CHP Bottoming-Cycles:
An "Outside-the-Box" Energy Efficiency Technology

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ABSTRACT

Many industrial process systems require heat to generate their product. Heat recovery involves capturing the waste heat from one part of the process and utilizing in a productive manner somewhere else in the process or plant. The familiar method of heat recovery in industrial systems is to utilize the heat to preheat working fluids such as combustion air or water. In addition to direct application of the waste heat, this energy can also be used to generate electricity. An Organic Rankine Cycle (ORC) generator common in geothermal power plants has recently begun to gain acceptance in some industrial facilities.

This paper will utilize a case study at a fertilizer manufacturer as the basis of the technical discussion, energy savings potential, and financial payback parameters of the ORC installation. Traditionally, in California, this measure has not been incentivized through the standard Investor Owned Utility (IOU) incentive programs. However, with the increasing energy efficiency goals of the IOUs and the increasing difficulty in obtaining these goals with the much of the low hanging fruit already installed, it is imperative that incentive programs investigate and incentivize non-standard energy efficiency measures. This paper will address this technology within the scope of the standard definitions of energy efficiency measures and illustrate the benefit and the need for this technology to be incentivized.

Introduction

Many industrial manufacturing plants require the heating and cooling of process streams. Waste-heat recovery and re-use – capturing the waste heat from one process and utilizing it in a productive manner somewhere else in the plant to reduce fuel consumption – is a commonly used energy efficiency measure. A familiar application in industrial systems is to utilize recovered waste heat to preheat working fluids such as boiler make-up water, feed-water, or combustion-air. The "outside-the box" application described in this paper is the re-use of low-temperature waste heat electricity in an organic Rankine-cycle (ORC) system to generate electricity. This thermodynamic system is conceptually identical to the familiar water-steam Rankine cycle system. This paper will utilize as a case study the application of a bottoming-cycle[1] ORC system at a fertilizer manufacturing plant.

Traditionally, in California and in other states, efficiency measures that involve the generation of electricity are rarely eligible for financial incentives through utility-sponsored energy-efficiency programs. However, with the nation's increasing focus on energy efficiency to reduce reliance on imported fuels and simultaneously to address Climate Change, and the

[1] The most common type of combined heat and power (CHP) or cogeneration system is the topping cycle, where energy in the input fuel first generates electricity and then serves a useful thermal need. In a bottoming cycle, the energy in the fuel first serves a thermal need, and then is used for electricity generation.

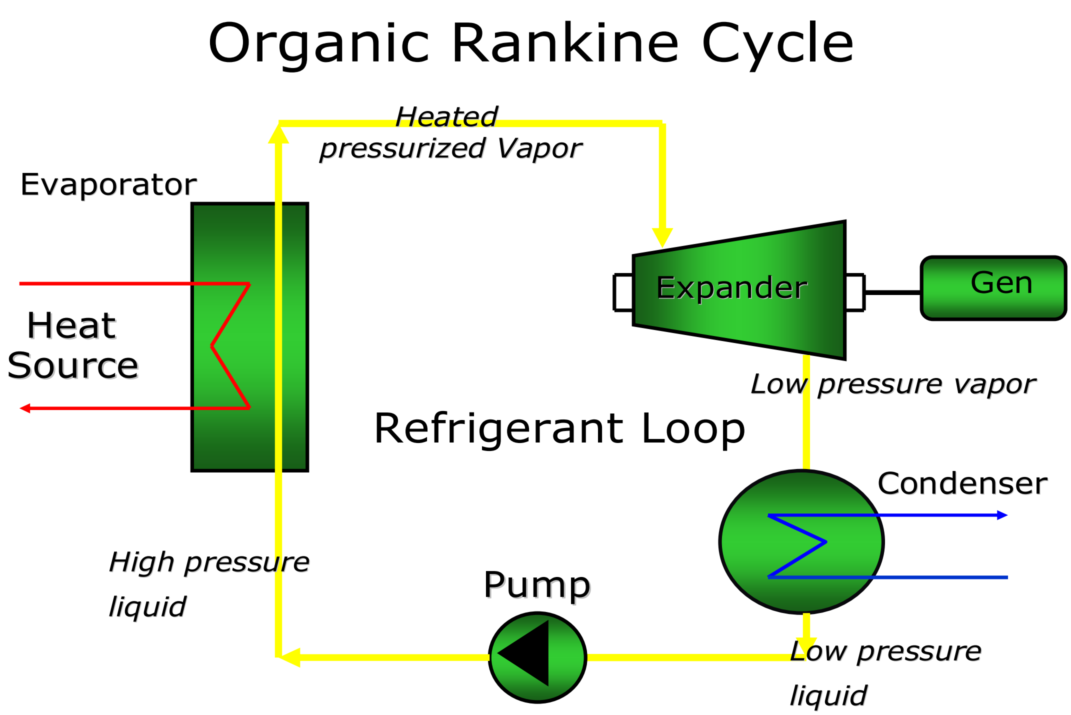
increasing difficulty in obtaining savings goals with the much of the low-cost measure opportunities already addressed, it is imperative that energy efficiency programs include bottoming-cycle CHP systems among the list of energy efficiency measures eligible to receive financial incentivizes.

Organic-Rankine Cycle (ORC)

An ORC is an externally fueled (heated) power cycle comprised mainly of an evaporator (boiler), expander, condenser and feed pump. It derives its name because the motive fluid is normally a carbon-based fluid such as ammonia or another refrigerant; thus the "organic" name. Use of an organic working fluid in a Rankine cycle has the advantage that the specific volume of the vapor phase at the operating temperature level (which typically is in the 280F to 100F range) is very much smaller than that of steam. As a result, the turbine, condenser, and piping are physically smaller and less expensive. And, because the key components are smaller than they are in a steam power plant, the entire system can be factory-built, skid-mounted, and shipped to the application site, which further reduces the installed cost of these systems.

A schematic process-flow diagram of an ORC system is shown in Figure 1.

Figure 1: ORC Flow Diagram



Although it has the same basic structure and design as a utility or industry steam power plant, many are also likely to note that is appears to be similar to a vapor-compression refrigeration plant. But – while they may look similar, the ORC and a refrigeration cycle operate in opposite directions. Work must be *added to* the refrigeration cycle via a motor-driven compressor, while work is *produced by* the ORC via an expander-driven generator. Both use a low-temperature fluid (refrigerant) that evaporates and condenses at low temperature.

The ORC technology was developed in the 1960's and is now in widespread use throughout the geothermal industry for heat sources as low as 200F. More than 800-MW of ORC geothermal plants are currently in operation worldwide, working 24/7 with online availability exceeding 98%. (See www.ormat.com) The ORC is also gaining in popularity as a means to generate additional power from fuel-fired prime mover (gas turbines, reciprocating engines) exhaust gases.

Case Study

The sequence of process steps used to convert anhydrous ammonia to nitric acid to a mixture of urea and ammonium nitrate fertilizer (UAN) in a large manufacturing plant include two condensing and cooling processes where potential exists for the recovery and re-use of waste heat. These sources have sufficient quantity and quality of unused heat (currently rejected to the atmosphere via cooling water) with which to produce economically viable electric power using an ORC bottoming-cycle generator. The 10,000 lb/h of 215F steam being condensed and cooled to 160F in one process contains trace amounts of weak acid (pH between 1 and 2). The second process involves cooling and condensing nitrogen-laden gases and steam. The first process was selected because of the simplicity of the condensing process and the fact that the second process's fluid contained much stronger nitric acid.

The application of ORC technology to the UAN production process is simple and straight-forward, and results in the production of 212-kW of net electric power. Low-pressure steam containing trace amounts of weak acid leaves the process condensate scrubber and, instead of flowing to a water-cooled condenser, is piped to the shell-side of the ORC evaporator, where all 10,000 lb/h of 215F steam is condensed and cooled to 160F. As the steam condenses, the ORC refrigerant (ammonia) is heated and evaporates (boils) in the tubes at 200F, 549.9 psia. The heat released by the condensing steam (about 10.34 MMBtu/h) is transferred to the ORC, producing 20,130 lb/hr of ammonia vapor that enters the expander in a dry and saturated condition and is expanded to 227.5 psia, 106F, which is a slightly wet (3.1% liquid) state. The expansion produces 320.6-hp of shaft power and then converted to about 227-kW of 60 Hz, 480V power in a synchronous generator. The low-pressure vapor is then condensed using available 80F cooling water, following which the refrigerant condensate is pumped up to evaporator pressure and sent back to the evaporator, and the cycle repeats. Required pumping power is 17.52 hp, requiring about 14.5 kW of electric power. Table 1 summarizes these temperatures, pressures, and flow rates.

Table 1: ORC Thermodynamic Conditions

Temperature (F)	Pressure (psia)	Flow Rate (lb/hr)
Heat Source (Steam)		
215	16.5	10,000
Working Fluid (Ammonia) Leaving Boiler		
200	549.9	20,130
Working Fluid (Ammonia) Leaving Expander		
105	227.5	20,130
Working Fluid (Ammonia) Leaving Feedpump		
107	650.0	20,130

The UAN plant normally operates at steady output around the clock for 345 days per year (8,280 hr/yr). The 212-kW of net power output can therefore generate 1,750,000 kWh/year, off-setting the purchase of $200,000 worth of electricity. The installed cost of the ORC system is $403,000 ($1,900/kW), resulting in a two-year payback period. On-going O&M costs are quite low because there is zero fuel cost.

Required time to design, engineer, procure equipment, assemble, and install an ORC project such as this would be about 35 to 50 weeks. Manufacturers who supply ORC systems include United Technologies, Ormat Technologies, and Calnetix Power Solutions.

We estimate that at least 20,000 MW of potential total ORC system generating capacity exists at U.S. manufacturing plants, principally in the chemical industries. Although the economics appear attractive and the technology is proven, manufacturing plants are reluctant to install the systems because of the risks of a high-pressure ammonia leak, explosive failure of piping or a heat-exchanger, or – if a lower pressure organic fluid is used – product contamination.