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# Waste Heat to Power (WH2P) Applications Using a Supercritical $CO_2$-Based Power Cycle

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**Abstract**

Echogen Power Systems (EPS) has developed a breakthrough power generation cycle for usable (waste) heat recovery. The supercritical $CO_2$ ($sCO_2$) Rankine Cycle utilizes carbon dioxide in place of water/steam for a heat-driven power cycle that converts waste heat into electricity for utility-scale power generation and industrial processes including steel and metal production, cement and lime, mining, glass, pulp & paper, petro-chemical, oil & gas, and other heat generating industries.

This paper presents an overview on three exemplary applications: combined cycle gas turbines using a $sCO_2$-based bottoming cycle, bottoming cycle for a reciprocating engine generator sets, and waste heat to power (WH2P) from energy-intensive manufacturing processes.

## The Supercritical $CO_2$-Based Power Cycle

The Thermafficient® Heat Engine uses supercritical carbon dioxide ($sCO_2$) and patent-pending operating cycles to deliver a flexible, low-cost thermal engine for a wide variety of applications. Echogen's cost-effective, emission-free power will enable fuel intensive operations to address growing concerns regarding power cost and environmental stewardship.

The $sCO_2$ heat engine consists of five main components: exhaust and recuperator heat exchangers, condenser, system pump, and power turbine (Figure 1). Ancillary components (valves and sensors) provide system monitoring and control. Heat energy is introduced to the sCO2 power cycle through an exhaust heat exchanger installed into the exhaust stack from a gas turbine or reciprocating engine or into a flue gas stream from a fuel-fired industrial process. Echogen's technology recycles the wasted thermal energy and provides integrated power and heating or cooling with flexible system architectures, configurable for power, co-generation or tri-generation.

Supercritical $CO_2$ ($sCO_2$) is an ideal working fluid for closed-loop power generation applications. It is a low-cost fluid that is non-toxic and non-flammable. The high fluid density of $sCO_2$ enables extremely compact turbo-machinery designs and permits the use of compact heat exchanger technology. Because of its high thermal stability and non-flammability, the exhaust heat

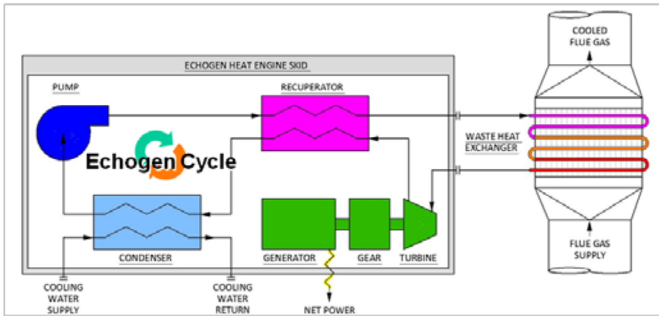


***Figure 1:*** *The supercritical $CO_2$ power cycle.*

***Figure 2:*** *The first production unit of the EPS100 7.5 MWe heat engine is completing factory checkout tests at Dresser-Rand.*


***Figure 3:*** *The EPS5 300 kWe, heat engine is derived from the 250 kWe demonstration system (above) which has completed checkout testing and is now in endurance testing.*

exchanger can be placed in direct contact with-high temperature heat sources, eliminating the cost and complexity of an intermediate heat transfer loop typically used in Organic Rankine Cycle (ORC) applications. Another advantage of $sCO_2$ derives from EPS's Cycle operation at well above the critical pressure for $CO_2$. The Echogen Cycle enables single-phase heat transfer resulting in improved heat exchanger effectiveness while reducing exhaust heat exchanger size and cost.

Echogen is currently building the EPS100, a 7.5 MWe thermal engine, which is designed for large industrial, fuel-fired processes, utility-scale power generation, and concentrated-solar thermal utility applications (Figure 2). The EPS100 uses a $sCO_2$ turbine generator and incorporates a patent-pending, advanced power cycle to maximize exhaust thermal energy utilization by reducing the exhaust temperature to a minimum practical limit. Because the EPS100 power turbine is a separate unit, two different options for the turbine are being offered, one a high-speed, single-stage radial turbine, the other an API-compliant lower-speed axial turbine (1).

A second system platform, the EPS5, is a 300 kWe thermal engine that is based on Echogen's 250 kWe demonstration system tested at the American Electric Power (AEP) Dolan Technology Center during 2010-11 (Figure 3). The EPS5 utilizes a turbo-alternator and is designed for industrial and distributed generation applications. More de-tails on the Echogen Cycle and the operating characteristics and advantages of supercritical $CO_2$ may be found elsewhere (1-5).

**Combined Cycle Gas Turbines with an $sCO_2$ Bottoming Cycle**

Across the United States, utility companies are turning to natural gas to generate electricity, with 258 plants expected to be built between 2011 through 2015, according to the U.S. Energy

Information Administration (EIA). Their forecast estimates that the nation will add 222 GW of generating capacity by 2035, which is equivalent to 20 percent of the current U.S. capacity, or 58 percent of all of the expected new power generation to be added (6).

Historically, natural-gas-fired combustion turbines have been used by utilities to provide both baseload and peaking power generation. Typically, larger systems (i.e., greater than 100MW output) are used in baseload operations while smaller gas turbines handle peaking and mid-merit capacity. With changes in the power industry, EPA emissions regulations, and technology advancements, the gas turbine is now used increasingly for baseload power as a combined-cycle system. By way of example, although gas turbines accounted for 15 percent of the power generation industry in 1998, they are expected to account for 40 percent of U.S. power generation by 2020. A 2009 Forecast International study (6) estimates the global installed base for industrial gas turbines at 46,455 units consisting of 33 percent (15,330 units) heavy frame gas turbines, 21 percent (9,755 units) aero-derivative, and 46 percent (21,370 units) light frame units.

Often, particularly on larger units, the gas turbine is combined with heat recovery steam generators (HRSGs) to recycle usable (waste) heat found in the turbine exhaust streams for co-generation or bottom cycling to increase system efficiencies from the typical 35 to 40 percent for simple-cycle turbines to over 60 percent for combined-cycle systems. However smaller systems have not been able to deploy a combined cycle architecture due to unfavorable economics.

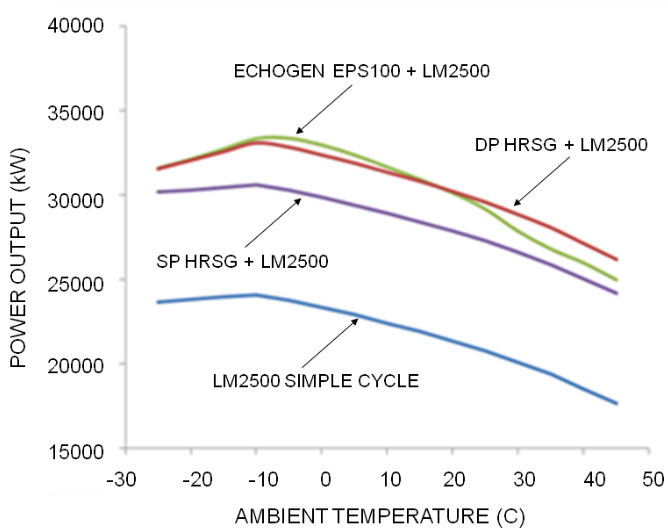


***Figure 4:*** *Performance model comparison between a standalone LM2500 gas turbine versus LM2500 combined cycle systems based on Echogen, single- and double-pressure steam and ORC technologies.*

**Combined Cycle Gas Turbine Example**

In 2011, Echogen conducted an exemplary trade study between the Echogen EPS100 heat engine and a comparably sized, double-pressure HRSG (DP-HRSG) (2). The study results show that the performance of the EPS100 system (power output versus ambient temperature) significantly exceeds single-pressure steam systems and is comparable to a double-pressure steam system (Figure 4). The Echogen system can increase net power production from heat in gas turbine exhaust. For example, net power on 20-to-50-MWe gas turbines can be increased by up to 35 percent (Figure 4), comparable to a DP-HRSG but at a lower cost for installation (Figure 5) (2).

All study cases for the EPS100 heat engine assume an evaporative-cooled system condenser. For most climates, the baseline cycle provides a good balance of performance. For high ambient temperature climates, especially where water restrictions are an operating constraint, a high-ambient, fully air-cooled version is under development.

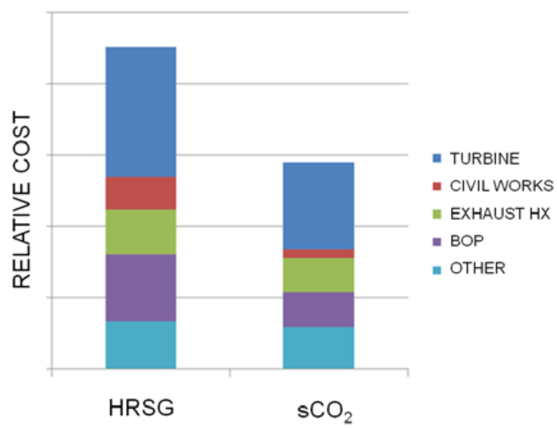


***Figure 5:*** *Compared to HRSG, an Echogen heat engine is estimated to cost less by 40 percent due to a more compact equipment set, smaller system footprint and lower balance of plant requirements for supercritical* $CO_2$.

**Reciprocating Engine Gensets with an $sCO_2$ Bottoming Cycle**

The traditional approach of building large centralized power plants to address the increasing demand for electrical power is frequently hindered by social, economic and environmental constraints. Distributed generation (DG) has emerged as a desirable option for adding capacity and consists of relatively small generating units (typically less than 30 MWe) located at or near consumer sites to meet specific customer needs. DG units can provide incremental capacity at relativity low capital cost and can be brought online in less time compared to centralized power systems. For distributed generation applications, reciprocating internal combustion engines fueled by natural gas or diesel fuel are a widespread and well-known technology (7). Typical distributed generation applications include: natural gas compressor stations, on-site gensets at industrial facilities, standby or emergency back-up power units for large institutional facilities (e.g., hospitals, schools, electrical substations, cell phone towers, etc.), and small (< 25MW) gas turbine-based and multiple reciprocating engine-based electrical power generation plants for remote and rural locations such as the smaller towns and villages of Alaska, Northern Canada, Mexico, and in developing regions abroad.

While distributed generation offers the advantages described above, the relatively small size of DG equipment results in lower overall efficiency than can be obtained with larger centralized power generation systems. As a result, a significant fraction of the fuel energy is unutilized, and escapes as waste heat. While this heat may be captured and utilized in providing thermal energy to the local site, in many cases local demand for this heat is much lower than the electrical demand – thus this energy continues to be underutilized. Electrical power usually remains the most fungible and in-demand product of the DG system. The conversion of relatively low-grade thermal energy to electrical power is traditionally accomplished through the use of heat recovery steam systems. While extremely successful at utility scales, the cost and performance of steam systems generally becomes unfavorable at the small scales commonly used in DG. The $sCO_2$ Cycle scales well into smaller sizes from both a performance and economic perspective for bottom cycling reciprocating engine gensets.

**Applications Example for a Remote Power Generation Facility**

A remote community located in northern Canada includes a 6.5 MWe electrical power collective containing four 1.05 MWe and two 1.13 MWe reciprocating engine gensets fueled by natural gas from a large gas transportation pipeline that passes through the region. The genset sizes and capacity factors and key operating characteristics are summarized in Table 1. Typically three gensets operate to provide 3.2 MWe baseload while maintenance is being performed on the second set of three units. For six months, coinciding with their spring/summer season, all units are operated to provide up to 6.5 MWe of peak power to support the additional demands of their local fishing and canning industry. Results of a waste heat to power analysis using an $sCO_2$ heat engine for bottom cycling for each type of recip genset are summarized in Table 2.

***Table 1:*** *Reciprocating Genset Operating Characteristics*

| Genset Unit No. | Nameplate Rating (kWe) | Capacity Factor (%) | Capacity Factor Profile | | | | Exhaust Gas Temperature (ºF) | Exhaust Gas Mass Flow Rate (lb/h) |
|---|---|---|---|---|---|---|---|---|
| | | | 1Q | 2Q | 3Q | 4Q | | |
| 1 | 1,050 | 75 | off | on | on | on | 763 | 14,500 |
| 2 | 1,050 | 75 | off | on | on | on | 763 | 14,500 |
| 3 | 1,050 | 75 | on | on | on | off | 763 | 14,500 |
| 4 | 1,050 | 75 | on | on | on | off | 763 | 14,500 |
| 5 | 1,135 | 75 | off | on | on | on | 794 | 18,000 |
| 6 | 1,135 | 75 | on | on | on | off | 794 | 18,000 |

Notes:

1) Units 1, 2 and 5 operate on the same capacity factor schedule to provide 3.2 MWe baseload.
2) Units 3, 4 and 6 operate on the same capacity factor schedule to provide 3.2 MWe baseload.
3) Quarters 2 and 3 (Apr - Sep) is peak power season to support local fishing and canning industry. All units operating provide 6.5 MWe seasonal baseload.

***Table 2:*** *Waste Heat to Power Analysis for Each Reciprocating Genset*

| Genset Unit No. | Nameplate Rating (kWe) | Generated Power by Operating Quarter (kWe) | | | | Net Power Recovered Per Unit (kWe) | Total Recovered Power by Operating Quarter (kWe) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1Q | 2Q | 3Q | 4Q | | 1Q | 2Q | 3Q | 4Q |
| 1 | 1,050 | --- | 1,050 | 1,050 | 1,050 | 93 | --- | 93 | 93 | 93 |
| 2 | 1,050 | --- | 1,050 | 1,050 | 1,050 | 93 | --- | 93 | 93 | 93 |
| 3 | 1,050 | 1,050 | 1,050 | 1,050 | --- | 93 | 93 | 93 | 93 | --- |
| 4 | 1,050 | 1,050 | 1,050 | 1,050 | --- | 93 | 93 | 93 | 93 | --- |
| 5 | 1,135 | --- | 1,135 | 1,135 | 1,135 | 124 | --- | 124 | 124 | 124 |
| 6 | 1,135 | 1,135 | 1,135 | 1,135 | --- | 124 | 124 | 124 | 124 | --- |
| **Total Generated Power by Operating Quarter (kWe):** | | **3,235** | **6,470** | **6,470** | **3,235** | | | | | |
| **Total Recovered Power by Operating Quarter (kWe):** | | | | | | | **310** | **620** | **620** | **310** |

Based on analytical results, two Echogen EPS5 300 kWe heat engines could serve this application with genset Units 1, 2 and 5 connected to one EPS5 and genset Units 3, 4 and 6 connected to the second heat engine. A detailed engineering study would be required to determine which waste heat exchanger (WHX) configuration would be the most cost- and performance-effective:

- One heat engine with one WHX supplied by three gensets (1 x 1 x 3 configuration)
- One heat engine with three smaller WHXs; one per genset exhaust duct (1 x 3 x 3 configuration)

**Waste Heat to Power (WH2P) for Energy-Intensive Manufacturers**

As manufacturers worldwide face an increasingly competitive environment, they seek out opportunities to reduce costs. With today's fluctuating energy prices, often this means investment into cost-effective energy saving technologies and practices that will reduce operating costs while maintaining or increasing product quality and yield. Energy-efficient technologies often include additional benefits, such as increasing productivity or achieving future or current environmental goals, thus reducing the regulatory "burden".

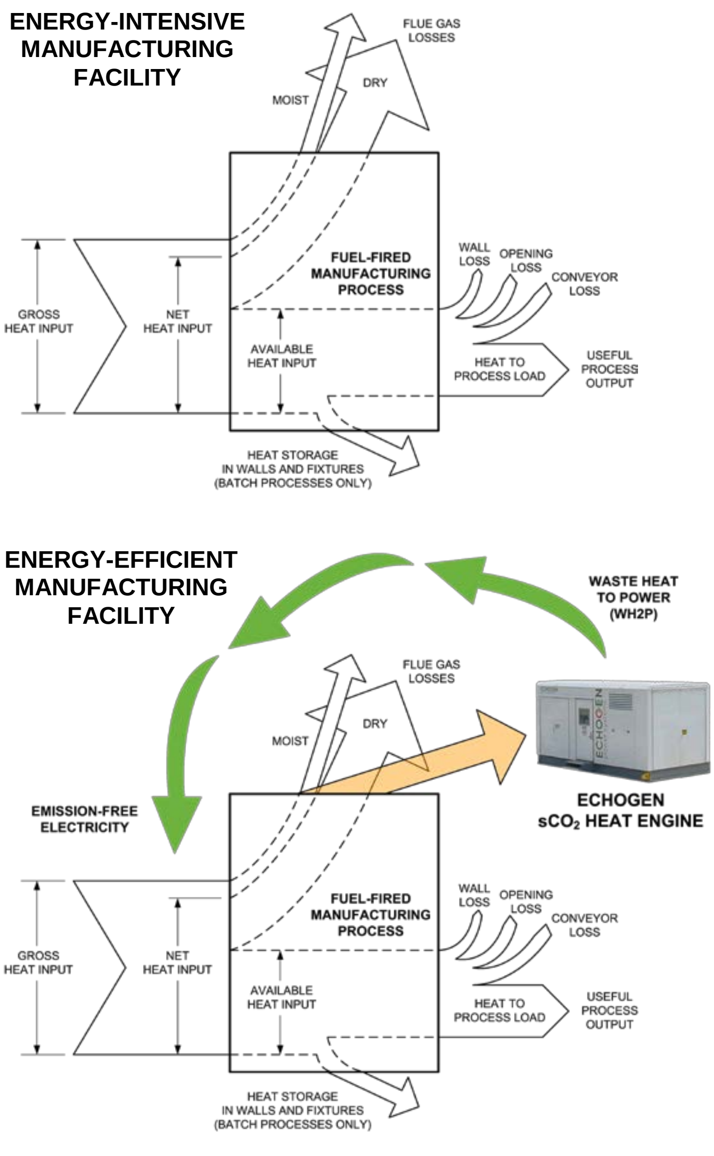


***Figure 6:*** *Supercritical $CO_2$ heat engines allow energy-intensive manufacturers across all economic sectors to improve their operating and bottom line performance by reducing their grid power demand. (Modified from Ref. 8).*

Waste heat can be captured from an array of industrial processes through waste heat recovery technology. For large energy consumers in the industrial sector, waste heat recovery opportunities are found in their respective steam generating and direct-fired heating processes (e.g., furnaces, kilns, etc.). Prospective industrial customers include chemical processing, oil and gas exploration and transmission, petroleum refining, iron, steel, glass, cement, pulp and paper, and power generation (e.g., older fossil fuel fired generation assets and simple or combined cycle power generation), typically operating with large sources of energy loss from hot exhaust gases and residual heat in liquid product streams.

Waste heat recovery represents the greatest opportunity for reducing energy loss in these industries while simultaneously reducing their carbon footprint and associated greenhouse emissions with improved overall energy production efficiency. An $sCO_2$ heat engine with a waste heat exchanger installed into the hot process exhaust duct can enable industrial users to repurpose this emission-free energy to the facility's internal power grid to drive large process fans, blowers, pumps or motors, or sell it to the grid to support clean energy production, distribution and use to enable their local utility to meet their Renewable Portfolio Standards (RPS). This approach is summarized in Figure 6 using two Sankey Diagrams to visually compare the major flow of thermal and electrical power within a typical fuel-fired manufacturing process system without and with an $sCO_2$ heat engine to generate emission-free electricity for improved plant energy efficiency. Table 3 further summarizes where these large quantities and varying qualities of waste heat are generated and how they are recovered and used.

***Table 3:*** *Classification of Waste Heat Sources and Heat Recovery Applications*

| HEAT SOURCE CLASS | EXAMPLE INDUSTRIAL HEAT SOURCES | TEMPERATURE RANGE ( °F ) | TEMPERATURE RANGE ( °C ) | APPLICATIONS |
|---|---|---|---|---|
| **HIGH**<br>**> 1,200 °F (> 650 °C)** | NICKEL REFINING FURNACE | 2,500 – 3,000 | 1,370 – 1,650 | • HIGH-QUALITY THERMAL ENERGY<br>• INDUSTRIAL PLANT FOR LARGE-SCALE MATERIALS MANUFACTURING<br>• WASTE HEAT TO POWER (WH2P)<br>• COMBINED HEAT AND POWER (CHP)<br>• COMBINED HEAT, COOLING AND POWER (TRIGENERATION) |
| | STEEL ELECTRIC ARC FURNACE | 2,500 – 3,000 | 1,370 – 1,650 | |
| | BASIC OXYGEN FURNACE | 2,200 | 1,200 | |
| | ALUMINUM REVERBERATORY FURNACE | 2,000 – 2,200 | 1,100 – 1,200 | |
| | STEEL REHEAT FURNACE | 1,700 – 1,900 | 930 – 1,040 | |
| | FUME INCINERATORS AND THERMAL OXIDIZERS | 1,200 – 2,600 | 650 – 1,430 | |
| | GLASS MELTING FURNACE | 2,400 – 2,800 | 1,300 – 1,540 | |
| | COKE OVEN | 1,200 – 1,800 | 650 – 1,000 | |
| | COPPER REFINING FURNACE | 1,400 – 1,500 | 760 - 820 | |
| **MEDIUM**<br>**450 – 1,200 °F (230 – 650 °C)** | STEAM BOILER EXHAUST | 450 – 900 | 230 – 480 | • MEDIUM-QUALITY THERMAL ENERGY<br>• TRADITIONAL FOSSIL FUEL POWER AND STEAM GENERATION<br>• INDUSTRIAL PLANTS FOR LARGE-SCALE MATERIALS MANUFACTURING<br>• ON-SITE AND DISTRIBUTED POWER GENERATION<br>• TYPICAL HEAT SOURCES FOR BOTTOMING CYCLE APPLICATIONS<br>• COMBINED CYCLE POWER GENERATION<br>• WASTE HEAT TO POWER (WH2P)<br>• COMBINED HEAT AND POWER (CHP)<br>• COMBINED HEAT, COOLING AND POWER (TRIGENERATION) |
| | GAS TURBINE EXHAUST | 700 – 1,000 | 370 – 540 | |
| | RECIPROCATING ENGINE EXHAUST | 600 – 1,100 | 320 – 590 | |
| | HEAT TREATING FURNACE | 800 – 1,200 | 430 – 650 | |
| | DRYING AND BAKING FURNACE | 450 – 1,100 | 230 – 590 | |
| | CERAMIC KILNS | 840 – 1,150 | 450 – 620 | |
| | CEMENT KILNS | 840 – 1,150 | 450 - 620 | |
| **LOW**<br>**< 450 °F (< 230 °C)** | PROCESS STEAM CONDENSATE | 130 – 190 | 50 – 90 | • LOW-QUALITY THERMAL ENERGY<br>• INDUSTRIAL PLANTS FOR LIGHT MATERIALS, PULP/PAPER, PLASTICS, FOOD, PHARMACEUTICALS, AND BIOLOGICAL MATERIALS PROCESSING<br>• COMBINED HEAT AND POWER (CHP)<br>• COMBINED HEAT, COOLING AND POWER (TRIGENERATION)<br>• PROCESS WATER AND AIR HEATING AND COOLING |
| | HOT PROCESS LIQUIDS AND SOLIDS | 90 – 450 | 30 – 230 | |
| | DRYING, BAKING AND CURING OVENS | 200 – 450 | 90 – 230 | |
| | HRSG EXHAUST | 150 – 450 | 70 – 230 | |
| | ETHYLENE FURNACE EXHAUST | 150 – 450 | 70 – 230 | |
| | GAS-FIRED BOILER EXHAUST | 150 – 450 | 70 – 230 | |
| | COOLING WATER RETURN, FURNACE DOORS | 90 – 130 | 30 – 50 | |
| | COOLING WATER RETURN, ANNEALING FURNACES | 150 – 450 | 70 – 230 | |
| | COOLING WATER RETURN, IC ENGINES | 150 – 250 | 70 – 120 | |
| | COOLING WATER RETURN, REFRIGERATION CONDENSERS | 90 - 110 | 30 - 40 | |

*Sources: Echogen Power Systems; U.S. DOE Midwest Clean Energy Application Center (MCEAC);* www.midwestcleanenergy.org*; and Refs (9 and 10).*

**Exemplary Steel Plant Analysis**

Steel manufacturing facilities consume large quantities of thermal and electrical power in the processing of raw ores and scrap steel into new slabs for hot rolling into sheet steel. Typical heat sources found in steel mills include: reheat furnace flue gas, coke oven flue gas, blast furnace stoves flue gas, and power boiler flue gas. As an example, consider a hot strip steel mill operation reheats steel slabs prior to hot rolling. After preheating furnace combustion air, 1,000 ºF flue gas is discharged to atmosphere. A direct flue gas-to-s$CO_2$ waste heat exchanger installed downstream of the existing combustion air heater absorbs waste heat energy and delivers the heated s$CO_2$ to a s$CO_2$ heat engine. The heat engine converts thermal power into electrical power. The subsequent electrical power savings reduces the effective furnace operating cost from \$8.60/ton to \$6.79/ton of steel processed. The detailed waste heat to power analysis is summarized in Tables 4 and 5.

***Table 4:*** *Reheat Furnace Operation*

| Process Parameter | Furnace | s$CO_2$ Heat Engine | Furnace with sCO2 Heat Engine |
|---|---|---|---|
| Steel Charge (ton/h) | 134 | --- | 134 |
| Fuel Flow (mmBTU/h) | 262 | --- | 262 |
| Fuel Cost (\$/mmBTU) | 4.40 | --- | --- |
| Operating Cost (\$/ton) | 8.60 | --- | 6.79 |
| Flue Gas Mass Flow Rate (lb/h) | 250,200 | --- | 250,200 |
| Flue Gas Temperature (ºF) | 1,000 | --- | 226 |
| Thermal Power Recovered (kWth) | 0 | 16,600 | --- |
| **Electrical Power Generation (kW)** | **0** | **3,730** | **---** |

***Table 5:*** *Project Economics*

| Parameter | Value |
|---|---|
| s$CO_2$ Heat Engine Power (kWe) | 3,730 |
| Total Installed Cost (\$000) | 8,200 |
| Annual Operating Hours | 8,300 |
| Value of New Power (\$/kWh) | 0.065 |
| Annual Cash Flow from New Power (\$000) | 2,012 |
| Simple Payback without Incentives (yrs) | 4.0 |
| $CO_2$ Emissions Avoided (tons/yr) | 20,742 |
| Potential Carbon Credit Value (\$000 at \$15/ton) | 311 |

## Conclusions

Supercritical $CO_2$ heat engines are scalable across a broad system size range − from 250kWe to 45MWe and above, with net electrical output to support the widest possible variety of industrial and utility-scale applications. The $sCO_2$ Cycle is thermal source agnostic − suitable with a wide range of heat sources from 400°F to 1000+°F with efficiencies up to 30 percent depending on the heat source. New energy production can be offset with recovered energy without increasing associated greenhouse emissions while improving overall energy production efficiency. The sCO2 heat engine can add up to 35% more power to simple cycle gas turbines, 10% to 15% more power to reciprocating engines, and can significantly improve the energy efficiency and bottom line performance at steel mills, cement kilns, glass furnaces and other fuel-fired industrial processes by converting previously wasted exhaust & flue gas energy into usable electricity.

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