WASTE HEAT TO POWER SYSTEMS

Introduction

Waste heat to power (WHP) is the process of capturing heat discarded by an existing thermal process and using that heat to generate power (see Figure 1). Energy-intensive 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 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 (i.e., heating or cooling) and electricity.

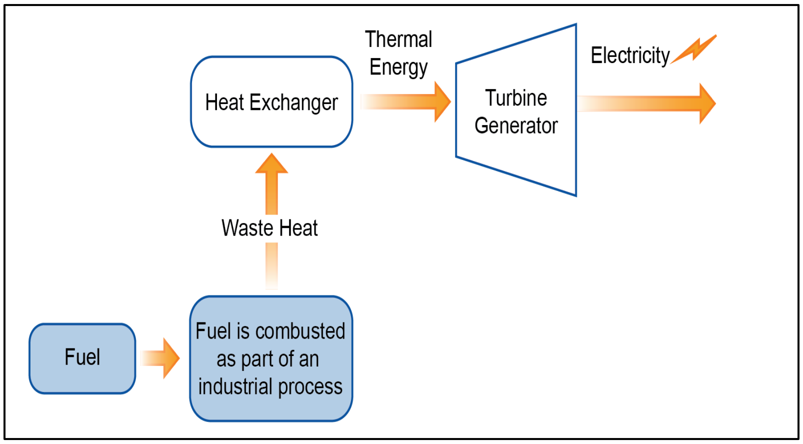

Figure 1: Waste Heat to Power Diagram

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 power generation that is located at or near the energy-consuming facility. By contrast, central station generation takes place at separate, centralized power plants. CHP's inherent higher efficiency and its ability to avoid transmission losses in delivering electricity from the central station power plant to the user result in reduced primary energy use and lower greenhouse gas 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, such as using fuel to power 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.

[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.*

The Opportunity for WHP

Industrial energy use represents the largest potential source of WHP generation.[2] In 2020, the industrial sector used the largest share of energy in the United States, accounting for more than 33 percent of all 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 existing processes 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., greater than 500 °F). Emerging technologies, such as organic Rankine cycles (ORCs), are beginning to lower this limit, and further advances in alternative power cycles will enable economic feasibility of generation at even lower temperatures over time.

The amount of recoverable waste heat available at high temperatures (i.e., 450 °F or higher) in the United States is estimated to support 7,600 megawatts (MW) of electric generating capacity.[5] ORC systems can produce electricity from lower temperature waste heat sources (i.e., less than 450 °F), but this potential has not yet been quantified.

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

- Is the waste heat source a gas or a liquid stream?[6]
- 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 the flow rate vary?
- Is the waste stream at a positive or negative pressure, and does this pressure vary?
- What is the composition of the waste stream?
- Are there contaminants that may corrode or erode the heat recovery equipment?

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

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

[3] "Use of energy explained," U.S. Energy Information Administration, https://www.eia.gov/energyexplained/use-of-energy/industry.php.

[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] *Combined Heat and Power (CHP) Technical Potential in the United States,* U.S. Department of Energy, March 2016, https://www.energy.gov/sites/default/files/2016/04/f30/CHP%20Technical%20Potential%20Study%203-31-2016%20Final.pdf.

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

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

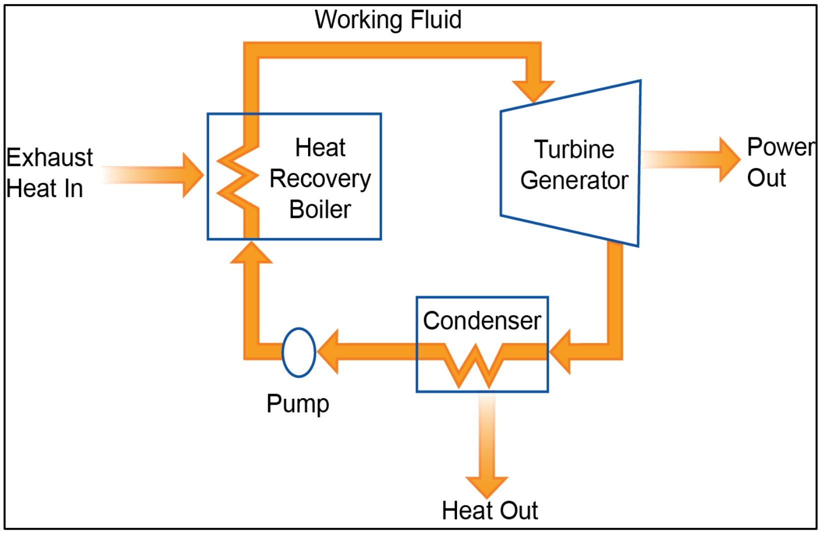

Figure 2: Rankine Cycle Heat Engine

The *steam Rankine cycle (SRC)* is the most commonly used system for power generation from waste heat and involves using waste 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 and steam turbine systems operate thermodynamically as a *Rankine Cycle,* as shown in Figure 2. In the SRC, the working fluid (i.e., 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 involve using other working fluids with better efficiencies at lower heat source temperatures 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, which can be used by a variety of facilities, and more recently in pipeline compressor heat recovery applications.

Veyo Heat Recovery Project WHP

An ORMAT ORC system is generating 7,800 kilowatts (kW) of net power from the exhaust of three Solar Mars 100 gas turbines driving a Kern River Gas Transmission Company natural gas pipeline compressor near Veyo, Utah. The installation is one of 15 ORC WHP systems at natural gas pipeline compressors in North America.

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. SRC and ORC systems are much more prevalent in the United States, but Kalina cycle systems are becoming increasingly popular overseas in geothermal power plants, where the hot fluid is often below 300 °F.[7]

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

- SRC systems are the most familiar to industry and are in general economically preferable when the source heat temperature exceeds 800 °F.
- For lower temperatures, ORC or Kalina cycle systems can be used. These systems can be applied at temperatures lower than for steam turbines and 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 MWs or greater.
- ORC systems can be economically sized in small, sub-MW 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.

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 pounds/hour 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 carbon dioxide emissions savings.

Waste Heat Boiler, Unit 4

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 devices. Several of these technologies have undergone prototype testing in automotive applications and are under development for industrial heat recovery.[8]

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 (e.g., cement, lime, alumina, petroleum coke), metal melting, glass melting, petroleum fluid heaters, thermal oxidizers, and exothermic synthesis processes. Additionally, there are plentiful opportunities for lower temperature applications across the United States, and ORC systems can be economical in areas with high electricity prices or WHP incentives. Key WHP opportunities within these operations are provided below:

[7] 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.

[8] *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.

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[9] cells and secondary melting processes. Metal foundries have a variety of waste heat sources, such as melting furnace exhaust, ladle preheating, core baking, pouring, shot blasting, castings cooling, heat treating, and quenching.

Table 1. WHP Cost Comparison

Cost Component	ORC	SRC
Installed Costs, $/kW	$1,900–$4,500	$1,200–$3,000
WHP Generating Costs		
Amortized Capital, $/kWh	$0.055–$0.125	
O&M Costs, $/kWh	$0.009–$0.018	$0.005–$0.013
Total Power Cost, $/kWh	**$0.060–$0.125**	

Source: *Combined Heat and Power Technology Fact Sheet Series: Waste Heat to Power, U.S. DOE, 2021.*

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, catalysis, 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.

4. **Chemical industry.** There are several major segments of the industry in which high-temperature exhaust is released that could be recovered for power generation, including petrochemicals, industrial gases, alkalis and chlorine, cyclic crudes and intermediates (e.g., ethylene, propylene, and benzene/ toluene/xylene), plastics materials, synthetic rubber, synthetic organic fibers, and agricultural chemicals (i.e., fertilizers and pesticides).

5. **Fabricated metals.** Processes generating waste heat include metal preheating, heat treatment, cleaning, drying, and furnace heating.

6. **Natural gas compressor stations.** There are 15 ORC power generation systems installed at natural gas compressor stations in North America. These systems have a total electric capacity of 85 MW using the exhaust heat from 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 caused by flaring.

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

[9] The Hall–Héroult process is used for producing aluminum.

Economics

The total cost to install WHP systems include the costs associated with the waste heat recovery equipment (i.e., boiler or evaporator), power generation equipment (i.e., SRC, ORC, or Kalina cycle), and power conditioning and interconnection equipment. The total cost would also include the soft costs associated with designing, permitting, and constructing the system. The installed costs of SRC, ORC, or Kalina cycle power systems are fairly similar, differing more as a function of project size and the complexity of site integration than type of system. Table 1, below, shows a first-cut estimate of the cost of producing power from WHP systems. The representative costs shown cover a range of project sizes (50 kW to greater than 20 MW) and site complexity. Capital costs are amortized over a 10-year period based on a cost of capital of 15 percent[10] 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, which can vary by technology and by site conditions. As an example, steam systems may require onsite boiler operators while ORCs can often run unattended. O&M costs of $0.005–$0.018 per kilowatt-hour (kWh) were used for Table 1 to reflect the wide range of maintenance requirements that might be experienced. There are no fuel costs for true WHP projects (i.e., no supplemental fuel use).

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 WHP systems use a heat recovery boiler, steam turbine, and generator, which are limited to waste streams with relatively high temperatures (i.e., greater than 800 °F).

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

Industries	Sites	Capacity MW
Chemicals	23	385.1
Wood Products	12	13.5
Petroleum Refining	7	35.6
Primary Metals	5	316.0
Pulp and Paper	4	2.8
Food Processing	3	3.9
Electrical Equipment	3	2.2
Stone, Clay, Glass	2	50.2
Furniture	2	0.3
Transportation Equipment	1	1.8
Misc. Manufacturing	1	0.6
Total	**63**	**812.0**

Source: *CHP Installation Database, DOE/ORNL, 2022.*

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 thermoelectric generators (still in development) that use solid-state systems that require no moving parts and sit directly in the waste stream. However, utilizing liquid streams below 200 °F and gas streams below 500 °F typically remains economically impractical with today's technologies. 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 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.

[10] 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 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. Businesses may be reluctant to take on projects with perceived risks, such as energy recovery projects that are outside their core business. These concerns often lead to unrealistically high project hurdle rates for capital-intensive WHP projects. Small projects (i.e., 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).

End users also lack a general 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 from businesses 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. Prices offered for export power are usually low in the absence of some sort of credit. One key policy for the WHP industry is a federal investment tax credit that was adopted by the U.S. Congress in December 2020. The tax credit, set at 26 percent of project costs in 2022 and 22 percent in 2023, applies to WHP systems less than or equal to 50 MW that begin construction before December 31, 2023.

At a state level, incentives are in place only in certain states. Currently, nine of the 29 states with binding renewable portfolio standards[11] include WHP as a qualifying source (Colorado, Connecticut, Illinois, Maryland, Michigan, Minnesota, North Carolina, Ohio, and Vermont), while three states with nonbinding renewable energy goals include WHP in some fashion (Indiana, South Dakota, and Utah).

[11] Database of CHP Policies and Incentives (dCHPP), EPA, https://www.epa.gov/chp/dchpp-chp-policies-and-incentives-database.

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.

One of the EPA CHP Partnership resources available online is *d*CHPP (Database of CHP Policies and Incentives), which is an online database that allows users to search for CHP policies and incentives at the state or federal level and is available at https://www.epa.gov/chp/dchpp-chp-policies-and-incentives-database.

The U.S. Department of Energy's (DOE's) CHP Deployment Program provides stakeholders with the resources necessary to identify CHP market opportunities and support implementation of CHP systems in industrial, federal, commercial, institutional, and other applications. As part of this program, DOE supports 10 regional CHP Technical Assistance Partnerships, which promote and assist in transforming the market for CHP, waste heat recovery, and district energy technologies and concepts throughout the United States. See https://betterbuildingssolutioncenter.energy.gov/chp/chp-taps.

DOE also published a *Combined Heat and Power (CHP) Technical Potential in the United States* report in 2016, which includes data on WHP technical potential across the United States.

The Heat is Power Association (HiP) is the trade association for the WHP industry. HiP educates policymakers about the benefits of WHP and advocates for policies that provide parity for WHP with other sources of clean energy. HiP partners with other business and trade associations and clean energy organizations to ensure coordinated, consistent, and effective messaging. See www.heatispower.org.

The Combined Heat and Power Alliance is the leading national voice for the deployment of CHP and WHP. It is a coalition of businesses, labor organizations, contractors, nonprofit organizations, and educational institutions who share the vision that CHP can make America's manufacturers and other businesses more competitive, reduce energy costs, enhance grid reliability, and reduce emissions. See https://chpalliance.org.

The Database of State Incentives for Renewable Energy website provides information about renewable energy and energy efficiency incentives and policies in the United States. The database includes relevant incentives and policies established by the federal government, state governments, local governments, utilities, and nonprofit organizations. See www.dsireusa.org.

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 – Reciprocating 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 for gaseous streams, > 175 °F for liquid streams) • Kalina cycle (> 200 °F)

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