U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY & RENEWABLE ENERGY

Combined Heat and Power Technology Fact Sheet Series

Waste Heat to Power

Figure 1. WHP system (16 MW) at J.R. Simplot fertilizer manufacturing plant in Idaho.
Photo credit: Heat is Power Association

Waste heat to power (WHP) technologies produce electricity by capturing waste heat—typically from exhaust gas or industrial processes—and converting this waste heat to electricity. WHP systems utilize otherwise wasted thermal energy to drive turbines or engines that can produce electricity for on-site consumption or grid export. WHP is used most often in industrial applications, but opportunities also exist in institutional buildings, commercial operations, and district energy systems. WHP is a clean energy technology; it produces no new emissions from the use of waste heat and often displaces electricity produced from carbon-based fuels. When waste heat is recovered from a thermal process and used to generate electricity, it is considered to be a combined heat and power (CHP) system. As indicated in Table 1, waste heat sources that drive WHP technologies can be divided into three categories, each with its own attributes.

Table 1. Types of Waste Heat Streams

Waste heat from a thermal process	High-temperature waste heat can be recovered from a boiler, furnace, oven, kiln, or other thermal process[1] and converted to electricity using a system such as a Rankine cycle steam turbine. Lower-temperature waste heat can be recovered from thermal systems and processes and converted to electricity using other technologies, such as the organic Rankine cycle coupled with turbines or reciprocating engines. This WHP configuration is also referred to as "bottoming cycle" CHP.
Waste heat from a mechanical drive	Engines and turbines can be used to drive mechanical shafts that, in turn, spin compressors, pumps, and electrical generators. An example is a pipeline compressor station that uses a gas turbine to drive a compressor to move natural gas through a pipeline. Low-temperature waste heat can be recovered from the gas turbine exhaust, typically using organic Rankine cycle technology, and used to generate electricity.
Waste heat from other systems[2]	Some industrial processes generate heat as a byproduct. Examples of operations that yield byproduct heat that can be used for WHP include exothermic reactions (e.g., fertilizer manufacturing), incineration of sewage sludge, and heat released from pressure relief valves (PRVs).

For all types of waste heat streams, the U.S. Department of Energy (DOE) CHP Installation Database lists 938 MW of installed WHP capacity at over 100 U.S. sites as of 2019.[3] In 2016, DOE published a report summarizing CHP technical potential, which included a bottom-up analysis of industrial waste streams above 450°F. The report identified 8,840 MW of WHP potential from 2,946 sites.

[1] Other processes include calciners, kilns, flares, incinerators, ovens, reciprocating engines, regenerative oxidizers, thermal oxidizers, and exhaust from petroleum refining.

[2] Capture and use of heat for a thermal purpose is classified as waste heat recovery, while capture and use of that heat to make electricity is WHP. While this fact sheet focuses on WHP applications, recovered waste heat can also be used for compressed air, industrial steam, absorption chillers, drying, hot water, preheated combustion air, or a combination of these.

[3] U.S. Department of Energy CHP Installation Database, 2019, https://doe.icfwebservices.com/chp.

Table 2 shows the estimated technical potential categorized by North American Industry Classification System (NAICS) code. Petroleum refining and primary metals (iron and steel) have the greatest potential for WHP applications, followed by non-metallic minerals (stone/clay/glass). These estimates do not include low-temperature (<450°F) commercial/institutional waste heat sources.

Table 2. Industrial WHP Technical Potential (>450°F)

NAICS Code	NAICS Description	Primary Waste Heat Sources	Capacity (MW)
324	Total Petroleum and Coal Products	Petroleum coke calciners	3,593
331	Total Primary Metals	Blast furnaces, coke ovens, furnaces	2,186
327	Total Non-Metallic Minerals	Melting furnaces, lime/cement kilns	1,173
486	Pipeline Transportation	Natural gas compressor stations	1,102
211	Oil and Gas Extraction	Flared gas	538
562	Waste Management	Incinerators	113
325	Chemical	Petrochemicals, exothermic processes	92
– – –	Other Industrial Sources	Combustion for heating/drying	43

Source: ICF

To determine and characterize the WHP potential for any source of waste heat, several attributes of the heat source must be defined:

- Composition of waste stream (e.g., whether it is liquid or gaseous and whether contaminants are present)
- Availability of waste heat source (whether continuous, cyclic, or intermittent)
- Temperature and flow rate variability

Each of these characteristics can have an impact on system design and economic viability.

The U.S. Environmental Protection Agency's CHP Partnership, in its report titled "Waste Heat to Power Systems," provides more information on opportunities for WHP, including project-level considerations to determine economic feasibility of power generation from waste heat.[4]

Technology Description

Most commercially available WHP technologies in the United States are based on the Rankine thermodynamic cycle—either the steam Rankine cycle (SRC) or the organic Rankine cycle (ORC). A related process is the Kalina cycle, which leverages aspects of both.

The Rankine Thermodynamic Cycle

In a Rankine cycle, a liquid working fluid is pumped to elevated pressure before entering a heat recovery boiler, as illustrated in Figure 2. The pressurized fluid is vaporized using energy captured from a waste heat stream, and then expanded to lower temperature and pressure in a turbine, generating mechanical power that can drive an electric generator. The low-pressure working fluid is then exhausted to a condenser; condensate from the condenser is returned to the pump, and the cycle is repeated. For WHP applications, the Rankine cycle efficiency typically ranges from 30%–50% of the Carnot Efficiency.[5] For example, if the Carnot Efficiency is calculated to be 60% for a 900°F heat source, the actual efficiency achieved will likely be in the range of 18%–30% percent.

[4] "Waste Heat to Power Systems," U.S. Environmental Protection Agency, 2012, https://www.epa.gov/sites/production/files/2015-07/documents/waste_heat_to_power_systems.pdf.

[5] The Carnot Efficiency is the theoretical maximum efficiency for a heat engine operating between two temperatures.

Steam Rankine Cycle (SRC)

The most commonly used Rankine cycle is the steam turbine, or steam Rankine cycle (SRC). In an SRC system, the working fluid is water, and steam is created to drive a turbine. Steam turbines are a mature and versatile technology and have been in use for more than 100 years. Most of the electricity produced in the United States is generated by conventional steam turbine power plants that use coal, natural gas, or nuclear energy as a fuel source. In WHP applications, the capacity of steam turbines can range from 50 kW to several hundred megawatts. SRC systems require high-grade waste heat to superheat water to non-saturated steam; therefore, SRC is typically used in high-temperature WHP applications.

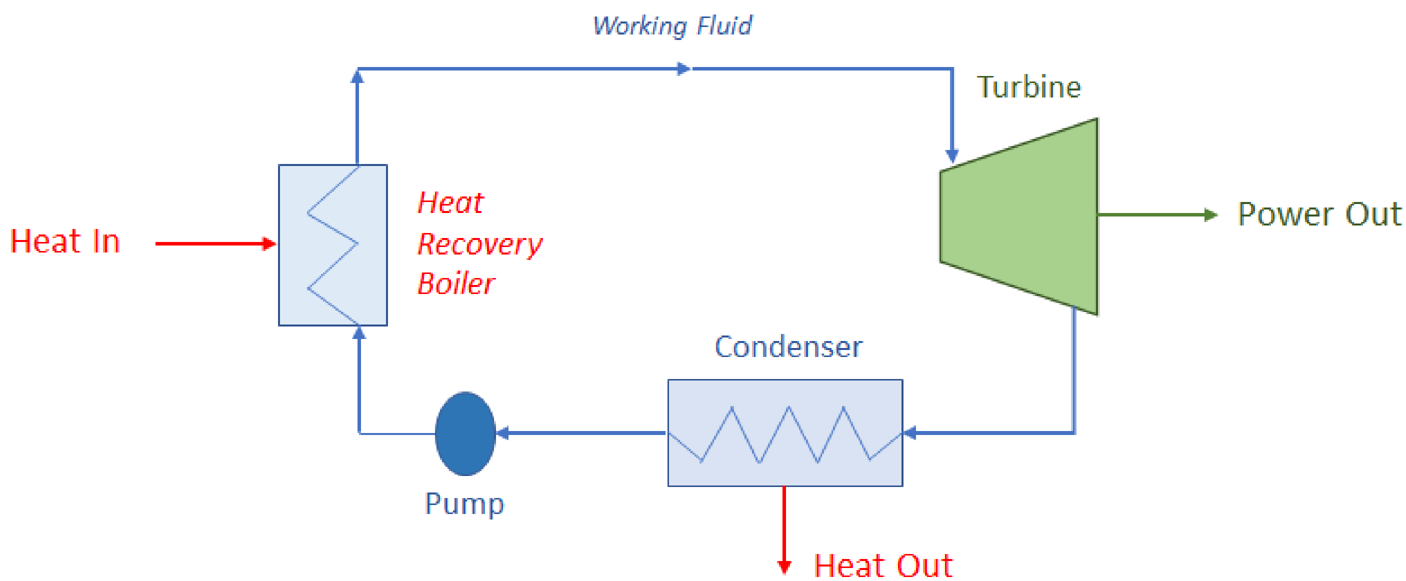

Figure 2. Rankine thermodynamic cycle schematic. *Graphic credit: ICF*

Organic Rankine Cycle (ORC)

ORC systems have been used for decades to generate power in geothermal power plants and, more recently, in pipeline compressor station applications. ORC systems are similar to SRC systems, but instead of water, the working fluid is typically a hydrocarbon or ammonia. ORC working fluids include hydrofluorocarbons, silicone oil, propane, isopentane, isobutane, xylene, and toluene. The fluid is chosen based on the best thermodynamic match to the available heat source. The working fluid in an ORC machine typically has a much lower boiling point than that of water, which allows ORC systems to operate with relatively low-temperature heat sources.

Along with an evaporator (boiler), expander (turbine), and condenser, some ORC designs incorporate a regenerator, which improves efficiency by pre-heating the working fluid with energy that would otherwise be rejected.

ORC innovations are allowing efficient operation at temperatures far lower than 450°F—sometimes as low as 200ºF—opening up more potential WHP applications. However, electric efficiencies generally decline along with the temperature of the waste heat stream. A comparison of traditional and low-temperature ORC technologies is shown in Table 3.

Table 3. Comparison of Traditional and Low-Temperature ORC

Characteristic	ORC Technology	
	Traditional	Low-Temperature
Inlet Waste Heat Temperature	320°F–500°F	200°F–300°F
Conversion Efficiency from Thermal to Electric Energy	15%–20%[6]	8%–9%[7]

6 "Waste Heat Recovery – Technology and Opportunities in U.S. Industry," prepared by BCS, Inc., for the DOE Industrial Technologies Program, March 2008.

7 Includes parasitic loads.

Kalina Cycle

The Kalina cycle uses two fluids with different boiling points (ammonia and water) as the working fluid. The range of boiling points enables a two-step evaporation process, which allows more heat to be extracted from the source.

Emerging Technologies

In addition to commercially available Rankine and Kalina cycle WHP technologies, there are emerging WHP systems: thermoelectric generation, thermionic generation, Stirling engines, piezoelectric generation, thermo photovoltaic generation, and supercritical carbon dioxide cycles. These WHP technologies are largely in the research and development stage but are moving toward commercialization.

Capital Cost

SRC and ORC systems account for nearly all WHP systems currently installed and are expected to be the dominant technologies installed for the next several years. Typical installation and operations and maintenance (O&M) costs are shown in Table 4. SRC capital costs range from $1,200 to $3,000/kW. ORC capital costs are higher, ranging from $1,900 to $4,500/kW. Increased deployment of smaller ORCs in recent years has helped reduce capital costs, and this trend is expected to continue. O&M costs, too, are currently lower for SRC (from 0.5 to 1.3 cents/kWh) than for ORC (0.9 to 1.8 cents/kWh). O&M requirements of the heat recovery boiler and balance of plant must also be included, and these can vary by technology and by site conditions. Heat recovery maintenance tends to be more costly when the exhaust stream has significant contaminants. The installed capital costs shown here are based predominantly on information obtained from equipment suppliers. These costs may vary significantly based on site-specific conditions.

Table 4. Estimated WHP Capital and O&M Costs

Technology	Cost Characteristic	Electric Capacity for WHP Technology				
		50–500 kW	500–1,000 kW	1–5 MW	5–20 MW	>20 MW
Steam Rankine Cycle	Installed Capital Costs, $/kW	$3,000	$2,500	$1,800	$1,500	$1,200
	O&M Costs, $/kWh	$0.013	$0.009	$0.008	$0.006	$0.005
Organic Rankine Cycle	Installed Capital Costs, $/kW	$4,500	$4,000	$3,000	$2,500	$1,900
	O&M Costs, $/kWh	$0.018	$0.014	$0.012	$0.011	$0.009

Source: ICF

The largest hurdles for WHP system adoptions are often site-specific requirements for heat recovery. Heat sources may be non-continuous, contaminated, difficult to reach, or highly dispersed. These factors can sometimes require complex engineering solutions that may not be included in the cost estimates. However, there are many sources of waste heat at industrial, institutional, and commercial facilities that can provide accessible and economic opportunities for efficient, zero-emission CHP solutions.

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DOE/EE-2347 • April 2021