below about 510°F [270°C].

The most common method for preventing chemical corrosion is designing heat exchangers with exhaust temperatures well above the dew point temperature. However, there are some cases where heat exchangers use advanced alloys and composite materials to further recover low temperature heat. These systems have not seen much commercial application due to challenges such as high material costs, large surface areas required for heat exchange, and lack of an available endues for low temperature waste heat.

3.5 Economies of Scale, Accessibility, and Other Factors

Several additional factors can determine whether heat recovery is feasible in a given application. For example, small scale operations are less likely to install heat recovery, since sufficient capital may not be available, and because payback periods may be longer. Operating schedules can also be a concern. If a waste heat source is only available for a limited time every day, the heat exchanger may be exposed to both high and low temperatures. In this case, one must ensure that the heat exchange material does not fatigue due to thermal cycling. Additionally, it is important that the schedule for the heat source match the schedule for the heat load. If not, additional systems may be required to provide heat when the waste heat source is not available.

Another concern is the ease of access to the waste heat source. In some cases, the physical constraints created by equipment arrangements prevent easy access to the heat source, or prevent the installation of any additional equipment for recovering the heat. Additionally, constraints are presented by the transportability of heat streams. Hot liquid streams in process industries are frequently recovered, since they are easily transportable. Piping systems are easy to tap into and the energy can be easily transported via piping to the recovery equipment. In contrast, hot solid streams (e.g., ingots, castings, cement clinkers) can contain significant amounts of energy but their energy is not easily accessible or transportable to recovery equipment. As a result, waste energy recovery is not widely practiced with hot solid materials.

4.0 Classification and Application of waste heat

TABLE 3- WASTE SOURCE AND QUALITY		
S.No.	**Source**	**Quality**
1.	Heat in flue gases.	The higher the temperature, the greater the potential value for heat recovery
2.	Heat in vapour streams.	As above but when condensed, latent heat also recoverable.
3	Convective and radiant heat lost from exterior of equipment	Low grade – if collected may be used for space heating or air preheats.
4.	Heat losses in cooling water.	Low grade – useful gains if heat is exchanged with incoming fresh water.
5.	Heat losses in providing chilled water or in the disposal of chilled water.	a) High grade if it can be utilized to reduce demand for refrigeration. b) Low grade if refrigeration unit used as a form of heat pump.
6.	Heat stored in products leaving the process	Quality depends upon temperature.
7.	Heat in gaseous and liquid effluents leaving process.	Poor if heavily contaminated and thus requiring alloy heat exchanger.

4.1 High Temperature Heat Recovery

Note: All of these results from direct fuel fired processes.

TABLE 5- TYPICAL WASTE HEAT TEMPERATURE AT MEDIUM TEMPERATURE RANGE FROM VARIOUS SOURCES

TABLE 4 TYPICAL WASTE HEAT TEMPERATURE AT HIGH TEMPERATURE RANGE

FROM VARIOUS SOURCES

TYPES OF DEVICES	**TEMPERATURE, °C**	**ADVANTAGES**	**BARRIERS**
Nickel refining furnace	1370 –1650	High quality energy available for diverse uses with varying temperature requirement Effective power generation High rate of heat transfer per unit area	Increased thermal stresses on heat transfer material Increased rate of chemical activity and corrosion
Aluminium refining furnace	650-760		
Zinc refining furnace	760-1100		
Copper refining furnace	760- 815		
Steel heating furnaces	925-1050		
Copper reverberatory furnace	900-1100		
Open hearth furnace	650-700		
Cement kiln (Dry process)	620- 730		
Glass melting furnace	1000-1550		
Hydrogen plants	650-1000		
Solid waste incinerators	650-1000		
Fume incinerators	650-1450		

Type of Device	**Temperature, °C**	**ADVANTAGES**	**BARRIERS**
Steam boiler exhausts	230-480	Better compatibility with heat exchanger Practical for power generation	Low rate of heat exchange
Gas turbine exhausts	370-540		
Reciprocating engine exhausts	315-600		
Reciprocating engine exhausts (turbo charged)	230- 370		
Heat treating furnaces	425 - 650		
Drying and baking ovens	230 - 600		
Catalytic crackers	425 - 650		
Annealing furnace cooling systems	425 - 650		

4.2 Medium Temperature Heat Recovery

Note: Most of the waste heat in this temperature range comes from the exhaust of directly fired process units.

4.3 Low temperature waste heat recovery

Note: low temperature waste heat may be useful in a supplementary way for preheating purposes.

TABLE 6- TYPICAL WASTE HEAT TEMPERATURE AT LOW TEMPERATURE RANGE FROM VARIOUS SOURCES

SOURCE	**TEMPERATURE, °C**	**ADVANTAGE**	**BARRIERS**
Process steam condensate	55-88	Large number of processes generate great amount of energy at low temperature	Less end use for low temperature heat Low efficiency of power generation
Bearings	32-88		
Welding machines	32-88		
Injection molding machines	32-88		
Annealing furnaces	66-230		
Forming dies	27-88		
Air compressors	27-50		
Pumps	27-88		
Internal combustion engines	66-120		
Air conditioning and refrigeration condensers	32–43		
Liquid still condensers	32-88		
Drying, baking and curing ovens	93-230		

5.0 Benefits of Waste Heat Recovery

Benefits of ‘waste heat recovery’ can be broadly classified in two categories:

5.1 Direct Benefits:

Recovery of waste heat has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption & costs, and process cost.

5.2 Indirect Benefits:

a) **Reduction in pollution**: A number of toxic combustible wastes such as carbon monoxide gas, sour gas, carbon black off gases, oil sludge, Acrylonitrile and other plastic chemicals etc, releasing to atmosphere if/when burnt in the incinerators serves dual purpose i.e. recovers heat and reduces the environmental pollution levels.

b) **Reduction in equipment sizes**: Waste heat recovery reduces the fuel consumption, which leads to reduction in the flue gas produced. This results in reduction in equipment sizes of all flue gas handling equipments such as fans, stacks, ducts, burners, etc.

c) **Reduction in auxiliary energy consumption**: Reduction in equipment sizes gives additional benefits in the form of reduction in auxiliary energy consumption like electricity for fans, pumps etc.

5.3 Barriers and Research, Development, and Demonstration Needs Identified for Promoting Waste Heat Recovery Practices

Numerous barriers impact the economy and effectiveness of heat recovery equipment and impede their wider installation. Many of these barriers, described below, are interrelated, but can generally be categorized as related to cost, temperature restrictions, chemical composition, application specifics, and inaccessibility/transportability of heat sources.

1. Costs

a. Long Payback Periods
Costs of heat recovery equipment, auxiliary systems, and design services lead to long payback periods in certain applications. Additionally, several industry subsectors with high quality waste heat sources (e.g., metal casting) are renowned for small profit margins and intense internal competition for limited capital resources.

b. Material Constraints and Costs
Certain applications require advanced and more costly materials. These materials are required for high temperature streams, streams with high chemical activity, and exhaust streams cooled

below condensation temperatures. Overall material costs per energy unit recovered increase as larger surface areas are required for more efficient, lower temperature heat recovery systems.

c. Economies of Scale

Equipment costs favor large scale heat recovery systems and create challenges for small scale operations.

d. Operation and Maintenance Costs

Corrosion, scaling, and fouling of heat exchange materials lead to higher maintenance costs and lost productivity.

2. Temperature Restrictions

a. Lack of a Viable End Use

Many industrial facilities do not have an onsite use for low temperature heat. Meanwhile, technologies that create endues options (e.g., low temperature power generation) are currently less developed and more costly.

b. Material Constraints and Costs

i. High temperature

Materials that retain mechanical and chemical properties at high temperatures are costly. Therefore, waste heat is often quickly diluted with outside air to reduce temperatures. This reduces the quality of energy available for recovery.

ii. Low temperature

Liquid and solid components can condense as hot streams cool in recovery equipment. This leads to corrosive and fouling conditions. The additional cost of materials that can withstand corrosive environments often prevents low temperature recovery.

iii. Thermal cycling

The heat flow in some industrial processes can vary dramatically and create mechanical and chemical stress in equipment.

c. Heat Transfer Rates

Small temperature differences between the heat source and heat sink lead to reduced heat transfer rates and require larger surface areas.

3. Chemical Composition

a. Temperature Restrictions

Waste heat stream chemical compatibility with recovery equipment materials will be limited both at high and low temperatures.

b. Heat Transfer Rates

Deposition of substances on the recovery equipment surface will reduce heat transfer rates and efficiency.

c. Material Constraints and Costs
Streams with high chemical activity require more advanced recovery equipment materials to withstand corrosive environments.

d. Operation and Maintenance Costs
Streams with high chemical activity that damage equipment surfaces will lead to increased maintenance costs.

e. Environmental Concerns
Waste heat recovery from exhaust streams may complicate or alter the performance of environmental control and abatement equipment.

f. Product/Process Control
Chemically active exhaust streams may require additional efforts to prevent cross contamination between streams.

4.) Application specific Constraints

a. Process specific Constrains
Equipment designs are process specific and must be adapted to the needs of a given process. For example, feed preheat systems vary significantly between glass furnaces, blast furnaces, and cement kilns.

b. Product/ Process Control
Heat recovery can complicate and compromise process/quality control systems.

5.) Inaccessibility/Transportability

a. Limited Space
Many facilities have limited physical space in which to access waste heat streams (e.g., limited floor or overhead space)

b. Transportability
Many gaseous waste heat streams are discharged at near atmospheric pressure (limiting the ability to transport them to and through equipment without additional energy input).

c. Inaccessibility
It is difficult to access and recover heat from unconventional sources such as hot solid product streams (e.g., ingots) and hot equipment surfaces (e.g., sidewalls of primary aluminium cells). RD&D needs to address these barriers are summarized in Table A.

6.0 Waste Heat Recovery Options and Technologies

Methods for waste heat recovery include transferring heat between gases and/or liquids (e.g., combustion air preheating and boiler feed water preheating), transferring heat to the load entering furnaces (e.g., batch/cullet preheating in glass furnaces), generating mechanical and/or electrical power, or using waste heat with a heat pump for heating or cooling facilities. The terminology for heat recovery technologies frequently varies among different industries. Since this report addresses multiple industries, the terminology used below is the basis for all subsequent discussion of heat exchange technologies in different industries.

6.1 Heat Exchangers

Heat exchangers are most commonly used to transfer heat from combustion exhaust gases to combustion air entering the furnace. Since preheated combustion air enters the furnace at a higher temperature, less energy must be supplied by the fuel. Typical technologies used for air preheating include recuperators, furnace regenerators, burner regenerators, rotary regenerators, and passive air preheaters.

6.1.1 Recuperator

Recuperators recover exhaust gas waste heat in medium to high temperature applications such as soaking or annealing ovens, melting furnaces, afterburners, gas incinerators, radiant tube burners, and reheat furnaces. Recuperators can be based on radiation, convection, or combinations:

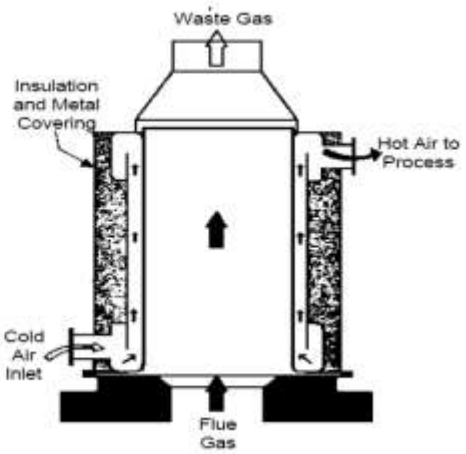


Figure 2 -Metallic Radiation Recuperator Design (Source: PG&E)

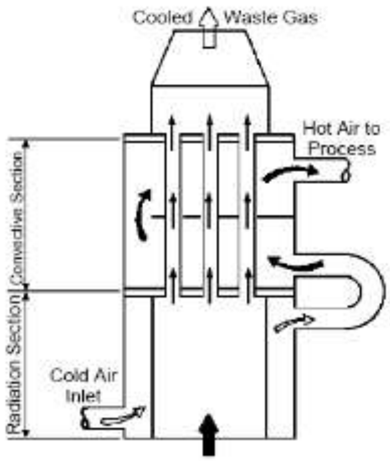


Figure 3-Combined Radiation/Convection Recuperator

- A simple radiation recuperator consists of two concentric lengths of ductwork, as shown in Figure 2. Hot waste gases pass through the inner duct and heat transfer is primarily radiated to the wall to the cold incoming air in the outer shell. The preheated shell air then travels to the furnace burners.

- The convective or tube type recuperator passes the hot gases through relatively small diameter tubes contained in a larger shell. The incoming combustion air enters the shell and is baffled around the tubes, picking up heat from the waste gas.
- Another alternative is the combined radiation/convection recuperator, shown in Figure 3. The system includes a radiation section followed by a convection section in order to maximize heat transfer effectiveness. Recuperators are constructed out of either metallic or ceramic materials. Metallic recuperators are used in applications with temperatures below 2,000°F [1,093°C], while heat recovery at higher temperatures is better suited to ceramic tube recuperators. These can operate with hot side temperatures as high as 2,800°F [1,538°C] and cold side temperatures of about 1,800°F [982°C][6].

6.2 Regenerator

6.2.1 Furnace Regenerator

Regenerative furnaces consist of two brick “checkerwork” chambers through which hot and cold airflow alternately (Figure 4). As combustion exhausts pass through one chamber, the bricks absorb heat from the combustion gas and increase in temperature. The flow of air is then adjusted so that the incoming combustion air passes through the hot checkerwork, which transfers heat to the combustion air entering the furnace. Two chambers are used so that while one is absorbing heat from the exhaust gases, the other is transferring heat to the combustion air. The direction of airflow is altered about every 20 minutes.

Regenerators are most frequently used with glass furnaces and coke ovens, and were historically used with steel open hearth furnaces, before these furnaces were replaced by more efficient designs. They are also used to preheat the hot blast provided to blast stoves used in iron making; however, regenerators in blast stoves are not a heat recovery application, but simply the means by which heat released from gas combustion is transferred to the hot blast air . Regenerator systems are specially suited for high temperature applications with dirty exhausts. One major disadvantage is the large size and capital costs, which are significantly greater than costs of recuperators[7].

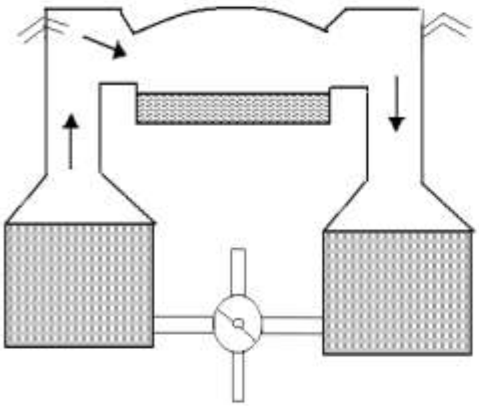


Figure 4- Regenerative Furnace Diagram

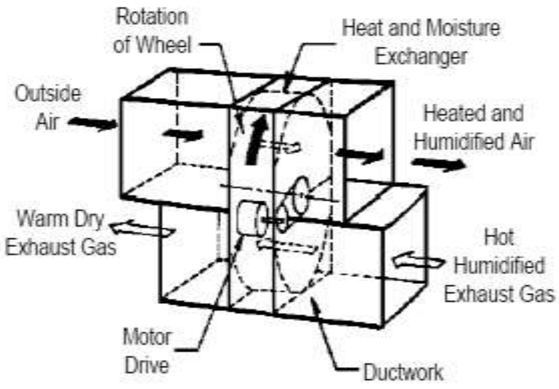


Figure 5- Rotary Regenerator(Source:PG&E, 1997)

6.2.2 Rotary Regenerator/Heat Wheel

Rotary regenerators operate similar to fixed regenerators in that heat transfer is facilitated by storing heat in a porous media, and by alternating the flow of hot and cold gases through the regenerator. Rotary regenerators, sometimes referred to as air preheaters and heat wheels, use a rotating porous disc placed across two parallel ducts, one containing the hot waste gas, the other containing cold gas (Figure 5). The disc, composed of a high heat capacity material, rotates between the two ducts and transfers heat from the hot gas duct to the cold gas duct. Heat wheels are generally restricted to low and medium temperature applications due to the thermal stress created by high temperatures. Large temperature differences between the two ducts can lead to differential expansion and large deformations, compromising the integrity of ductwheel air seals. In some cases, ceramic wheels can be used for higher temperature applications. Another challenge with heat wheels is preventing cross contamination between the two gas streams, as contaminants can be transported in the wheel's porous material.

One advantage of the heat wheel is that it can be designed to recover moisture as well as heat from clean gas streams. When designed with hygroscopic materials, moisture can be transferred from one duct to the other. This makes heat wheels particularly useful in air conditioning applications, where incoming hot humid air transfers heat and moisture to cold outgoing air. Besides its main application in space heating and air conditioning systems, heat wheels are also used to a limited extent in medium temperature applications. They have also been developed for high temperature furnace applications such as aluminium furnaces, though they are not widely implemented in the United States due to cost[8].They are also occasionally used for recovery from boiler exhausts, but more economical recuperators and economizers are usually preferred.

6.3 Passive Air Preheaters

Passive air preheaters are gas to gas heat recovery devices for low to medium temperature applications where cross contamination between gas streams must be prevented. Applications include ovens, steam boilers, gas turbine exhaust, secondary recovery from furnaces, and recovery from conditioned air.

Passive preheaters can be of two types – the plate type and heat pipe. The plate type exchanger (Figure 6) consists of multiple parallel plates that create separate channels for hot and cold gas streams. Hot and cold flows alternate between the plates and allow significant areas for heat transfer. These systems are less susceptible to contamination compared to heat wheels, but they are often bulkier, more costly, and more susceptible to fouling problems.

The heat pipe heat exchanger consists of several pipes with sealed ends. Each pipe contains a capillary wick structure that facilitates movement of the working fluid between the hot and cold ends of the pipe. As shown in Figure 7 below, hot gases pass over one end of the heat pipe, causing the working fluid inside the pipe to evaporate. Pressure gradients along the pipe cause the hot vapour to move to the other end of the pipe, where the vapour condenses and transfers heat to the cold gas. The condensate then cycles back to the hot side of the pipe via capillary action.

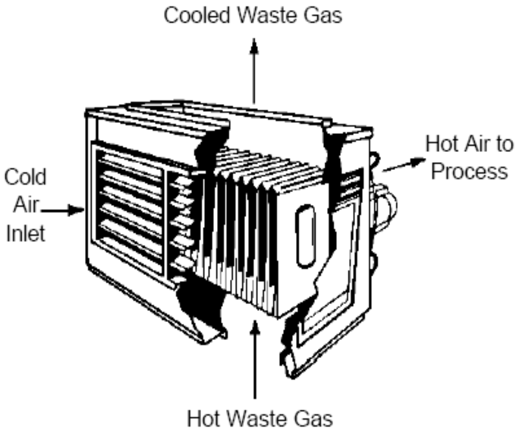


Figure 6- Passive Gas to Gas Air Preheater
(Source, PG & E, 1997)

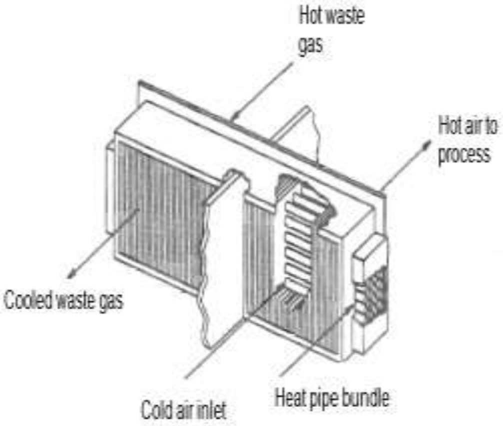


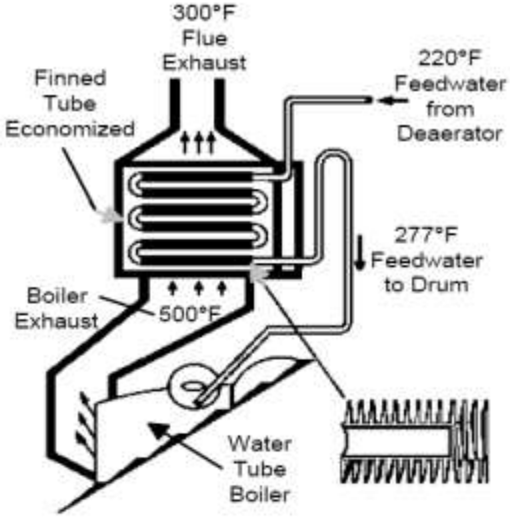
Figure 7- Heat Pipe Heat Exchanger
(Source: Turner, 2006)

6.4 Regenerative/Recuperative Burners

Burners that incorporate regenerative or recuperative systems are commercially available. Simpler and more compact in design and construction than a standalone regenerative furnaces or recuperators these systems provide increased energy efficiency compared to burners operating with ambient air. A self recuperative burner incorporates heat exchange surfaces as part of the burner body design in order to capture energy from the exiting flue gas, which passes back through the body. Self regenerative burners pass exhaust gases through the burner body into a refractory media case and operate in pairs similar in a manner to a regenerative furnace. Typically, recuperative burner systems have less heat exchange area and regenerative burner systems lower mass than standalone units. Hence, their energy recovery is lower but their lower costs and ease of retrofitting make them an attractive option for energy recovery.

6.5 Finned Tube Heat Exchangers/Economizers

Finned tube heat exchangers are used to recover heat from low to medium temperature exhaust gases for heating liquids. Applications include boiler feedwater preheating, hot process liquids, hot water for space heating, or domestic hot water. The finned tube consists of a round tube with attached fins that maximize surface area and heat transfer rates. Liquid flows through the tubes and receive heat from hot gases flowing across the tubes. Figure 8 illustrates a finned tube exchanger where boiler exhaust gases are used for feedwater preheating, a setup commonly referred to as a boiler “economizer”



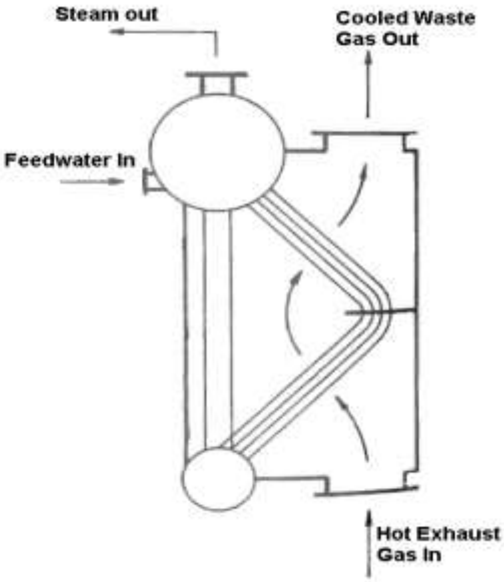


Figure 8 Finned Tube Exchanger/ Boiler Economizer

Figure 9 Waste Heat Boiler
(Source: PG&E 2007)

6.6 Waste Heat Boilers

Waste heat boilers, such as the two pass boiler shown in Figure 11, are water tube boilers that use medium to high temperature exhaust gases to generate steam. Waste heat boilers are available in a variety of capacities, allowing for gas intakes from 1000 to 1million ft3/min. In cases where the waste heat is not sufficient for producing desired levels of steam, auxiliary burners or an afterburner can be added to attain higher steam output. The steam can be used for process heating or for power generation. Generation of superheated steam will require addition of an external superheater to the system.

7.0 Power Generation technologies using waste heat

Generating power from waste heat typically involves using the waste heat from boilers to create mechanical energy that then drives an electric generator. While these power cycles are well developed, new technologies are being developed that can generate electricity directly from heat, such as thermoelectric and piezoelectric generation. When considering power generation options for waste heat recovery, an important factor to keep in mind is the thermodynamic limitations on power generation at different temperatures. As discussed in Section 2, the efficiency of power generation is heavily dependent on the temperature of the waste heat source. In general, power generation from waste heat has been limited to only medium to high temperature waste heat sources. However, advances in alternate power cycles may increase the feasibility of generation at low temperatures. While maximum efficiency at these temperatures is lower, these systems can still be economical in recovering large quantities of energy from waste heat. Table 7 summarizes different power generation technologies.

Table 7- Different power generation technologies

Thermal conversion technology	Temperature range	Sources of waste heat	Capital cost
Traditional Steam Cycle (a)	M,H	Exhaust from gas turbines, reciprocating engines, incinerators, and furnaces.	$11001,400/kW(f)
Kalina Cycle (d)	L,M,	Gas turbine exhaust, boiler exhaust, cement kilns	$11001,500/kW(f)
Organic Rankine Cycle (c,e)	L,M	Gas turbine exhaust, boiler exhaust, heated water, cement kilns	$1,5003,500/kW(f)
Thermoelectric Generation (b)	MH	Not yet demonstrated in industrial applications	$20,00030,0000/kW(b)
Piezoelectric generation (b)	L	Not yet demonstrated in industrial applications	$10,000,000/kW(b)
Thermal Photovoltaic	MH	Not yet demonstrated in industrial applications	N/A

a. Sean Casten, 2003. Update on US Steam Turbine technology, Presented to Canadian District Energy Association
8th Annual Conference June 20th 2003.
b. BCS, Inc., Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery
c. Daniel Duffy, “Better Cogeneration through Chemistry: the Organic Rankine Cycle

d. based on cement kiln waste heat recovery project economics. Mark Mirolli, “The Kalina Cycle for Cement Kiln
Waste Heat Recovery Power Plants.” Cement Industry Technical Conference, 2005. 1520 May 2005.
e. “Organic Rankine Cycle for Electricity Generation. http://www.stowaselectedtechnologies.nl
f. Paul Cunningham, “Waste Heat/ Cogen Opportunities in the Cement Industry” Cogeneration and Competitive Power Journal. Vol 17, No 3 p. 3150

7.1 Generating Power via Mechanical Work

7.1.1 Steam Rankine Cycle

The most frequently used system for power generation from waste heat involves using the heat to generate steam, which then drives a steam turbine. A schematic of waste heat recovery with a Rankine cycle is shown in Figure 10. The traditional steam Rankine cycle is the most efficient option for waste heat recovery from exhaust streams with temperatures above about 650-700° F [340-370° C][9].At lower waste heat temperatures, steam cycles become less cost effective, since low pressure steam will require bulkier equipment. Moreover, low temperature waste heat may not provide sufficient energy to superheat the steam, which is a requirement for preventing steam condensation and erosion of the turbine blades.
Therefore, low temperature heat recovery applications are better suited for the organic Rankine Cycle or Kalina cycle, which use fluids with lower boiling point temperatures compared to steam.

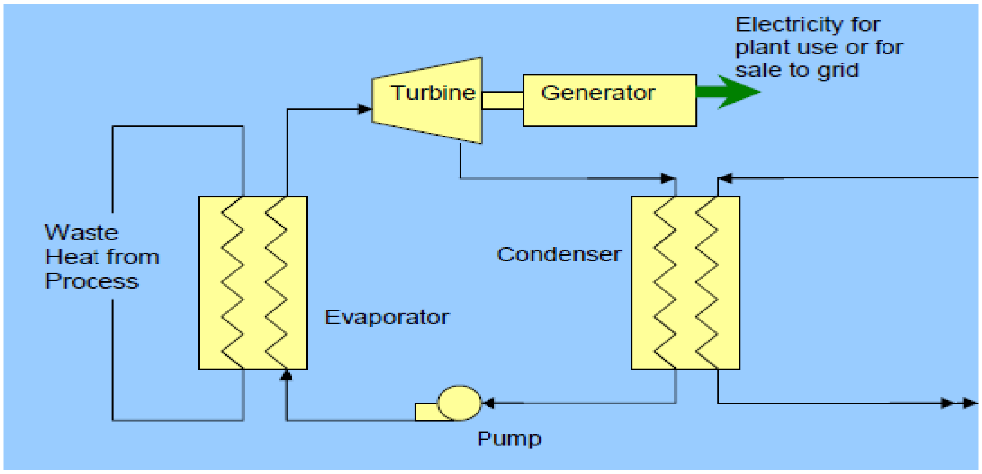


Figure 10 Waste Heat Recovery with Rankine Cycle

7.1.2 Organic Rankine Cycle

The Organic Rankine Cycle (ORC) operates similar to the steam Rankine cycle, but uses an organic working fluid instead of steam. Options include silicon oil, propane, haloalkanes (e.g., “freons”), isopentane, isobutane, pxylene, and toluene, which have a lower boiling point and higher vapor pressure than water. This allows the Rankine cycle to operate with significantly lower waste heat temperatures— sometimes as low as 150oF [66oC]. The most appropriate temperature range for ORCs will depend on the fluid used, as fluids’ thermodynamic properties will influence the efficiency of the cycle at various temperatures. In comparison with water vapor, the fluids used in ORCs have a higher molecular mass, enabling compact designs, higher mass flow, and higher turbine efficiencies (as high as 80-85%)[10,11].However, since the cycle functions at lower temperatures, the overall efficiency is only around 10-20%, depending on the temperature of the condenser and evaporator. While this efficiency is much lower than a high temperature steam power plant (30-40%), it is important to remember that low temperature cycles are inherently less efficient than high temperature cycles. Limits on efficiency can be expressed according to Carnot efficiency—the maximum possible efficiency for a heat engine operating between two temperatures. A Carnot engine operating with a heat source at 300°F [150°C] and rejecting it at 77oF [25°C] is only about 30% efficient. In this light, an efficiency of 1020% is a substantial percentage of theoretical efficiency, especially in comparison to other low temperature options, such as piezoelectric generation, which are only 1% efficient. ORC technology is not particularly new; at least 30 commercial plants worldwide were employing the cycle before 1984[12]. Its applications include power generation from solar, geothermal, and waste heat sources. As per an article published in Distributed Energy, ORCs are most useful for waste heat recovery among these three applications[13].Waste heat recovery can be applied to a variety of low to medium temperature heat streams. An example of a recent successful installation is in Bavaria, Germany, where a cement plant installed an ORC to recover waste heat from its clinker cooler, whose exhaust gas is at about 930°F [500°C]. The ORC provided 12% of the plant’s electricity requirements and reduced CO_2 emissions by approximately 7,000 tons[14]. Although the economics of ORC heat recovery need to be carefully analyzed for any given application, it will be a particularly useful option in industries that have no in house use for additional process heat or no neighbouring plants that could make economic use of the heat.

7.1.3 Kalina Cycle

The Kalina cycle is a variation of the Rankine cycle, using a mixture of ammonia and water as the working fluid. A key difference between single fluid cycles and cycles that use binary fluids is the temperature profile during boiling and condensation. For single fluid cycles (e.g., steam or organic Rankine), the temperature remains constant during boiling. As heat is transferred to the working medium (e.g., water), the water temperature slowly increases to boiling temperature, at which point the temperature remains constant until all the water has evaporated. In contrast, a binary mixture of water and ammonia (each of which has a different boiling point) will increase its temperature during evaporation. This allows better thermal matching with the waste heat source and with the cooling medium in the condenser. Consequently, these systems achieve significantly greater energy efficiency.

The cycle was invented in the 1980s and the first power plant based on the Kalina cycle was constructed in Canoga Park, California in 1991. It has been installed in several other locations for power generation from geothermal energy or waste heat. Applications include a 6 million metric tons per year steelworks in Japan (1999)[15] heat recovery from a municipal solid waste incinerator (1999), and from a hydrocarbon process tower (2003)[16].The steelworks application involved using a Kalina cycle to generate power from cooling water at 208°F [98°C]. With a water flow rate of 1,300 metric tons per hour, the electric power output was about 4,500 kW. The total investment cost was about $4 million or about $1,100/kW[17].

7.2 Direct Electrical Conversion Devices

Whereas traditional power cycles involve using heat to create mechanical energy and ultimately electrical energy, new technologies are being developed that can generate electricity directly from heat. These include thermoelectric, thermionic, and piezoelectric devices. There is no evidence that these systems have been tested in industrial waste heat recovery applications, although a few have undergone some prototype testing in applications such as heat recovery in automotive vehicles.

7.2.1 Thermoelectric Generation

Thermoelectric (TE) materials are semiconductor solids that allow direct generation of electricity when subject to a temperature differential. These systems are based on a phenomenon known as the Seebeck effect: when two different semiconductor materials are subject to a heat source and heat sink, a voltage is created between the two semiconductors. Conversely, TE materials can also be used for cooling or heating by applying electricity to dissimilar semiconductors. Thermoelectric technology has existed for a long time (the thermoelectric effect was first discovered in 1821), but has seen limited use due to low efficiencies and high cost. Most TE generation systems in use have efficiencies of 2 to 5%; these have mainly been used to power instruments on spacecraft or in very remote locations. However, recent advances in nanotechnology have enabled advanced TE materials that might achieve conversion efficiencies 15% or greater. A recent study by PNNL and BCS, Incorporated examines the opportunity for TE generation in various industrial waste heat streams and identifies performance requirement and RD&D needs[18].The study concluded that advanced TE packages would be appropriate in medium to High temperature, high flow rate exhaust streams where facilities have little use for recovered waste heat. Two example opportunities are glass furnaces and molten metal furnaces. Before TE materials can be used in these applications, advances are needed in both TE production technology and in heat transfer systems. Competing with current electricity costs will mandate a TE package cost of about $5/watt instead of the current $30/watt[19]. Low cost, high volume production methods for TE materials must be developed in order to achieve this goal. Meanwhile, maintaining a high temperature differential across thin TE devices will present a significant engineering challenge. Obtaining high heat transfer rates will require advances in heat transfer materials and heat exchange systems with high heat transfer coefficients.

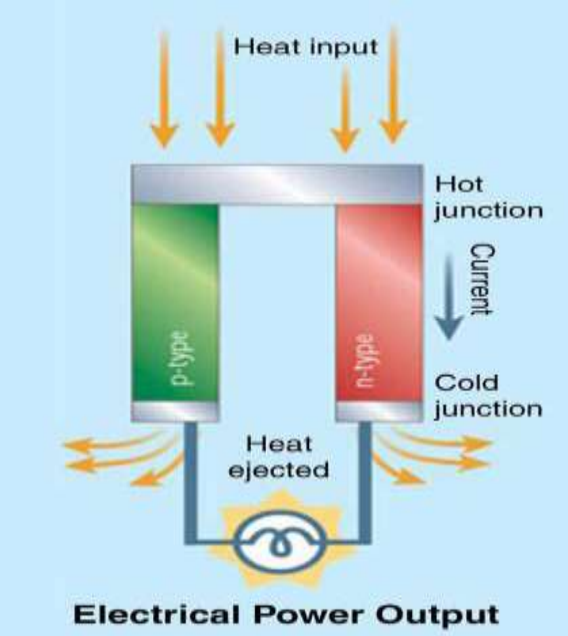


Figure 11 Thermoelectric Generation Unit

7.2.2 Piezoelectric Power Generation

Piezoelectric Power Generation (PEPG) is an option for converting low temperature waste heat (200300 °F or [100150° C]) to electrical energy[20]. Piezoelectric devices convert mechanical energy in the form of ambient vibrations to electrical energy. A piezoelectric thin film membrane can take advantage of oscillatory gas expansion to create a voltage output. A recent study[21] identified several technical challenges associated with PEPG technologies:

- low efficiency: PEPG technology is only about 1% efficient; difficulties remain in obtaining high enough oscillatory frequencies; current devices operate at around 100 Hz, and frequencies closer to 1,000 Hz are needed,
- high internal impedance,
- complex oscillatory fluid dynamics within the liquid/vapour chamber,
- need for long term reliability and durability, and
- high costs ($10,000/W).

While the conversion efficiency of PEPG technology is currently very low (1%), there may be opportunities to use PEPG cascading, in which case efficiencies could reach about 10%[22].Other key issues are the costs of manufacturing piezoelectric devices, as well as the design of heat exchangers to facilitate sufficient heat transfer rates across a relatively low temperature difference[23].

7.2.3 Thermionic Generation

Thermionic devices operate similar to thermoelectric devices; however, whereas thermoelectric devices operate according to the Seebeck effect, thermionic devices operate via thermionic emission. In these systems, a temperature difference drives the flow of electrons through a vacuum from a metal to a metal oxide surface. One key disadvantage of these systems is that they are limited to applications with high temperatures above 1,800°F [1,000°C]. However, some development has enabled their use at about 210-570° F [100-300°C][24].

7.2.4 Thermo Photo Voltaic (TPV) Generator

TPV Generators can be used to convert radiant energy into electricity. These systems involve a heat source, an emitter, a radiation filter, and a PV cell (like those used in solar panels). As the emitter is heated, it emits electromagnetic radiation. The PV cell converts this radiation to electrical energy. The filter is used to pass radiation at wavelengths that match the PV cell, while reflecting remaining energy back to the emitter. These systems could potentially enable new methods for waste heat recovery. A small number of prototype systems have been built for small burner applications and in a helicopter gas Turbine[25].

8.0 CASE STUDY

Power generation from waste heat in cement plant

Waste Heat Recovery Power Systems

Waste heat recovery power systems used for cement kilns operate on the Rankine Cycle.This thermodynamic cycle is the basis for conventional thermal power generating stations and consists of a heat source (boiler) that converts a liquid working fluid to high-pressure vapor (steam, in a power station) that is then expanded through a turbo generator producing power. Low-pressure vapor exhausted from the turbo generator is condensed back to a liquid state, with condensate from the condenser returned to the boiler feed water pump to continue the cycle. Waste heat recovery systems consist of heat exchangers or heat recovery steam generators (HRSGs) that transfer heat from the exhaust gases to the working fluid inside, turbines, electric generators, condensers, and a working fluid cooling system. Three primary waste heat recovery power generation systems are available, differentiated by the type of working fluid (Gibbon 2013, EPA 2012, CII 2009), as follows:

Steam Rankine Cycle (SRC) – The most commonly used Rankine cycle system for waste heat recovery power generation uses water as the working fluid and involves generating steam in a waste heat boiler, which then drives a steam turbine. Steam turbines are one of the oldest and most versatile power generation technologies in use. As shown in Figure 4,in the steam waste heat recovery steam cycle, the working fluid—water—is first pumped to elevated pressure before entering a waste heat recovery boiler. The water is vaporized into high-pressure steam by the hot exhaust from the process and then expanded to lower temperature and pressure in a turbine, generating mechanical power that drives an electric generator. The low-pressure steam is then exhausted to a condenser at vacuum conditions, where the expanded vapor is condensed to low-pressure liquid and returned to the feed water pump and boiler. Steam cycles are by far the most common waste heat recovery systems in operation in cement plants, and generally reflect the following:

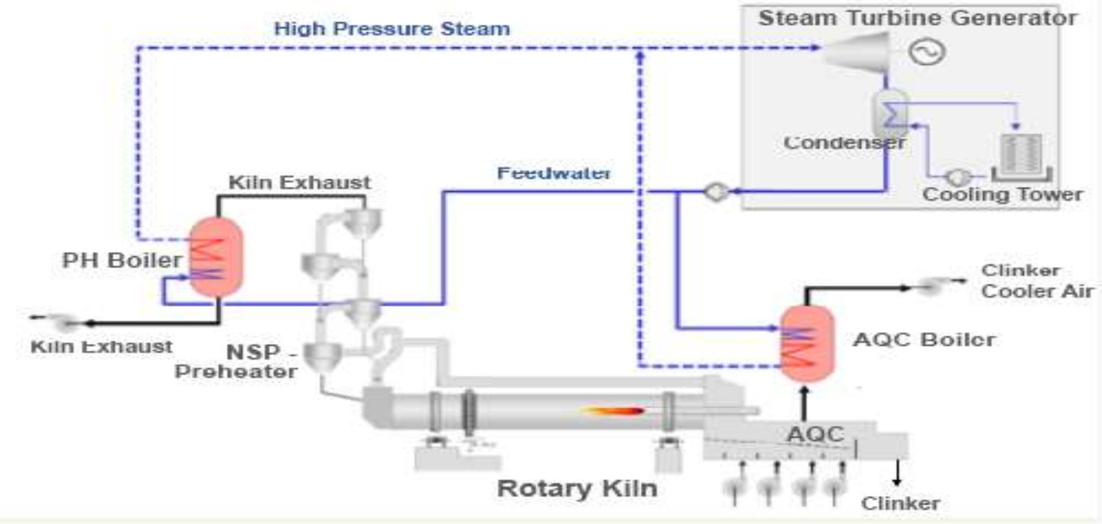


Figure 12 Schematic flow diagram of cement manufacturing process using waste heat

- Most familiar to the cement industry and are generally economically preferable where source heat temperature exceeds 300° C (570° F)
- Based on proven technologies and generally simple to operate
- Widely available from a variety of suppliers
- Generally have lower installation costs than other Rankine cycle systems on a specific cost basis (US$/kW)
- Need higher-temperature waste heat to operate optimally (minimum >260° C (500° F))—generation efficiencies fall significantly at lower temperatures, and lower pressure and temperature steam conditions can result in partially condensed steam exiting the turbine, causing blade erosion
- Often recover heat from the middle of the air cooler exhaust flow to increase waste gas temperatures to an acceptable level for the system, but at the expense of not recovering a portion of cooler waste heat
- Often require a full-time operator, depending on local regulations
- Require feed water conditioning systems
- Generally require a water-cooled condenser; air cooled condensers can be used but create a performance penalty due to higher condenser vacuum pressures
- In general, match well with large kilns and systems with low raw material water content (resulting in higher waste gas temperatures)

Organic Rankine Cycles (ORC) – Other types of working fluids with better generation efficiencies at lower heat source temperatures are used in organic Rankine cycle (ORC) systems. The ORCs typically use a high molecular mass organic working fluid such as butane or pentane that has a lower boiling point, higher vapor pressure, higher molecular mass, and higher mass flow compared to water. Together, these features enable higher turbine efficiencies than those offered by a steam system. The ORC systems can be utilized for waste heat sources as low as 150° C (300° F), whereas steam systems are limited to heat sources greater than 260° C (500° F). The ORC systems are typically designed with two heat transfer stages. The first stage transfers heat from the waste gases to an intermediate heat transfer fluid (e.g., thermal transfer oil). The second stage transfers heat from the intermediate heat transfer fluid to the organic working fluid. The ORCs have commonly been used to generate power in geothermal power plants, and more recently, in pipeline compressor heat recovery applications in the United States. The ORC systems have been widely used to generate power from biomass systems in Europe. A few ORC systems have been installed on cement kilns.10 The ORC's specific features include the following (Turboden 2012, Holcim 2011, Ormat 2012, Gibbon 2013):

- Can recover heat from gases at lower temperatures than is possible with conventional steam systems, enabling ORCs to utilize all recoverable heat from the air cooler
- Operate with condensing systems above atmospheric pressure, reducing risk of air leakage into the system and eliminating the need for a de-aerator
- Not susceptible to freezing
- Because ORCs operate at relatively low pressure, they can operate unattended and fully automated in many locations depending on local regulations
- The organic fluid properties result in the working fluid remaining dry (no partial condensation) throughout the turbine, avoiding blade erosion
- Can utilize air-cooled condensers without negatively impacting performance

- Lower-speed (rpm) ORC turbine allows generator direct drive without the need for and inefficiency of a reduction gear
- ORC equipment (turbines, piping, condensers, heat exchanger surface) is typically smaller than that required for steam systems, and the turbine generally consists of fewer stages • Although ORCs can provide generation efficiencies comparable to a steam Rankine system, ORCs are typically applied to lower temperature exhaust streams, and limited in sizing and scalability, and generally are smaller in capacity that steam systems.
- Depending on the application, ORC systems often have a higher specific cost (US$/kW) than steam systems
- The two-stage heat transfer process creates some system inefficiencies
- The heat transfer fluids and organic fluids normally used in ORCs are combustible, requiring fire protection measures and periodic replacement over time. Also, there may be environmental concerns over potential system leaks.
- In general, ORC systems are well-matched with small- to medium-size, high-efficiency kilns or kilns with elevated raw material moisture content

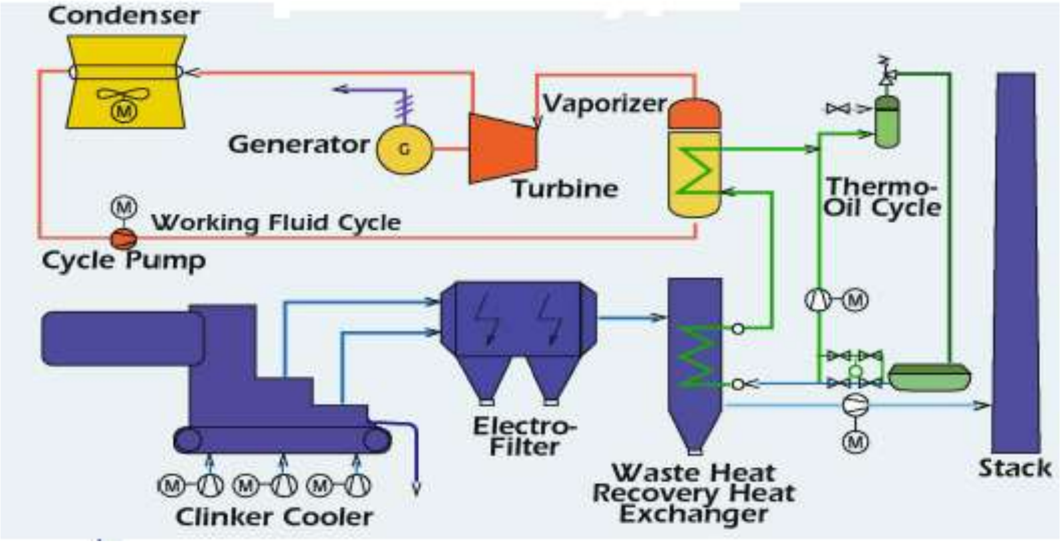


Figure 13 Schematic of cement manufacturing process using organic rankine cycle

The **Kalina** Cycle is another **Rankine** cycle, using a mixture of water and ammonia as the working fluid, which allows for a more efficient energy extraction from the heat source. The Kalina cycle has an operating temperature range that can accept waste heat at temperatures of 200 °F to 1,000 °F and is 15 to 25 percent more efficient than ORCs at the same temperature level. Kalina cycle systems are becoming increasingly popular overseas in geothermal power plants, where the hot fluid is very often below 300 °F.

Gaggal Cement Plant

Process Description:

Waste gas discharged from the clinker cooler system, and the kiln pre-heater system all contain useful energy that can be converted into power by installation of a waste heat boiler system that runs a steam turbine system. This report focuses on the steam turbine system since these systems have been installed in many plants worldwide and have proven to be economic. Heat recovery has limited application for plants with in-line raw mills, as the heat in the kiln exhaust is used for raw material drying. So at each step in heat recovery system gases are re-circulated to existing system after Waste heat recovery boilers. Waste Heat Recovery Boilers have been installed between pre-heater and Raw Mill of Line-1 and Line-2. This step will lead to an energy efficient process and clinker electricity (KWh) cost will be reduced by 26% without using any extra fuel.

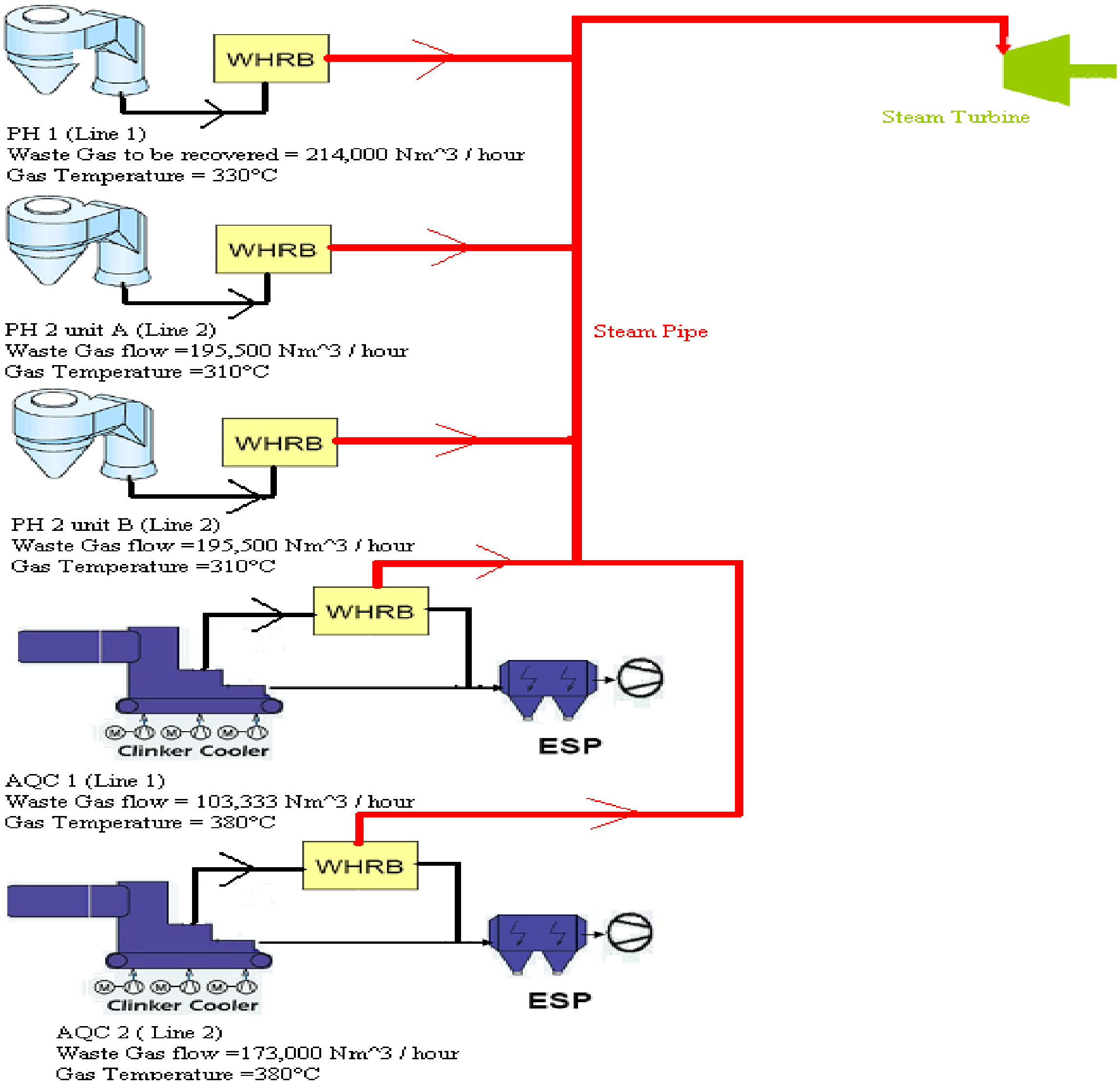


Figure 14 Block Diagram of Waste Heat Recovery Power with Two Cement Lines

Line-1 (4000 tons per day of clinker Kiln)

Its production is 4000 tons per day of clinker. Waste gases, rejected from preheater and clinker cooler, properties are as given below:

Preheater Heat Exchanger 1 (Line 1 Preheater)

Waste Gas characteristics are as given below:

Inlet Gas Temperature	Waste Gas to be recovered Nm^3 /hour	Outlet Gas Temperature
330°C	214,000	229°C

Steam characteristics to be generated by waste gas are as given below:

Steam Generated	Steam temperature	Steam Pressure
15.4 t/h	312 °C	1.63 MPa

Clinker Cooler Heat Exchanger 1

Waste Gas characteristics are as given below:

Inlet Gas Temperature	Waste Gas to be recovered Nm^3 / hour	Outlet Gas Temperature
380°C	103,333	98°C

Steam characteristics to be generated by waste gas are as given below:

Steam Generated	Steam temperature	Steam Pressure
8.5 t/h	355 °C	1.63 MPa

Line-2 (6700 tons per day of clinker Kiln)

Its production is 6700 tons per day of clinker. Waste gases, rejected from preheater and clinker cooler, properties are as given below:

Preheater Heat Exchanger 2 (Two Boilers)
Line-2 is a state of art technology and its preheater is double string. So at each string one boiler is installed and both are identical.

Waste Gas characteristics are as given below:

Inlet Gas Temperature	Waste Gas to be recovered Nm^3 / hour	Outlet Gas Temperature
310°C	195,500 x 2	228°C

Steam characteristics to be generated by waste gas are as given below:

Steam Generated	Steam temperature	Steam Pressure
23 t/h	301 °C	1.63 MPa

Clinker Cooler Heat Exchanger 2

Waste Gas characteristics are as given below:

Inlet Gas Temperature	Waste Gas to be recovered Nm^3 / hour	Outlet Gas Temperature
380°C	173,000	99°C

Steam characteristics to be generated by waste gas are as given below:

Steam Generated	Steam temperature	Steam Pressure
15.6 t/h	366 °C	1.63 MPa

Table 8- Characteristics of steam produced from different heat recovery lines					
ITEM	**LOCATION**	**WASTE GAS** **Nm^3/Hr**	**Steam Capacity** **TPH**	**Steam Press.** **MPA**	**Steam Temp.** **°C**
HRSG 1	Preheater line 1	214000	15.4	1.63	312
HRSG 2	Clinker cooler line 1	103333	8.5	1.63	355
HRSG 3	Preheater line 2	195500	11.5	1.63	301
HRSG 4	Preheater line 2	195500	11.5	1.63	301
HRSG 5	Clinker cooler line 2	173000	15.6	1.63	366

Thermal analysis of system

General equation of heat capacity

Q= mCT

Where, Q is heat possessed by body (KJ/s)

m is mass flow rate (kg/s)

C is specific heat (KJ/kg.k)

T is temperature (k)

Line 1

Heat possessed by waste gas of preheater	Heat absorbed by preheater boiler

$Q = \frac{214000}{3600} * 1.29 * 1.006 * 603$	$dQ = \frac{214000}{3600} * 1.29 * 1.006 * (330 - 229)$
= 46517.5 KJ/s	= 7791.5 KJ/s

Where, Density of air is 1.29
Specific heat is 1.006

$$\eta_1 = \frac{7791.5}{46517.5} * 100$$

=16.75%

Heat possessed by waste gas of clinker cooler	Heat absorbed by clinker cooler boiler
$Q = \frac{103333}{3600} * 1.29 * 1.006 * 653$	$dQ = \frac{103333}{3600} * 1.29 * 1.006 * (380 - 98)$
= 24324.15 KJ/s	= 10504.5 KJ/s

$$\eta_2 = \frac{10504.5}{24324.15} * 100$$

=43.18%

Line 2

Heat possessed by waste gas of preheater	Heat absorbed by preheater boiler
$Q = \frac{195500 * 2}{3600} * 1.29 * 1.006 * 583$	$dQ = \frac{195500 * 2}{3600} * 1.29 * 1.006 * (310 - 228)$
= 82173.25 KJ/s	= 14235.85 KJ/s

$$\eta_3 = \frac{14235.85}{82173.25} * 100$$

$$= 17.32\ \%$$

Heat possessed by waste gas of clinker cooler	Heat absorbed by clinker cooler boiler
$Q = \frac{173000}{3600} * 1.29 * 1.006 * 653$	$dQ = \frac{173000}{3600} * 1.29 * 1.006 * (380 - 99)$
= 40723.45 KJ/s	= 17524.2 KJ/s

$$\eta_4 = \frac{17524.2}{40723.45} * 100$$

$$= 43.03\ \%$$

Average system efficiency

$$\frac{\eta_1 + \eta_2 + \eta_3 + \eta_4}{4} = 30.07\ \%$$

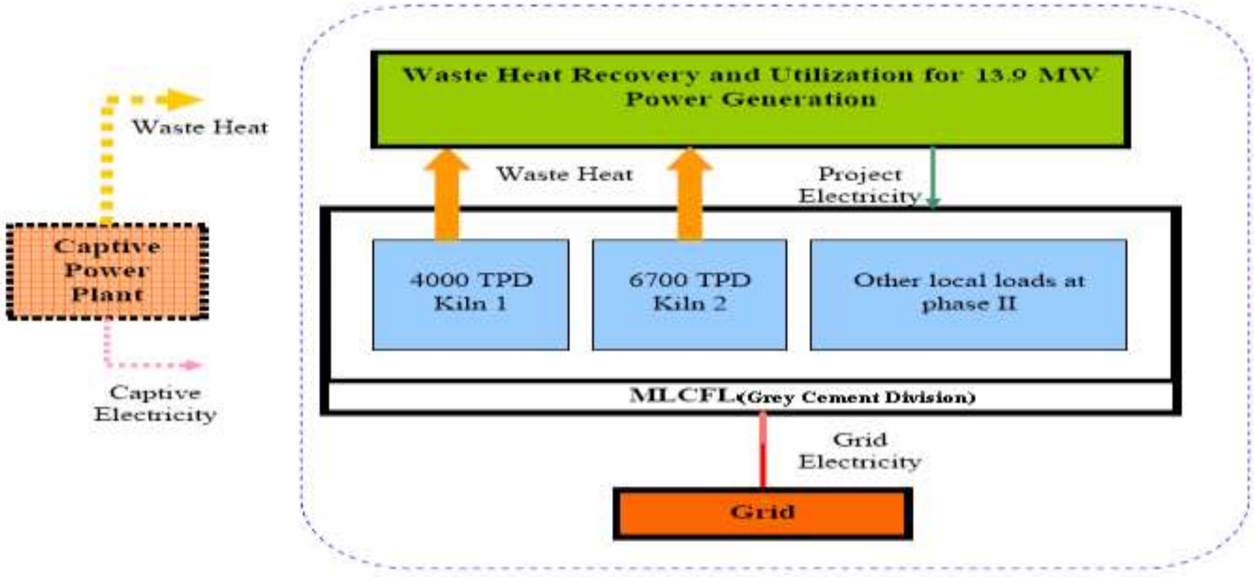


Figure 15 Power flow diagram of system

Percentile Electricity Generation

Line-1

I/p %age of Line-1= (Steam generated by Line 1)*100 / (Total Steam Generated)
I/p %age of Line-1 = 23.9*100/62.5
I/p %age of Line-1 = 38.24%
Electricity Proportion = 5.315 MW

Line-2

I/p %age of Line-2= (Steam generated by Line-2)*100 / (Total Steam Generated)
I/p %age of Line-2 = 38.6*100/62.5
I/p %age of Line-2 = 61.76%
Electricity Proportion = 8.584 MW

9.0 Conclusion

Process heating is a significant source of energy consumption in the industrial and manufacturing sectors, and it often results in a large amount of waste heat that is discharged into the atmosphere. Industrial process heat recovery effectively recycles this waste heat, which typically contains a substantial amount of thermal energy. The benefits of heat recovery include improving system efficiency, reducing fuel consumption, and reducing facility air emissions. While the type and cost-effectiveness of a heat recovery system are dependent on the process temperature and the facility’s thermal requirements, many heat recovery techniques are available across low, medium, and high temperature ranges.

A substantial amount of energy used by industry is wasted as heat in the form of exhaust gases, air streams, and liquids leaving industrial facilities. Although it is not technically and economically feasible to recover all waste heat, a gross estimate is that waste-heat recovery could substitute for 9% of total energy used by industry—or 1.4 quadrillion BTU. An increased use of waste-heat recovery technologies by industry would also serve to mitigate greenhouse gas (GHG) emissions. The primary sources of waste heat in industrial facilities include exhaust gases from fossil fuel-fired furnaces, boilers, and process heating equipment. These types of high-grade waste-heat sources can readily be used to preheat combustion air, boiler feedwater, and process loads. Waste-heat recovery from lower temperature sources, such as cooling water from machines and condensers, is generally somewhat more problematic, and typically involves the use of heat pumps to increase the temperature to a suitable temperature for distillation, evaporation, water heating, and space heating. This report summarizes the results of numerous studies conducted to identify opportunities for waste-heat recovery in industrial facilities. It also describes recent advancements and applications in waste-heat recovery technology. Typical “energy audits” identify annual energy cost savings of about 5%. However, this report confirms that systematic waste-heat recovery projects based on sound thermodynamic principles can yield annual energy cost savings of 10% to 20% with paybacks of 6 to 18 months for industrial facilities. Recent advancements in heat recovery technology may increase the energy savings by an additional 5% to 10%. Since only 5% of manufacturing facilities currently use waste-heat recovery, there is tremendous potential for energy savings in the industrial sector .

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