WASTE HEAT TO POWER SYSTEMS

Introduction

Waste heat to power (WHP) is the process of capturing heat discarded by an existing industrial process and using that heat to generate power (see Figure 1). Energy-intensive industrial processes—such as those occurring at refineries, steel mills, glass furnaces, and cement kilns—all release hot exhaust gases and waste streams that can be harnessed with well-established technologies to generate electricity (see Appendix). The recovery of industrial waste heat for power is a largely untapped type of combined heat and power (CHP), which is the use of a single fuel source to generate both thermal energy (heating or cooling) and electricity.

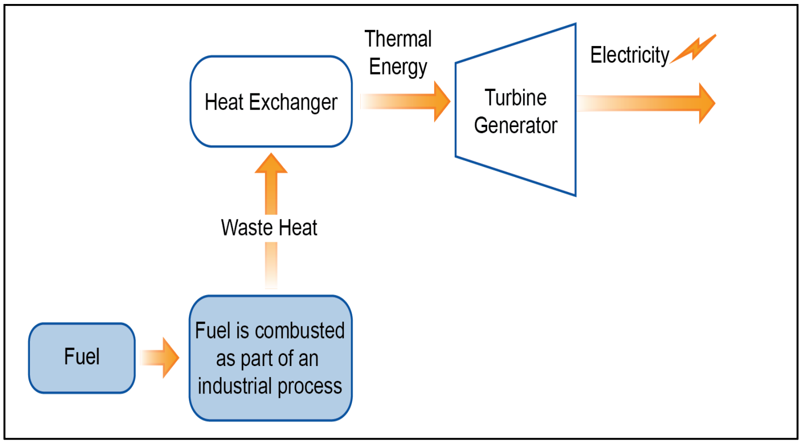

Figure 1: Waste Heat to Power Diagram

CHP generally consists of a prime mover, a generator, a heat recovery system, and electrical interconnection equipment configured into an integrated system. CHP is a form of distributed generation, which, unlike central station generation, is located at or near the energy-consuming facility. CHP's inherent higher efficiency and its ability to avoid transmission losses in the delivery of electricity from the central station power plant to the user result in reduced primary energy use and lower greenhouse gas (GHG) emissions.

The most common CHP configuration is known as a *topping cycle*, where fuel is first used in a heat engine to generate power, and the waste heat from the power generation equipment is then recovered to provide useful thermal energy. As an example, a gas turbine or reciprocating engine generates electricity by burning fuel and then uses a heat recovery unit to capture useful thermal energy from the prime mover's exhaust stream and cooling system. Alternatively, steam turbines generate electricity using high-pressure steam from a fired boiler before sending lower pressure steam to an industrial process or district heating system.

Waste heat streams can be used to generate power in what is called *bottoming cycle* CHP—another term for WHP.[1] In this configuration, fuel is first used to provide thermal energy in an industrial process, such as a furnace, and the waste heat from that process is then used to generate power. The key advantage of WHP systems is that they utilize heat from existing thermal processes, which would otherwise be wasted, to produce electricity or mechanical power, as opposed to directly consuming additional fuel for this purpose.

The Opportunity for WHP

Industrial energy use represents the largest potential source of WHP generation.[2] In 2009, the industrial sector used the largest share of energy in the United States, accounting for more than 28 Quads, or 30 percent of all

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[1] *Title 18: Conservation of Power and Water Resources; Part 292—Regulations under Sections 201 and 210 of the Public Utility Regulatory Policies Act of 1978; Subpart A – General Provisions, 292.101 Definitions.*

[2] Waste heat streams in other segments are generally either too low in temperature (power generation) or too small in volume (commercial and residential) to represent viable WHP sources.

energy consumed domestically.[3] Roughly one-third of the energy consumed by industry is discharged as thermal losses directly to the atmosphere or to cooling systems.[4] These discharges are the result of process inefficiencies and the inability of the existing process to recover and use the excess energy streams. Most of this waste energy, however, is of low quality (i.e., available in waste streams with temperatures below 300 °F or dissipated as radiation heat loss) and is typically not practical or economical to recover with current technology.
The efficiency of generating power from waste heat recovery is heavily dependent on the temperature of the waste heat source. In general, economically feasible power generation from waste heat has been limited primarily to medium- to high-temperature waste heat sources (i.e., > 500 °F). Emerging technologies, such as organic Rankine cycles, are beginning to lower this limit, and further advances in alternative power cycles may enable economic feasibility of generation at even lower temperatures over time.

Estimates of the amount of industrial waste heat available at a temperature high enough for power generation with today's technologies (i.e., >500 °F) are in the range of 0.6 to 0.8 Quads (or 6,000 to 8,000 megawatts [MW] of electric generating capacity)[5] on a national basis.[6,7,8,9] Nonindustrial applications, such as exhaust from natural gas pipeline compressor drives and landfill gas engines, represent an additional 1,000 to 2,000 MW of power capacity,[10] for a total of seven to ten gigawatts.

At the project level, a number of factors in addition to the temperature of the waste heat must be considered to determine the economic feasibility of power generation from waste heat sources:

- Is the waste heat source a gas or a liquid stream?[11]
- What is the availability of the waste heat—is it continuous, cyclic, or intermittent?
- What is the load factor of the waste heat source—are the annual operating hours sufficient to amortize the capital costs of the WHP system?
- Does the temperature of the waste stream vary over time?
- What is the flow rate of the waste stream, and does it vary?
- Is the waste stream at a positive or negative pressure, and does this vary?
- What is the composition of the waste stream?
- Are there contaminants that may corrode or erode the heat recovery equipment?

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[3] 1 Quad = 10^{15} Btu

[4] *Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery,* Terry Hendricks, Pacific Northwest National Laboratory, William Choate, BCS Incorporated, Report to U.S. DOE Industrial Technologies Program, November 2006.

[5] Based on a range of net generation efficiencies of 20 to 30 percent and annual load factors of 50 to 85 percent.

[6] Hendricks, *Op cit*.

[7] *Waste Heat Recovery in Industrial Facilities: Opportunities for Combined Heat and Power and Industrial Heat Pumps.* EPRI, Palo Alto, CA: 2010.

[8] *Waste Heat Recovery: Technology and Opportunities in the United States,* Report for U.S. DOE, BCS, Incorporated, March 2008

[9] *An Inventory of Industrial Waste Heat and Opportunities for Thermally Activated Technologies*, Report for Oak Ridge National Laboratory, United Technologies Research Center, 2004.

[10] Estimate prepared by ICF International, Inc., 2011.

[11] WHP systems operating with a liquid waste heat source can be designed around lower temperatures than one based on a gaseous heat source, such as industrial process flue gases. The minimum liquid waste temperature for economically feasible operation is 200 °F compared to 500 °F for gaseous waste streams.

The answers to these questions will determine system design and, ultimately, the economic viability of a WHP project. Many high-temperature waste heat sources are straightforward to capture and use with existing technologies. Other sources must be cleaned prior to use. The cleaning process is typically expensive, and removing the contaminants often removes the heat at the same time. Other waste heat sources are difficult to recover because of equipment configuration or operational issues.

Applicable Technologies

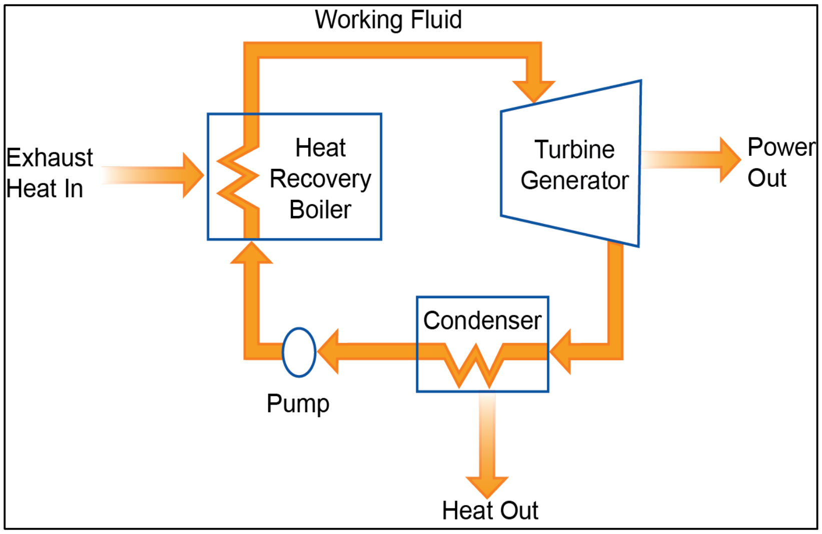

Figure 2: Rankine Cycle Heat Engine

Steam Rankine Cycle (SRC) – The most commonly used system for power generation from waste heat involves using the heat to generate steam in a waste heat boiler, which then drives a steam turbine. Steam turbines are one of the oldest and most versatile prime mover technologies. Heat recovery boiler/steam turbine systems operate thermodynamically as a *Rankine Cycle,* as shown in Figure 2**.** In the steam Rankine cycle, the working fluid—water—is first pumped to elevated pressure before entering a heat recovery boiler. The pressurized water is vaporized by the hot exhaust and then expanded to lower temperature and pressure in a turbine, generating mechanical power that can drive an electric generator. The low-pressure steam is then exhausted to a condenser at vacuum conditions, where heat is removed by condensing the vapor back into a liquid. The condensate from the condenser is then returned to the pump and the cycle continues.

Organic Rankine Cycles (ORC) – Other working fluids, with better efficiencies at lower heat source temperatures, are used in ORC heat engines. ORCs use an organic working fluid 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 in an SRC. ORC systems can be utilized for waste heat sources as low as 300 °F, whereas steam systems are limited to heat sources greater than 500 °F. ORCs have commonly been used to generate power in geothermal power plants, and more recently, in pipeline compressor heat recovery applications.

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.[12]

The three types of Rankine power cycles discussed above overlap to a certain degree. There are advantages to each, however:

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[12] A Rankine cycle operating with a liquid waste heat source can be designed around lower temperatures than for one based on a gaseous heat source, such as industrial process flue gases. The minimum liquid waste temperature for economically feasible operation is 200 °F.

- SRCs are the most familiar to industry and are generally economically preferable where the source heat temperature exceeds 800 °F.
- For lower temperatures, ORC or Kalina cycle systems are used. They can be applied at temperatures lower than for steam turbines, and they are more efficient in moderate temperature ranges.
- Kalina systems have the highest theoretical efficiencies. Their complexity makes them generally suitable for large power systems of several megawatts or greater.
- ORC systems can be economically sized in small, sub-megawatt packages, and they are also well suited for using air-cooled condensers, making them appropriate for applications such as pipeline compressor stations that do not have access to water.

In addition to Rankine cycle systems, there are a number of advanced technologies in the research and development stage that can generate electricity directly from heat, and that could in the future provide additional options for power generation from waste heat sources. These technologies include thermoelectric, piezoelectric, thermionic, and thermo-photovoltaic (thermo-PV) devices. Several of these have undergone prototype testing in automotive applications and are under development for industrial heat recovery.[13]

Applications

Economically feasible WHP applications are generally based on recovering waste heat from combustion exhaust streams with temperatures above 500 °F. Industrial processes that produce these temperatures include calcining operations (cement, lime, alumina, and petroleum coke), metal melting, glass melting, petroleum fluid heaters, thermal oxidizers, and exothermic synthesis processes. Key WHP opportunities within these operations are provided below:

1. **Primary Metals** – Primary metals manufacturing involves a large number of high-temperature processes from which waste heat can be recovered. Steel mills, for example, have various high-temperature heat- recovery opportunities. In integrated mills, waste heat can be recovered from coke ovens, blast furnaces for iron production, and basic oxygen furnaces for steel production. There are also opportunities to recover waste heat from electric arc furnaces. In the aluminum industry there is energy recovery potential from the exhaust of the Hall Héroult[14] cells and secondary melting processes. Metal foundries have a variety of waste heat sources, such as melting furnace exhaust, ladle pre-

Port Arthur Steam Energy
WHP from Petroleum Coke Plant

A heat recovery boiler/steam turbine WHP project at a petroleum coke plant in Port Arthur, Texas, recovers energy from 2,000 °F exhaust from three petroleum-coke calcining kilns. The project produces 450,000 lb/hr of steam for process use at an adjacent refinery and 5 MW of power. The project creates an estimated 159,000 tons per year of CO_2 emissions savings.

Waste Heat Boiler, Unit 4

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[13] *Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery,* Terry Hendricks, Pacific Northwest National Laboratory, William Choate, BCS Incorporated, Report to U.S. DOE Industrial Technologies Program, November 2006.

[14] The Hall–Héroult process is used for the production of aluminum.

heating, core baking, pouring, shot-blasting, castings cooling, heat treating, and quenching.

2. **Nonmetallic Mineral Product Manufacturing** – There are a number of strong opportunities for WHP in this sector. Calcining in rotary kilns is a high-temperature process that is used in the manufacture of cement, gypsum, alumina, soda ash, lime, and kaolin clay. The glass industry uses raw material melting furnaces, annealing ovens, and tempering furnaces, all operated at high temperatures.

3. **Petroleum Refining** – Basic processes used in petroleum refineries include distillation (fractionation), thermal cracking, catalytic, and treatment. These processes use large amounts of energy, and many involve exothermic reactions that also produce heat. Modern refineries are highly integrated systems that recover heat from one process to use in other processes. However, many operations still release high-quality waste heat that could be recovered for power production. An example is the exhaust from petroleum coke calciners. Petroleum coke is heated to 2,400 °F, and the exhaust is typically 900 to 1,000 °F leaving the calciner.

TransGas Pipeline Compressor Drive WHP

A Pratt & Whitney ORC system is generating 865 kW of net power from the exhaust of a Solar Centaur 40 gas turbine driving a natural gas pipeline compressor on a TransGas Pipeline in Saskatchewan, Canada. The installation is one of over 20 ORC WHP systems on natural gas pipeline compressors in North America.

4. **Chemical Industry** – There are several major segments of the industry, including petrochemicals, industrial gases, alkalies and chlorine, cyclic crudes and intermediates (e.g., ethylene, propylene, and benzene/ toluene/xylene), plastics materials, synthetic rubber, synthetic organic fibers, and agricultural chemicals (fertilizers and pesticides), in which high-temperature exhaust is released that could be recovered for power generation. There are five CHP systems in U.S. ethanol plants operating on waste heat produced by thermal oxidizers (which are operated for volatile organic compound destruction). These five plants have a combined capacity of 17 MW.

5. **Fabricated Metals** – Processes generating waste heat include metal pre-heating, heat treatment, cleaning, drying, and furnace heating.

6. **Natural Gas Compressor Stations** – There are more than 20 ORC power generation systems installed at natural gas compressor stations in North America. These systems have a total electric capacity of 105 MW using the exhaust heat from 668,000 horsepower of gas turbine-driven compressors.

7. **Landfill Gas Energy Systems** – Landfills that use reciprocating internal combustion engines or turbines to produce power could generate additional power with ORC systems using exhaust gases. Other landfills could install ORC systems to generate power from the waste heat from flaring.

8. **Oil and Gas Production** – There are a number of flared energy sources in oil and gas production that could utilize WHP.

Economics

The total cost to install WHP systems include the costs associated with the waste heat recovery equipment (boiler or evaporator), the power generation equipment (steam, ORC, or Kalina cycle), power conditioning and interconnection equipment. It would also include the soft costs associated with designing, permitting and constructing the system. The installed costs of Rankine cycle power systems (steam, ORC or Kalina) are fairly similar, differing more as a function of project size and the complexity of site integration than type of system. A first-cut estimate of the cost of producing power from WHP systems is presented in Table 1. Representative costs are shown that represent a range of project sizes (<400 kW to > 5 MW) and site complexity. Capital costs are amortized over a 10 year period based on a cost of capital of 15 percent[15] and 7,500 annual operating hours. Operation and maintenance (O&M) cost estimates can vary widely. Rankine cycle power systems themselves have relatively low maintenance costs. However, maintenance requirements of the heat recovery boilers and balance of plant must also be included and these can vary by technology and by site conditions. As an example, steam systems may require on-site boiler operators while ORCs can often run unattended. O&M costs of $0.005 - $0.020/kWh were used for this comparison to reflect the wide range of maintenance requirements that might be experienced. There are no fuel costs for true waste heat to power projects (i.e., no supplemental fuel use).

Table 1 - Waste Heat to Power Cost Comparison

Cost Component	
Installed Costs, $/kW	$2,000 - $4,000
WHP Generating Costs	
Amortized Capital, $/kWh	$0.055 - $0.125
O&M Costs, $/kWh	$0.005 - $0.020
Total Power Cost, $/kWh	**$0.060 - $0.125**

Source: *ICF International estimates, 2012*

Current Market Status

Current market penetration of WHP projects in the United States is limited compared to other types of CHP. There are currently 34 WHP projects in place totaling 557 MW of power generation capacity in the United States, as shown in Table 2. Most of the existing industrial WHP systems use a heat recovery boiler, steam turbine, and generator, which are limited to waste streams with relatively high temperatures (> 500 °F).

Other options are entering the market that can be used at lower temperatures and smaller sizes, including ORCs, ammonia-water systems (e.g., Kalina cycles), and thermo-electric generators (still in development) that use solid state systems that require no moving parts and sit directly in the waste stream. Utilizing liquid streams below 200 °F and gas streams below 500 °F typically remains economically impractical with today's technologies, however. Conversion to electricity is less efficient with all these technologies compared to traditional electric generators, and project costs currently run high for a variety of reasons, including the cost of the equipment and the cost of integrating the waste heat recovery system with the waste heat source. WHP is generally considered only when the waste heat cannot be used directly within the process, or other recovery methods are not practical within the facility. While the costs of these systems currently remain high, and commercial demonstration is limited, the technologies continue to evolve rapidly.

Table 2: Existing WHP Projects in the United States by Application

Industries	Sites	Capacity MW
Chemicals	12	224
Petroleum Refining	5	131
Non-metallic Mineral Industries	2	10
Primary Metals	2	127
Landfill Gas Power	1	<1
Natural Gas Compressor Stations	12	65
Total	**34**	**557**

Source: *CHP Installation Database, DOE/ORNL, 2012*

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[15] The relatively high cost of capital of 15 percent reflects current perceptions of technology and market risks.

Market Barriers

Technical Barriers. The principal hurdle for WHP systems is the heat recovery itself. While the power generation equipment is commercially established and relatively standardized, each heat recovery situation presents unique challenges. Some of the project-specific technical issues that affect project economics include:

- The waste heat sources at a plant are dispersed and difficult to reach or consolidate, or are from non-continuous or batch processes.
- Seasonal operations and low-volume operations reduce the economic benefits of WHP.
- Waste heat sources often contain chemical and/or mechanical contaminants that impact the complexity, cost, and efficiency of the heat recovery process
- There may be added cost and complexity for integrating the WHP system controls with existing process controls.
- Space limitations and equipment configurations make WHP systems difficult or impossible to site economically.

Business Barriers. As industry recovers from the 2008 economic downturn, most businesses are reluctant to make investments that do not increase production and ensure their economic survival. They are especially reluctant to take on projects with perceived risks, such as energy recovery projects that are outside of their core business. These concerns often lead to unrealistically high project hurdle rates for capital-intensive WHP projects. Small projects (less than $5 million) can be particularly difficult to develop because the returns are often reduced by the costs of due diligence, permitting, and siting. The economic downturn has exacerbated the inherent risk of financing projects with long paybacks, especially projects dependent on uncertain future fuel prices and variable electricity rates.

Securing financing from banks for WHP projects is a challenge because the systems can be technically complicated, and they combine the risk associated with power generation with the risk inherent in the primary business itself (i.e., there is no heat to recover if the plant shuts down).

There is also a general lack of end-user awareness of WHP technologies and how to implement them. Few technology demonstrations or case studies currently exist, and most projects are very site- and process-specific. There is resistance to accept new, unproven technology that could potentially jeopardize existing production processes, despite significant potential benefits.

Regulatory Barriers. Economic issues related to equipment costs and forecasted energy savings may be the greatest determinant of a successful WHP project; however, regulations and policies can have a substantial impact on project economics. For example, if the power cannot be used on site, projects will require a power purchase agreement with the utility. This is the case with WHP systems on natural gas pipeline compressor stations. While 20 ORC-based systems have been installed in North America since 1999, all projects to date are in states or provinces with renewable portfolio standards (RPS) or environmental credit systems that recognize waste heat as a renewable or "renewable equivalent" resource. Prices offered for export power are usually extremely low in the absence of some sort of emissions credit system. Because power from WHP systems produces no additional GHG emissions if supplemental fuel firing is not used, industry advocates believe the technology warrants incentives similar to those enjoyed by other clean energy technologies. To date, these incentives are in place only in certain states. Currently, nine of 29 states with binding RPS[16] include WHP as a qualifying source (i.e., Colorado, Connecticut, Hawaii, Michigan, Nevada, North Carolina, Ohio, Pennsylvania, and West Virginia), while six states with nonbinding renewable energy goals include WHP in some fashion (i.e., Indiana, Louisiana [pilot program], Oklahoma, North Dakota, South Dakota, and Utah). The more critical issue

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[16] http://www.ferc.gov/market-oversight/othr-mkts/renew/othr-rnw-rps.pdf

from the industry viewpoint may be that WHP projects do not currently qualify for the 10-percent federal investment tax credit for CHP.

Resources and Additional Information

The U.S. Environmental Protection Agency CHP Partnership is a voluntary program that seeks to reduce the environmental impact of power generation by promoting the use of cost-effective CHP. The Partnership works closely with energy users, the CHP industry, state and local governments, and other clean energy stakeholders to facilitate the development of new projects and to promote their environmental and economic benefits. . See www.epa.gov/chp.

The U.S. Department of Energy's (U.S. DOE) eight regional Clean Energy Application Centers formerly called the Combined Heat and Power (CHP) Regional Application Centers (RACs), promote and assist in transforming the market for CHP, waste heat recovery, and district energy technologies and concepts throughout the United States. See http://www1.eere.energy.gov/manufacturing/distributedenergy/ceacs.html

The U.S. Clean Heat and Power Association (UCHPA) is a trade association that brings together diverse market interests to promote the growth of clean, efficient local energy generation in the United States. USCHPA's mission is to increase deployment of combined heat and power and waste energy recovery systems to benefit the environment and the economy. See www.uschpa.org.

Heat is Power is a trade association that works to educate decision-makers and the public about the characteristics of waste heat as a resource for emission-free electricity and the development of WHP as an economic driver and boost to U.S. global competitiveness. See www.heatispower.org.

The Database of State Incentives for Renewable Energy (DSIRE) website provides information about renewable energy and energy efficiency incentives and policies in the United States. Relevant incentives and policies established by the federal government, state governments, local governments, utilities and non-profit organizations are included. DSIRE is funded by U.S. DOE. See www.dsireusa.org.

Waste Heat Recovery: Technology and Opportunities in U.S. Industry, BCS Incorporated, Report to U.S. DOE Industrial Technologies Program, March 2008. Available at: http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf.

Appendix: Waste Heat Streams Classified by Temperature

Temperature Classification	Waste Heat Source	Characteristics	Commercial Waste Heat to Power Technologies
High (>1,200 °F)	• Furnaces – Steel electric arc – Steel heating – Basic oxygen – Aluminum reverberatory – Copper reverberatory – Nickel refining – Copper refining – Glass melting • Iron cupolas • Coke ovens • Fume incinerators • Hydrogen plants	• High quality heat • High heat transfer • High power-generation efficiencies • Chemical and mechanical contaminants	• Waste heat boilers and steam turbines
Medium (500 –1,200 °F)	• Prime mover exhaust streams – Gas turbine – Reciprocal engine • Heat-treating furnaces • Ovens – Drying – Baking – Curing • Cement kilns	• Medium power-generation efficiencies • Chemical and mechanical contaminants (some streams such as cement kilns)	• Waste heat boilers and steam turbines (>500 °F) • Organic Rankine cycle (<800 °F) • Kalina cycle (<1,000 °F)
Low (< 500 °F)	• Boilers • Ethylene furnaces • Steam condensate • Cooling Water – Furnace doors – Annealing furnaces – Air compressors – IC engines – Refrigeration condensers • Low-temperature ovens • Hot process liquids or solids	• Energy contained in numerous small sources • Low power-generation efficiencies • Recovery of combustion streams limited due to acid concentration if temperatures reduced below 250 °F	• Organic Rankine cycle (>300 °F gaseous streams, >175 °F liquid streams) • Kalina cycle (>200 °F)

For more information, contact:

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