ENERGY HARVESTING OF WASTE HEAT

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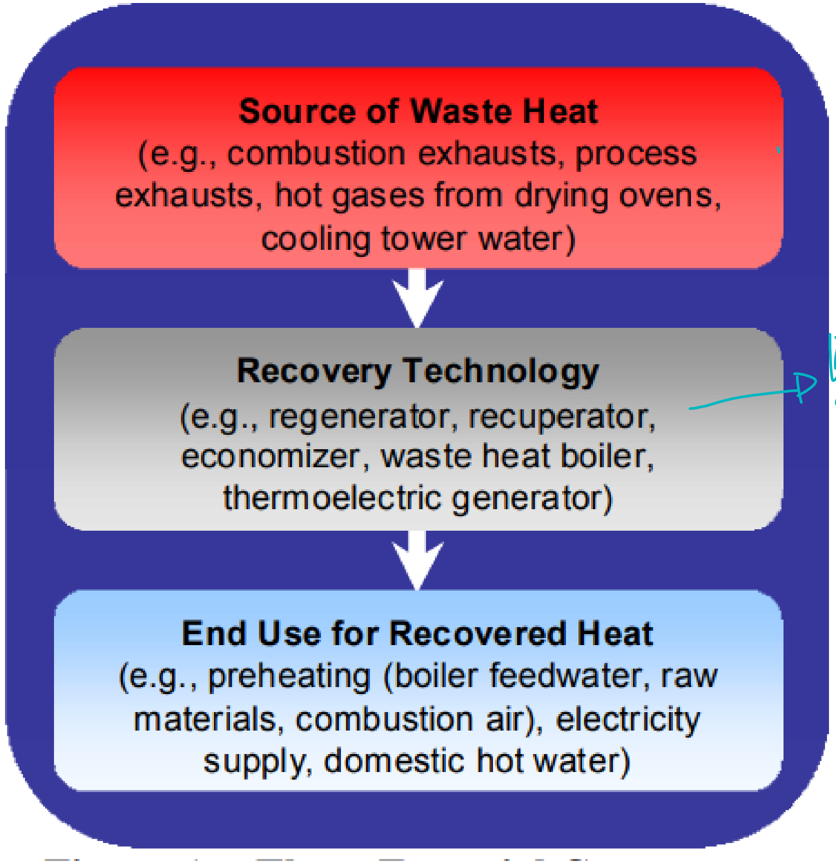
Introduction to Waste Heat

- With the ever-growing global energy demand and concerns about fossil fuel consumption and rising greenhouse gas emissions, recovering and reusing waste heat, especially low-grade waste heat from renewable energy sources such as industrial processes, solar energy, biomass, and geothermal energy, has become increasingly vital as a means of energy conservation and emission reduction.
- Waste heat is a byproduct of various industrial processes and power generation activities, and it is often considered a "free" and readily available energy source that can be harnessed to generate electricity or provide useful thermal energy.
- The recovery and utilization of waste heat can result in significant energy savings and a reduction in environmental impact.

reported that
60% ~70% from heat & input is lost

Sources of Waste Heat

- Waste heat is generated from a wide range of industrial processes, including metal production, chemical processing, and power generation. In the aluminium industry, for example, it has been reported that 70% of global energy demand is for heat or thermal processes, and the reclamation of this waste heat is a particular area of interest. Waste heat is also generated from transportation, such as in vehicle exhaust systems, and from residential sources, such as heating and cooling systems.



heat exchangers

•BCS Incorporated.(2008). Waste Heat Recovery: Technology and Opportunities in U.S. Industry.

Waste Heat Sources and End-Uses

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

a. Not currently recoverable with existing technology

•BCS Incorporated.(2008). Waste Heat Recovery: Technology and Opportunities in U.S. Industry.

Why Waste Heat Harvesting?

- Two main methods of waste heat recovery:
  - ✓ Local reuse: Preheat combustion air or boiler feedwater using exhaust gases to reduce energy consumption.
  - ✓ Heat transfer to other processes: Use heat exchangers to redirect waste heat (e.g., from exhaust gases to a drying oven).
- Benefits:
  - ✓ Lowers fossil fuel use and overall energy demand.
  - ✓ Reduces capacity needs for thermal equipment, decreasing capital and overhead costs (e.g., less need for additional space heating systems).
  - ✓ Provides a greenhouse-gas-free energy source and reduces greenhouse gas emissions.

Case Study

- Combustion air preheat can increase furnace efficiency by as much as 50%. Preheating the air before it enters the furnace increases the efficiency of the combustion process in the furnace.

Furnace Outlet Temperature	Combustion Air Preheat Temperature 400°F [204°C]	600°F [316°C]	800°F [427°C]	1,000°F [538°C]	1,200°F [649°C]
2,600°F [1,427°C]	22%	30%	37%	43%	48%
2,400°F [1,316°C]	18%	26%	33%	38%	43%
2,200°F [1,204°C]	16%	23%	29%	34%	39%
2,000°F [1,093°C]	14%	20%	26%	31%	36%
1,800°F [982°C]	13%	19%	24%	29%	33%
1,600°F [871°C]	11%	17%	22%	26%	30%
1,400°F [760°C]	10%	16%	20%	25%	28%

Source: EPA 2003, Wise Rules for Energy Efficiency. Based on a natural gas furnace with 10% excess air.

•BCS Incorporated.(2008). Waste Heat Recovery: Technology and Opportunities in U.S. Industry.

Classification of Waste Heat

TEG

- Waste heat can be classified based on temperature range: low-grade (less than 230°C), medium-grade (230-650°C), and high-grade (greater than 650°C).
- The temperature ranges for these classifications vary, but generally, low-grade waste heat refers to heat sources with relatively low temperatures, typically below 230°C, while medium-grade waste heat has a mid-range temperature, typically between 230°C and 650°C, and high-grade waste heat is characterized by higher temperatures, typically above 650°C . The choice of waste heat recovery technology depends on the temperature range of the available waste heat.

Classification of Waste Heat

Table 4 - Temperature Classification of Waste Heat Sources and Related Recovery Opportunity

Temp Range	Example Sources	Temp (°F)	Temp (°C)	Advantages	Disadvantages/ Barriers	Typical Recovery Methods/ Technologies
High >1,200°F [> 650°C]	Nickel refining furnace Steel electric arc furnace Basic oxygen furnace Aluminum reverberatory furnace Copper refining furnace Steel heating furnace Copper reverberatory furnace Hydrogen plants Fume incinerators Glass melting furnace Coke oven Iron cupola	2,500-3,000 2,500-3,000 2,200 2,000-2,200 1,400-1,500 1,700-1,900 1,650-2,000 1,200-1,800 1,200-2,600 2,400-2,800 1,200-1,800 1,500-1,800	1,370-1,650 1,370-1,650 1,200 1,100-1,200 760-820 930-1,040 900-1,090 650-980 650-1,430 1,300-1,540 650-1,000 820-980	High-quality energy, available for a diverse range of end-uses with varying temperature requirements High-efficiency power generation High heat transfer rate per unit area	High temperature creates increased thermal stresses on heat exchange materials Increased chemical activity/corrosion	Combustion air preheat Steam generation for process heating or for mechanical/ electrical work Furnace load preheating Transfer to med-low temperature processes usually reused in industrial processes

•BCS Incorporated.(2008). Waste Heat Recovery: Technology and Opportunities in U.S. Industry.

Classification of Waste Heat

Medium 450-1,200°F [230-650°C]	Steam boiler exhaust Gas turbine exhaust Reciprocating engine exhaust Heat treating furnace Drying & baking ovens Cement kiln	450-900 700-1,000 600-1,100 800-1,200 450-1,100 840-1,150	230-480 370-540 320-590 430-650 230-590 450-620	More compatible with heat exchanger materials Practical for power generation		Combustion air preheat Steam/ power generation Organic Rankine cycle for power generation Furnace load preheating, feedwater preheating Transfer to low-temperature processes

exhaust gases

•BCS Incorporated.(2008). Waste Heat Recovery: Technology and Opportunities in U.S. Industry.

Classification of Waste Heat

Low <450°F [<230°C]	Exhaust gases exiting recovery devices in gas-fired boilers, ethylene furnaces, etc.	150-450	70-230	Large quantities of low-temperature heat contained in numerous product streams.	Few end uses for low temperature heat	Space heating
	Process steam condensate	130-190	50-90		Low-efficiency power generation	Domestic water heating
	Cooling water from:					Upgrading via a heat pump to increase temp for end use
	furnace doors	90-130	30-50		For combustion exhausts, low-temperature heat recovery is impractical due to acidic condensation and heat exchanger corrosion	Organic Rankine cycle
	annealing furnaces	150-450	70-230			
	air compressors	80-120	30-50			
	internal combustion engines	150-250	70-120			
	air conditioning and refrigeration condensers	90-110	30-40			
	Drying, baking, and curing ovens	200-450	90-230			
	Hot processed liquids/solids	90-450	30-230			

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Thermodynamic Principles

- The second law of thermodynamics states that energy cannot be fully converted from one form to another without some loss, and this principle applies to the conversion of waste heat into useful energy. Indeed, when waste heat is converted to electricity or other forms of useful energy, there are always some unavoidable energy losses due to the inherent limitations and inefficiencies of the conversion processes.
- Various technologies have been developed to harness waste heat and convert it into useful energy, such as electricity or thermal energy for heating and cooling.

Carnot Efficiency and Limits

- Theoretical limits of waste heat conversion. The Carnot efficiency represents the theoretical maximum efficiency of a heat engine operating between two temperature reservoirs, and it serves as a fundamental limit on the conversion of waste heat into useful work.
- The Carnot efficiency is given by the formula $\eta_c = \frac{T_h - T_c}{T_h}$. T_c is the temperature of the cold reservoir (in this case, the ambient temperature) and T_h is the temperature of the hot reservoir (the waste heat source).
- For low-grade waste heat, the Carnot efficiency is relatively low, typically in the range of 5–30%, which presents a significant challenge in developing efficient waste heat recovery systems.

Exergy and Irreversibility

- Concepts relevant to waste heat recovery. Exergy is a measure of the maximum amount of work that can be obtained from a system or energy flow as it comes into equilibrium with the surrounding environment. This concept is particularly relevant in the context of waste heat recovery, as it provides a more accurate assessment of the potential for converting waste heat into useful work compared to using energy as the sole metric. In addition, the concept of irreversibility, which is associated with entropy generation, is crucial in understanding the limitations and inefficiencies involved in waste heat recovery processes.
- The difference between exergy and entropy is that exergy represents the maximum work potential, while entropy represents the unavoidable losses due to irreversible processes.

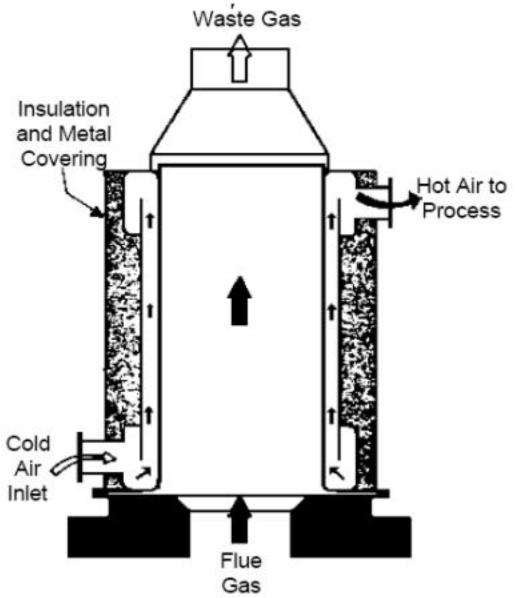
Overview of Waste Heat Harvesting Methods

- There are several technologies available for harnessing waste heat and converting it into useful energy. These include:
  - Heat Exchangers: Heat exchangers are widely used to transfer heat from combustion exhaust gases to the incoming combustion air in furnaces. By preheating the combustion air, the furnace requires less fuel to reach the desired temperature. Common air preheating technologies include **recuperators, furnace regenerators, burner regenerators, rotary regenerators, and passive air preheaters**.
  - Thermoelectric Generators: These solid-state devices convert temperature differences directly into electricity, making them suitable for low-grade waste heat recovery
  - Organic Rankine Cycle: This is a type of heat engine that uses an organic, high-molecular-mass fluid with a low boiling point for its working fluid, allowing it to efficiently generate electricity from low-grade waste heat.
  - Thermophotovoltaic Systems: These convert thermal radiation from a hot surface into electricity, and they can be used to harvest waste heat from high-temperature sources
  - Piezoelectric Generators: These devices convert mechanical strain induced by temperature changes into electrical energy, making them suitable for harvesting waste heat from vibrating or oscillating sources.

Heat Exchangers - Recuperator

- Types of Recuperators:
  - ✓Radiation Recuperators: Use concentric ducts where hot gases pass through the inner duct, transferring heat by radiation to the outer shell, which preheats the incoming air.
  - ✓Convective (Tube-Type) Recuperators: Direct hot gases through small tubes within a larger shell, where incoming air flows around the tubes, gaining heat by convection.
  - ✓Combined Radiation/Convection Recuperators: Maximize heat transfer by combining both methods.
- Material Selection Based on Temperature:
  - ✓Metallic Recuperators: For temperatures < 2,000°F (1,093°C).
  - ✓Ceramic Recuperators: For higher temperatures, up to 2,800°F (1,538°C).

Recuperator

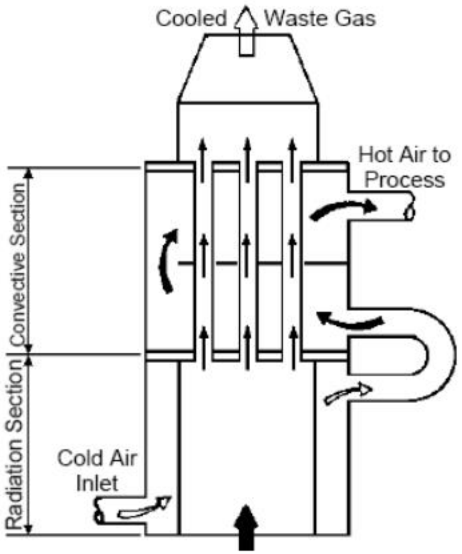


(a)


(b)

Figure 4 - (a) Metallic Radiation Recuperator Design (Source: PG & E), (b) Radiation Recuperator Installed at Glass Melter (Source: ALSTOM)


(a)



(b) -

Figure 5 - (a) Convection Recuperator (Source: Allstom, 2007), -
(b) Combined Radiation/Convection Recuperator (Source: PG&E)

•BCS Incorporated.(2008). Waste Heat Recovery: Technology and Opportunities in U.S. Industry.

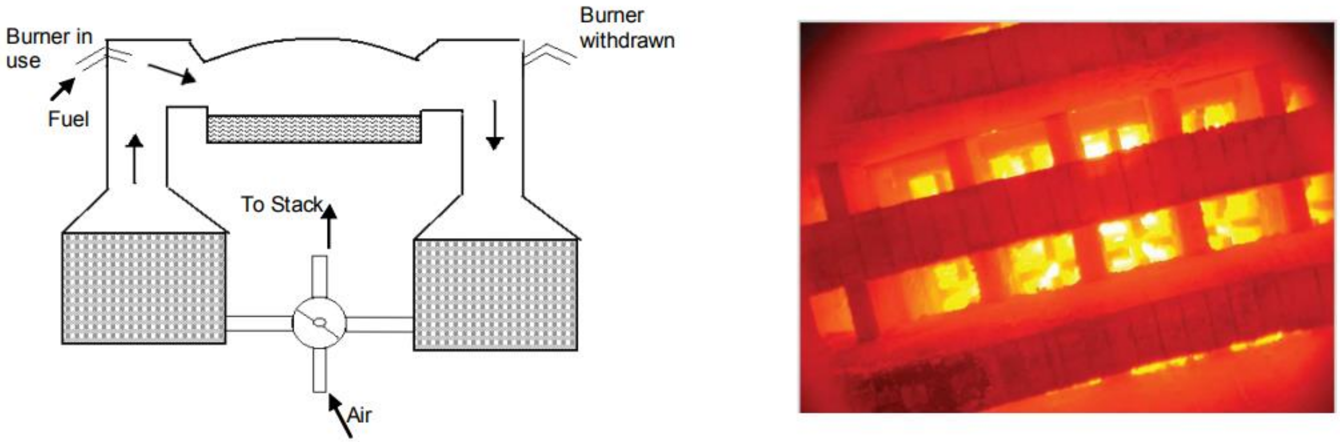
Regenerator

- In general, regenerator or regenerative heat exchangers are divided into two categories:
  - ✓Static or furnace regenerator
    - ❑Structure and Function: Regenerative furnaces have two brick "checker-work" chambers that alternate hot and cold airflow. One chamber absorbs heat from combustion gases, while the other transfers heat to incoming combustion air. The airflow direction changes every 20 minutes.
    - ❑Applications: Commonly used in glass furnaces, coke ovens, and historically in steel open-hearth furnaces. Also used to preheat hot blast air in ironmaking blast stoves.
    - ❑Advantages and Disadvantages: Ideal for high-temperature applications with dirty exhausts. However, they are large and have high capital costs compared to recuperators.

Regenerator

- In general, regenerator or regenerative heat exchangers are divided into two categories:
  - ✓ Dynamic or rotary regenerator
    - ❑ Operation and Structure: Rotary regenerators, also known as air preheaters or heat wheels, use a rotating porous disc to transfer heat between two parallel ducts containing hot waste gas and cold gas. They are typically used in low- and medium-temperature applications due to thermal stress concerns.
    - ❑ Challenges and Solutions: High temperature differences can cause differential expansion and deformation, affecting duct-wheel seals. Ceramic wheels can be used for higher temperatures, but cross-contamination between gas streams remains a challenge.
    - ❑ Applications and Advantages: Heat wheels can recover both heat and moisture, making them useful in air conditioning. They are also used in space heating, medium-temperature applications, and occasionally in high-temperature furnaces and boiler exhaust recovery, though more economical options are often preferred.

Regenerator



(a) (b)

Figure 6 - (a) Regenerative Furnace Diagram,
(b) Checkerwork in Glass Regenerative Furnace (Source: GS Energy & Environment, 2007)

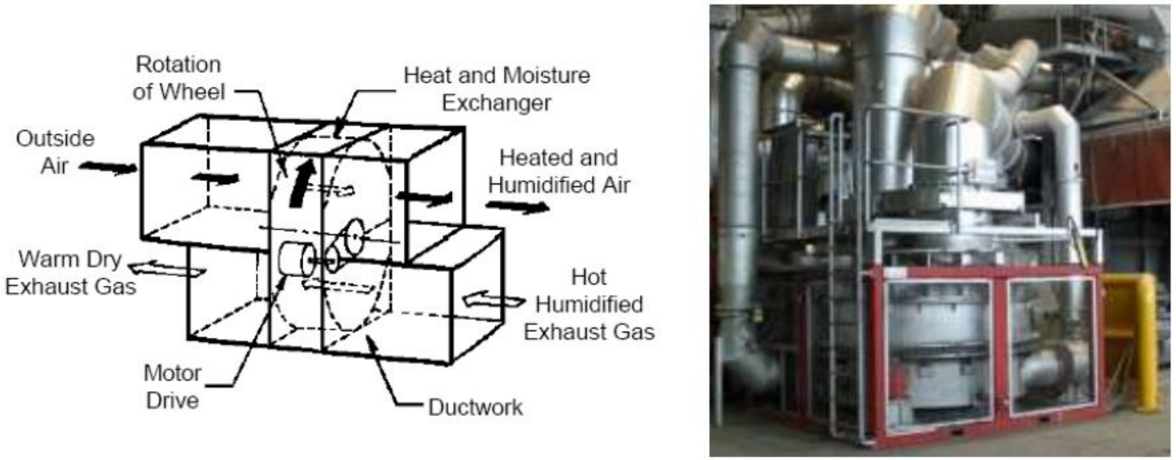


Figure 7 - (a) Rotary Regenerator (Source: PG&E, 1997)**,**
(b) Rotary Regenerator on a Melting Furnace (Source: Jasper GmbH, 2007)

Passive Air Preheater

- Function and Applications: Passive air preheaters are gas-to-gas heat recovery devices used in low- to medium-temperature applications where preventing cross-contamination between gas streams is crucial. They are used in ovens, steam boilers, gas turbine exhausts, secondary recovery from furnaces, and conditioned air recovery.
- Types and Characteristics: There are two types of passive preheaters: plate-type and heat pipe. Plate-type exchangers use parallel plates to create separate channels for hot and cold gas streams, allowing significant heat transfer but are bulkier and more costly. Heat pipe exchangers use sealed pipes with a capillary wick structure to transfer heat via evaporation and condensation of a working fluid.
- Advantages and Challenges: Plate-type systems are less susceptible to contamination but more prone to fouling and bulkiness. Heat pipe systems efficiently transfer heat but require careful management of pressure gradients and capillary action to prevent issues.

Passive Air Preheater

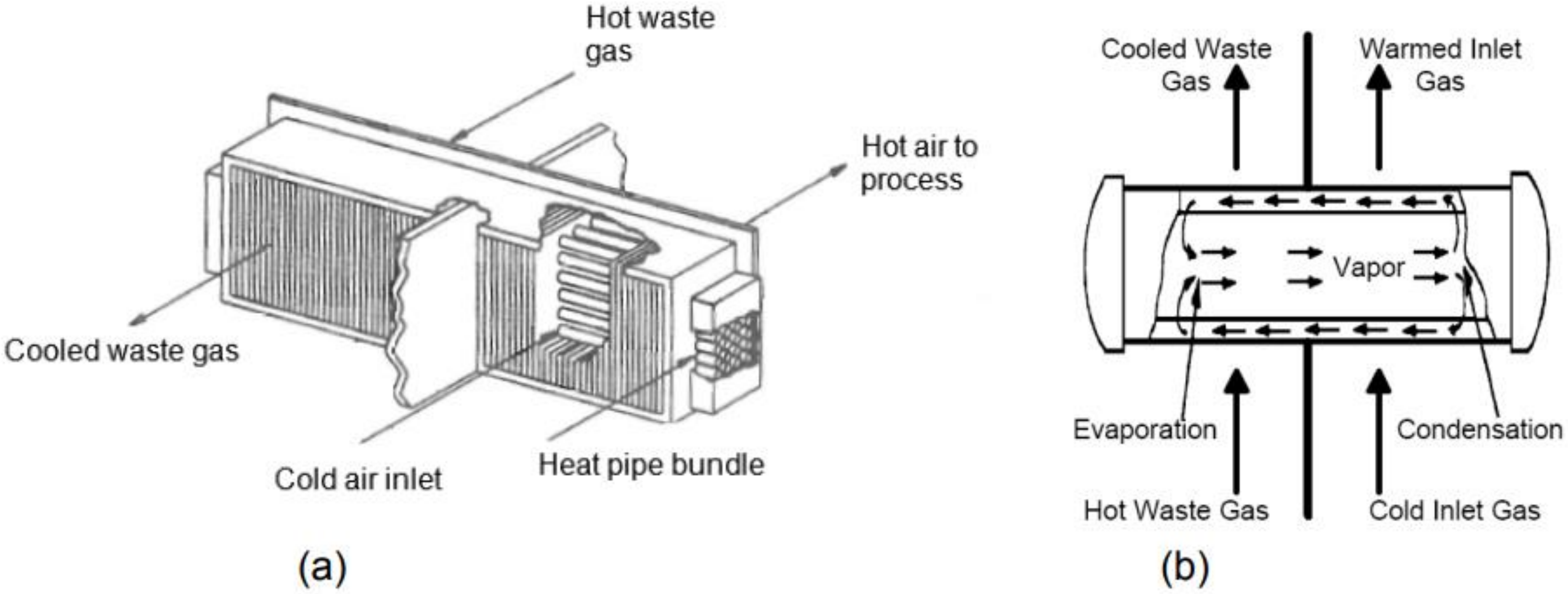


Figure 9 - (a) Heat Pipe Heat Exchanger (Source: Turner, 2006), **(b) Heat Pipe** (Source: PG&E, 1997)

Thermoelectric Generators (TEGs)

- Thermoelectric generators are solid-state devices that convert temperature differences directly into electricity based on the Seebeck effect . They are particularly suitable for harvesting waste heat from low-grade sources due to their ability to operate effectively at relatively low temperature differences
- Thermoelectric generators have no moving parts, are relatively simple in design, and can operate reliably for extended periods with minimal maintenance. However, they typically have relatively low conversion efficiencies, generally in the range of 5-10%. The low efficiency is a major limitation of thermoelectric generators, and significant research efforts are ongoing to improve their performance.
- Thermoelectric generators have been used in a variety of applications for waste heat recovery, including exhaust systems in vehicles, industrial processes, and residential heating and cooling systems.

Organic Rankine Cycle (ORC)

- The Organic Rankine Cycle is a type of heat engine that uses an organic, high-molecular-mass fluid with a low boiling point as the working fluid, rather than water as in a traditional Rankine cycle. This allows the Organic Rankine Cycle to efficiently generate electricity from low-grade waste heat sources, such as industrial processes, geothermal resources, and solar thermal applications.
- The Organic Rankine Cycle operates on a similar principle to the traditional Rankine cycle, with the key difference being the use of an organic working fluid. Examples of organic working fluids are toluene, pentane, and refrigerants like HFC-134a. It is called "organic" because the working fluid is an organic compound, not water.
- The advantages of the Organic Rankine Cycle for waste heat recovery include its ability to operate at lower temperatures, higher thermal efficiencies compared to thermoelectric generators, and the potential for modular and scalable design.
- Organic Rankine Cycle systems have been deployed in various industrial settings, such as cement plants, steel mills, and glass factories, where they can effectively harness waste heat and convert it into electricity.

Ideal Rankine Cycle

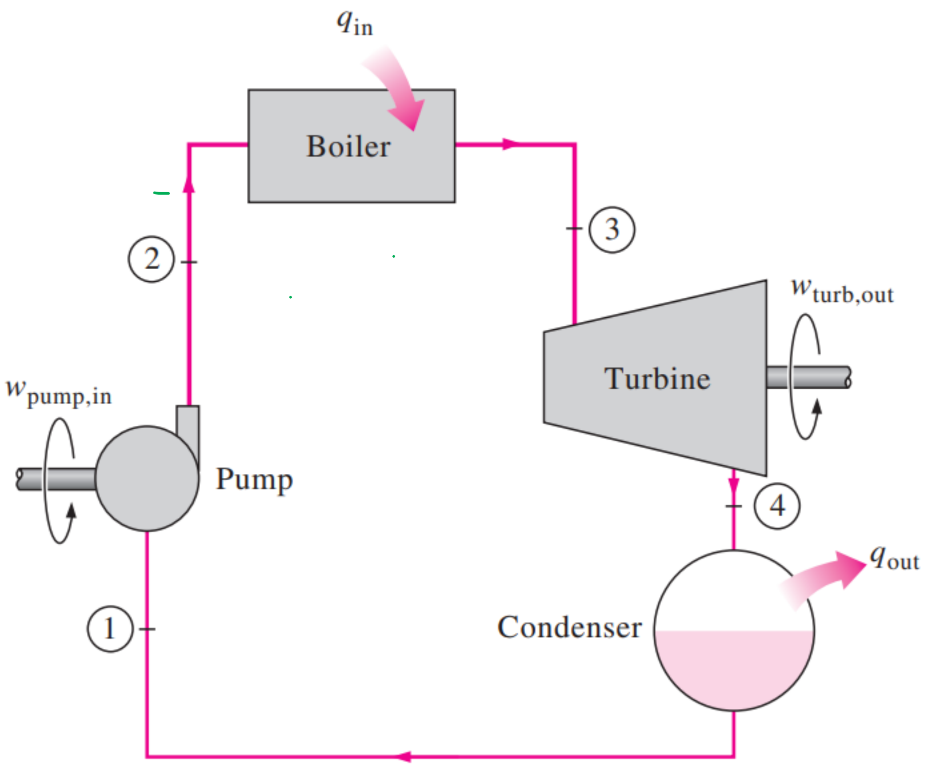
- The ideal Rankine cycle does not involve any internal irreversibility and consists of the following four process:

1-2 Isentropic compression in a pump constant Q

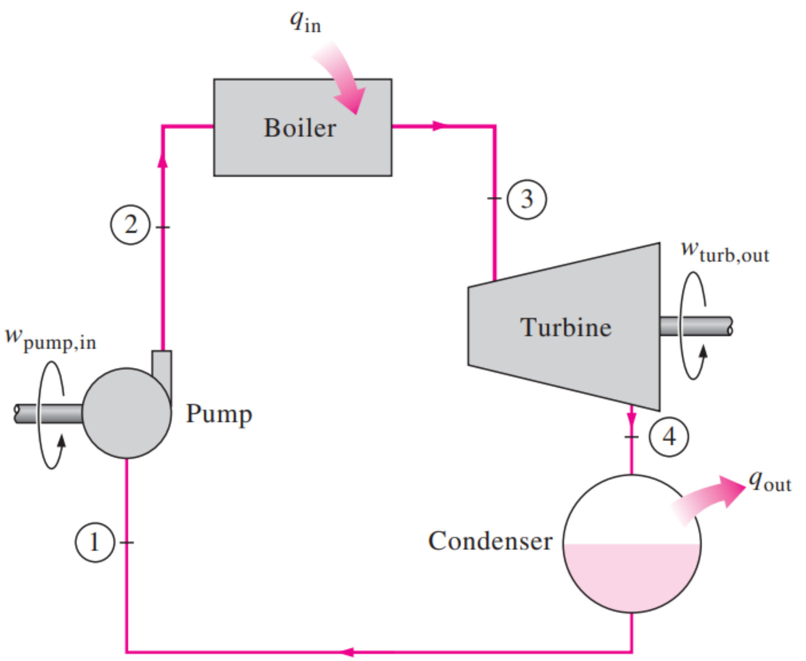
2-3 Constant pressure heat addition in a boiler
isobaric

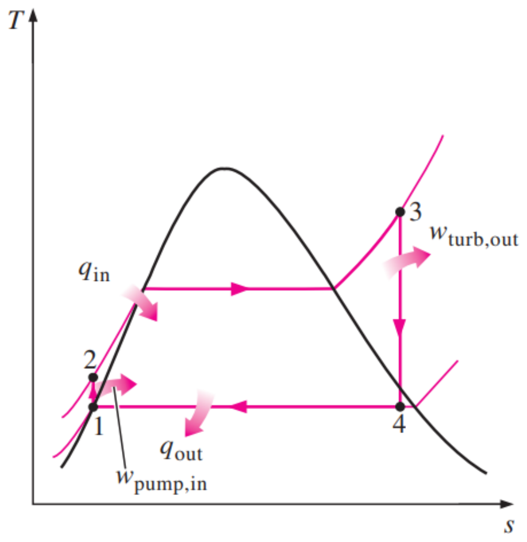
3-4 Isentropic expansion in a turbine → constant Q

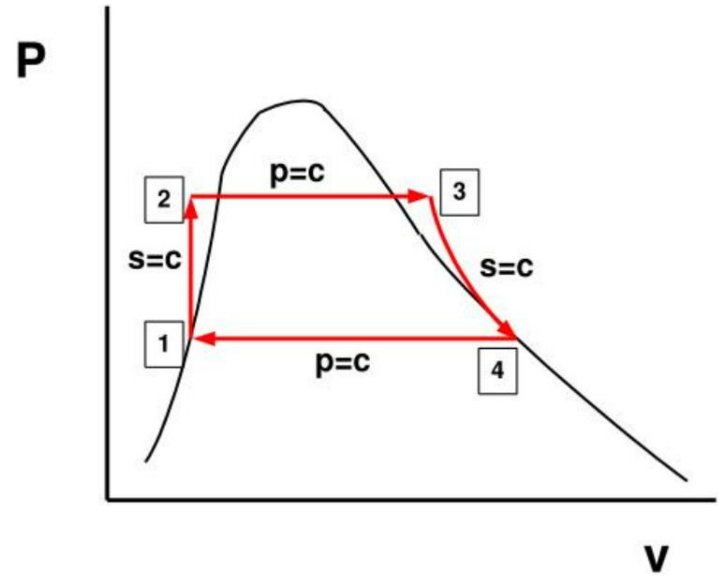
4-1 Constant pressure heat rejection in a condenser isobaric



Ideal Rankine Cycle







Çengel, Y.A., Boles, M.A.: Thermodynamics—An Engineering Approach, 4th edn. McGraw Hill, Boston (2002)

https://www.slideserve.com/jonas-goodwin/lec-23-brayton-cycle-regeneration-rankine-cycle

Ideal Rankine Cycle

- ❖ Water enters the pump at state 1 as saturated liquid and is compressed isentropically to the operating pressure of the boiler. The water temperature increases somewhat during this isentropic compression process due to a slight decrease in the specific volume of water.
- ❖ Water enters the boiler as a compressed liquid at state 2 and leaves as a superheated vapor at state 3. The boiler is basically a large heat exchanger where the heat originating from combustion gases, nuclear reactors, or other sources is transferred to the water essentially at constant pressure.
- ❖ The superheated vapor at state 3 enters the turbine, where it expands isentropically and produces work by rotating the shaft connected to an electric generator.
- ❖ The pressure and the temperature of steam drop during this process to the values at state 4, where steam enters the condenser. At this state, steam is usually a saturated liquid–vapor mixture with a high quality. Steam is condensed at constant pressure in the condenser, which is basically a large heat exchanger, by rejecting heat to a cooling medium such as a lake, a river, or the atmosphere. Steam leaves the condenser as saturated liquid and enters the pump, completing the cycle.

Ideal Rankine Cycle

- All four components associated with the Rankine cycle (the pump, boiler, turbine, and condenser) are steady-flow devices, and thus all four processes that make up the Rankine cycle can be analyzed as steady-flow processes.
- The kinetic and potential energy changes of the steam are usually small relative to the work and heat transfer terms and are therefore usually neglected. Then the ste[illegible] of steam reduces to:

$$(q_{\text{in}} - q_{\text{out}}) + (w_{\text{in}} - w_{\text{out}}) = h_e - h_i$$

- The boiler and the condenser do not involve any work, and the pump and the turbine are assumed to be isentropic.

Ideal Rankine Cycle

- Then the conservation of energy relation for each device can be expressed as f

Pump ($q = 0$): $$w_{\text{pump,in}} = h_2 - h_1$$

or,

$$w_{\text{pump,in}} = v(P_2 - P_1)$$

where

$$h_1 = h_{f\,@\,P_1} \quad \text{and} \quad v \cong v_1 = v_{f\,@\,P_1}$$

Boiler ($w = 0$): $$q_{\text{in}} = h_3 - h_2$$

Turbine ($q = 0$): $$w_{\text{turb,out}} = h_3 - h_4$$

Condenser ($w = 0$): $$q_{\text{out}} = h_4 - h_1$$

Ideal Rankine Cycle

- The thermal efficiency of the Rankine cycle is determined from

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

Di ma

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

Ideal and Actual Rankine Cycle

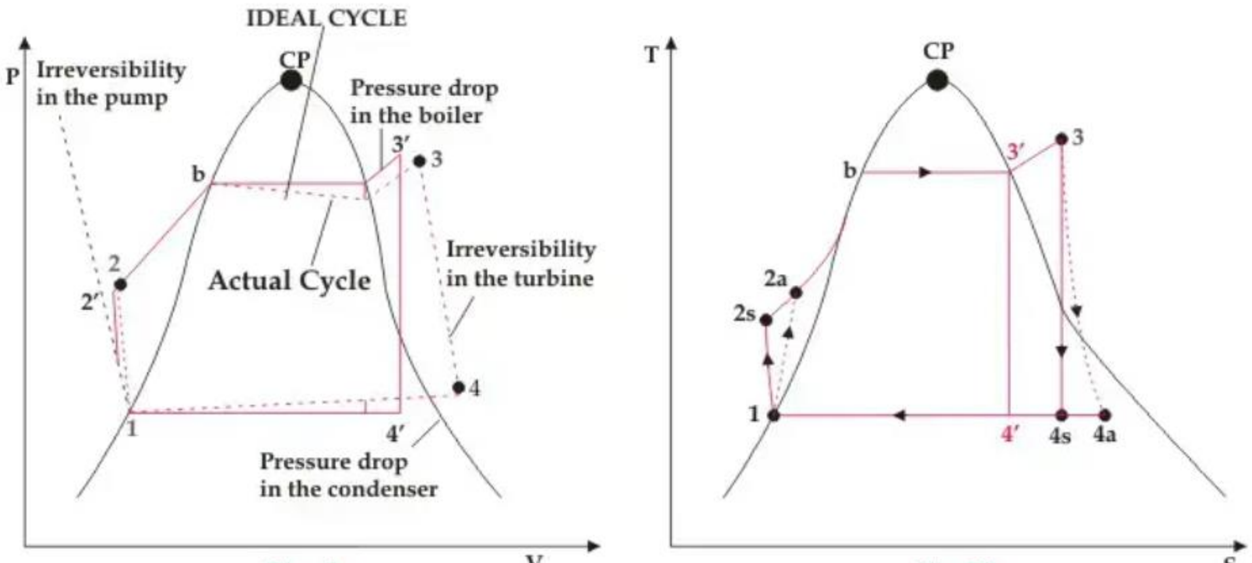


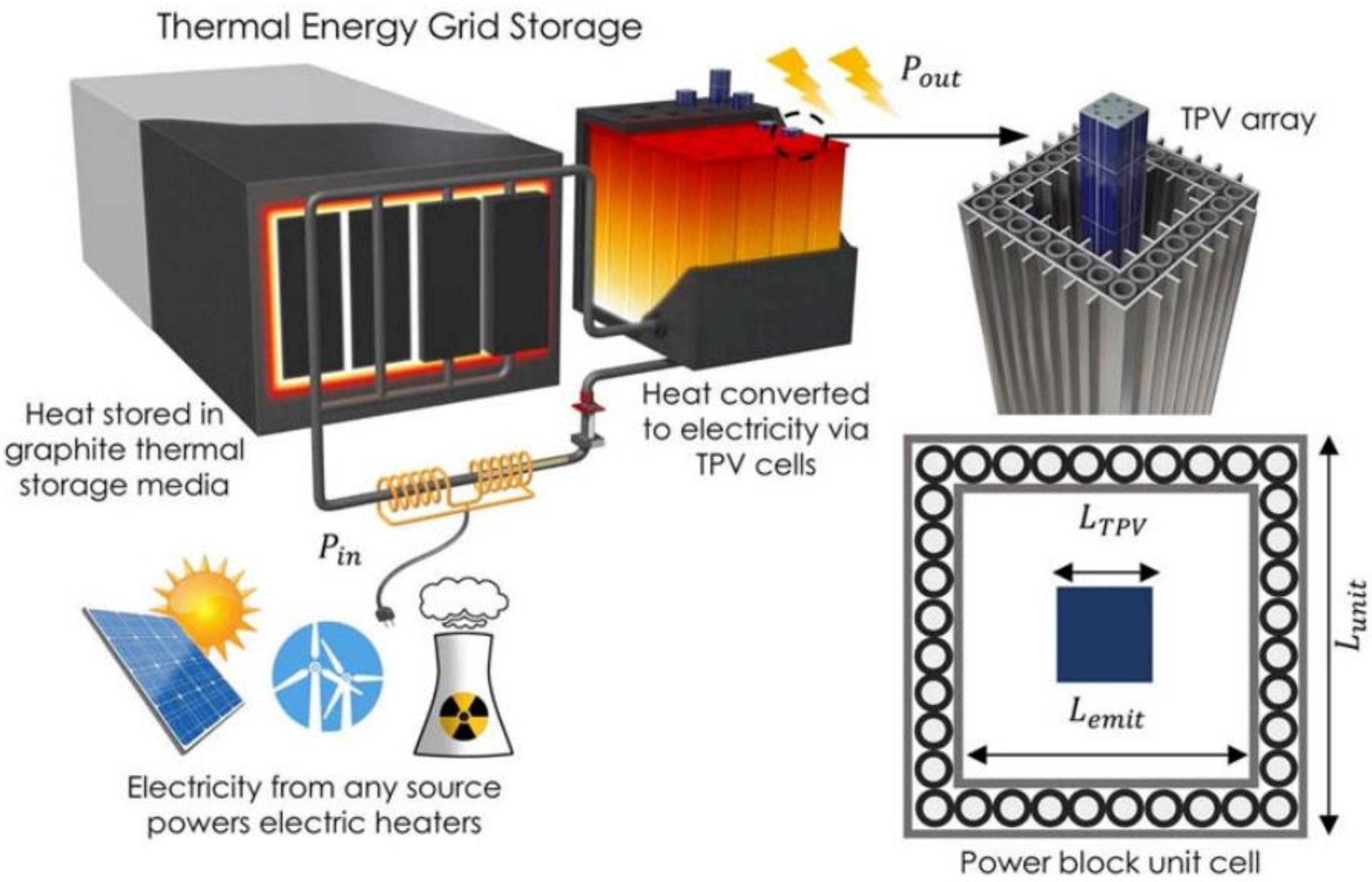
Fig- 1a Fig-1b

Rankine Cycle Representation is as follows on P-v and T-s diagrams:	
Ideal Rankine Cycle	1-2′-b-3′-4′-1
Actual Rankine Cycle	1-2-b-3-4-1

Thermophotovoltaic Energy Conversion

- Thermophotovoltaic systems are a unique approach to converting thermal radiation into electricity, which makes them a promising technology for waste heat recovery applications.
- In a thermophotovoltaic system, a hot surface (typically a blackbody emitter) absorbs waste heat and re-emits the energy as thermal radiation. This thermal radiation is then captured by a photovoltaic cell, which converts the radiant energy directly into electricity.
- Thermophotovoltaic systems can be used to harvest waste heat from various high-temperature sources, such as industrial processes, combustion systems, and nuclear reactors, where the high-grade waste heat can be effectively converted into electrical energy.

Thermophotovoltaic Energy Conversion



[milestone thermophotovoltaic cell converts 40% of heat energy to electricity]

Piezoelectric Waste Heat Harvesting

- Piezoelectric materials have the ability to generate an electric charge when subjected to mechanical stress or strain, a phenomenon known as the piezoelectric effect. This property can be exploited to harvest waste heat by converting temperature-induced mechanical deformations into electrical energy.
- Piezoelectric waste heat harvesting is particularly useful for applications where the waste heat source is associated with vibrations or oscillations, such as in rotating machinery, engine exhaust systems, or even building structures subjected to thermal expansion and contraction.
- The main advantage of piezoelectric waste heat recovery is that it can generate electricity from low-grade, distributed waste heat sources without the need for complex heat-to-electricity conversion systems.
- However, the power output of piezoelectric waste heat harvesters is typically low, and they are more suited for niche applications where low-power generation is sufficient, such as in self-powered sensors and wireless monitoring systems.

Thermoelectric Materials

- Thermoelectric materials are the core component of thermoelectric generators, and their performance is crucial in determining the overall efficiency of the waste heat recovery system.
- Thermoelectric materials are **typically semiconductors** that exhibit the Seebeck effect, which is the ability to generate an electric potential in response to a temperature difference across the material. The performance of thermoelectric materials is evaluated using the figure of merit, which is a dimensionless parameter that combines the Seebeck coefficient, electrical conductivity, and thermal conductivity of the material.
- Ongoing research efforts in thermoelectric materials aim to develop new materials and composites with improved figure of merit, higher thermal-to-electrical conversion efficiency, and better compatibility with specific waste heat applications. Some promising materials include lead telluride, bismuth telluride (Bi_2Te_3), and silver antimony lead telluride.

Advancements in Thermoelectric Technology

- Significant research efforts have been focused on improving the efficiency and performance of thermoelectric generators for waste heat recovery applications.
- One approach is to develop **novel thermoelectric materials** with **higher figures of merit**, such as through the use of nano structuring, doping, and the creation of composite materials. Another strategy is to improve the system-level design and integration of thermoelectric generators, such as by optimizing heat exchanger configurations, thermal management, and power conditioning circuitry.
- Recent advancements in thermoelectric technology have demonstrated improvements in conversion efficiency, power density, and cost-effectiveness, making them more viable for a wider range of waste heat recovery applications.

Heat Exchangers in Waste Heat Recovery

ketahanan the mechanical stress / temp (high)

- The design of heat exchangers is a critical component in the overall performance and efficiency of waste heat recovery systems.
- Factors such as heat transfer coefficients, pressure drops, and thermal resistances need to be carefully considered to ensure optimal heat transfer and minimize losses.
- Advancements in heat exchanger design, such as the use of compact and high-surface-area configurations, novel materials, and innovative manufacturing techniques, can significantly improve the performance and cost-effectiveness of waste heat recovery systems.
- Techniques like computational fluid dynamics modelling and optimization algorithms can be employed to design and optimize heat exchanger geometries for specific waste heat recovery applications.

Thermal Interface Materials

- Efficient heat transfer between components is crucial for the overall performance of waste heat recovery systems. Thermal interface materials, such as thermal greases, pads, or phase-change materials, play a critical role in reducing thermal resistance and improving heat transfer at the interfaces between various components, such as heat sources, heat exchangers, and thermoelectric modules.
- Advancements in thermal interface materials, including the development of high thermal conductivity composites and phase-change materials, can enhance the thermal management and overall efficiency of waste heat recovery systems.

molten salt, paraffin

Industrial Applications: Manufacturing

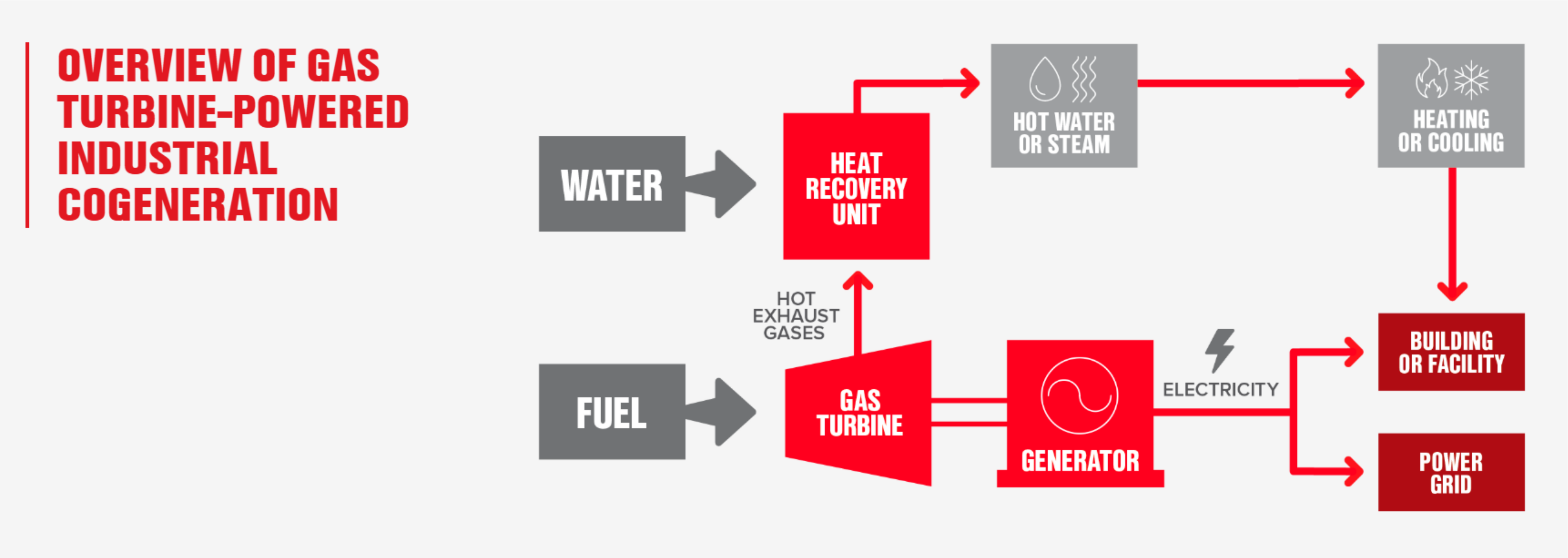
- Industrial processes, such as cement and steel production, often generate significant amounts of high-grade waste heat that can be effectively recovered and converted into electrical or thermal energy.
- In the cement industry, for example, the exhaust gases from cement kilns can reach temperatures up to 800°C, providing an excellent source of waste heat for energy recovery.
- Similarly, in steel production, the large amounts of waste heat generated from furnaces, coke ovens, and other process equipment can be harnessed to generate steam or electricity, improving the overall efficiency of the steel-making process.

Industrial Applications: Power Generation

- Combined heat and power (CHP) systems. Another key application of waste heat recovery is in combined heat and power systems, also known as cogeneration. In these systems, the waste heat from power generation processes, such as reciprocating engines or gas turbines, is captured and utilized for heating, cooling, or industrial processes, significantly improving the overall energy efficiency of the system.
- Cogeneration systems are particularly well-suited for industrial facilities that have a consistent demand for both electricity and thermal energy, such as food processing, paper mills, and chemical plants.

for e & heat

Combined Heat and Power (CHP) Systems



What is Industrial Cogeneration? | Combined Heat and Power (CHP)

Industrial Applications: Transportation

- Waste heat recovery is also an important consideration in the transportation sector, where significant amounts of waste heat are generated from vehicle engines and exhaust systems.
- Thermoelectric generators and other waste heat recovery technologies are being actively researched and developed for use in automotive and rail applications, with the goal of improving overall vehicle efficiency and reducing fuel consumption.

from exhaust etc

Emerging Trends: Hybrid Systems

- An emerging trend in waste heat recovery is the development of hybrid systems that leverage multiple energy harvesting technologies, such as thermoelectrics, organic Rankine cycles, and piezoelectrics, to capture and convert waste heat more efficiently.
- By integrating complementary energy harvesting technologies, hybrid systems can capture a broader range of waste heat temperatures and further improve the overall conversion efficiency, making waste heat recovery more economically viable for a wider range of applications.

Nanotechnology in Waste Heat Recovery

rekayasa material

- Nanotechnology has also played a significant role in the advancement of waste heat recovery technologies.
- The development of nanostructured thermoelectric materials, for example, has led to significant improvements in the figure of merit and conversion efficiency of thermoelectric generators.
- Similarly, the use of nano-engineered thermal interface materials and heat exchangers has enhanced heat transfer capabilities and reduced thermal resistances, contributing to the overall performance of waste heat recovery systems.

Environmental and Economic Benefits

- Effective waste heat recovery not only improves the efficiency of industrial processes and transportation systems but also offers significant environmental and economic benefits.
- By capturing and converting waste heat into useful energy, waste heat recovery systems can reduce the overall energy consumption and greenhouse gas emissions associated with these processes, contributing to a more sustainable energy landscape .
- Furthermore, the energy cost savings achieved through waste heat recovery can enhance the economic viability of industrial and transportation operations, making these systems an attractive investment for many companies and organizations.
- Industry that incorporates combined heat and power systems can see significant cost savings of 20-40% compared to purchasing electricity from the grid and using separate on-site boilers for heating.

Challenges and Limitations

- Despite the significant potential of waste heat recovery, there are still several challenges and limitations that need to be addressed.
- Achieving scalability and cost-effectiveness for large-scale waste heat recovery systems remains a significant challenge, particularly in industries with lower-grade waste heat or intermittent heat sources.
- The high capital costs and technical complexities associated with the integration of waste heat recovery systems can also hinder their widespread adoption.
- Additionally, the selection and development of suitable materials for waste heat recovery, such as high-performance thermoelectric materials or durable heat exchanger components, continues to be an active area of research and development.

- low efficiency

Future Prospects

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- As the global focus on sustainability and emissions reduction continues to grow, the importance of waste heat recovery will only become more pronounced.
- The ability to capture and convert waste heat into useful energy can contribute significantly to the overall energy efficiency and environmental performance of a wide range of industrial processes and transportation systems.
- With ongoing advancements in materials, systems integration, and hybrid technologies, the future of waste heat recovery holds great promise in helping to address the world's energy and environmental challenges.

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