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Transforming Waste Heat to Power through Development of a CO_2 - Based Power Cycle

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Abstract

With global demand for energy expected to increase 60% by 2030, concerns about energy affordability, security, and greenhouse gas emissions have heightened interest in energy efficiency and grid demand reduction. In the U.S., legislators are striving to regulate GHG emissions through market-based mechanisms, efficiency programs, demand reduction, and economic incentives. Most of the world's electrical power is generated by heat engines that convert heat from fuel combustion into mechanical energy which is then converted into electricity. The U.S. DOE estimates that 280,000 MW discharged annually in the U.S. as *waste heat* could be recycled to provide 20% of U.S. electricity needs while slashing GHG by 20% and saving USD $70-150B per year on energy costs. Various sources of independent data suggest that this waste heat recovery opportunity is valued at over USD $600B (1). Similar, large opportunities exist worldwide.

In response to this opportunity, Echogen Power Systems (Akron, OH U.S.A.) is developing power generation technologies that transform heat from waste and renewable energy sources into electricity and process heat. The thermal engine technology is based on a waste heat to power cycle using a supercritical carbon dioxide working fluid in a closed loop. Supercritical carbon dioxide is environmentally benign, non-toxic, with favorable heat and mass transport properties that make it energy dense. Compared to organic and steam-based waste heat recovery systems, supercritical CO_2 can achieve high efficiencies over a wide temperature range of heat sources with compact components resulting in a smaller system footprint.

This paper presents an overview on the Echogen system technology and associated leading applications. Results are reported on field testing currently underway for an Echogen 250 kW thermal engine at American Electric Power's Dolan Research Laboratory.

Echogen Heat Engine Technology

Echogen is currently commercializing a waste heat to power system through development of a proprietary thermal engine, which is entering the product introduction and customer demonstration phase of development for industrial markets.

The breakthrough thermal engine technology is based on a waste heat to power cycle using supercritical carbon dioxide ($ScCO_2$) as the working fluid. $ScCO_2$ is environmentally benign, non-toxic, with favorable heat and mass transport properties. The higher energy density of $ScCO_2$ reduces system component size and cost, and provides significant advantages regarding system efficiency, footprint, and ease of installation. Our patent-pending thermal engines can transform significant amounts of waste heat into electricity for applications ranging from bottom cycling in gas turbines, stationary diesel engine gensets, industrial waste heat recovery, solar thermal, geothermal, and hybrid alternatives to the internal combustion engine.

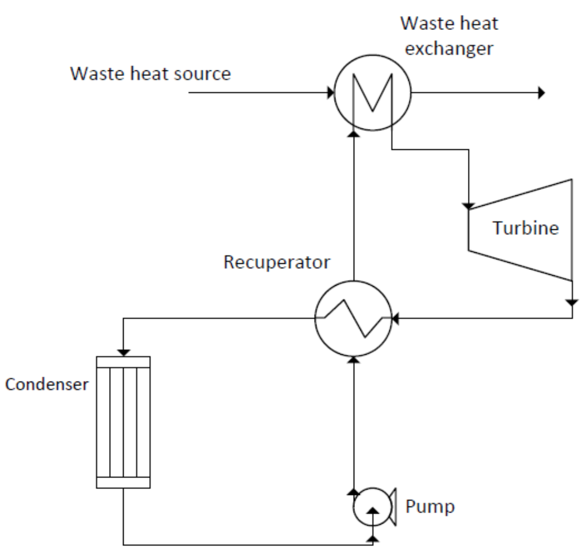

Figure 1: *Simplified process flow diagram for the Echogen heat engine.*

Figure 1 is a simplified process flow diagram for the Echogen heat engine and consists of five main components: waste heat and recuperator heat exchangers, condenser, system pump, and expander. Ancillary components (valves and sensors) provide system monitoring and control. Heat energy is introduced through a waste heat exchanger installed into the exhaust stack for a turbine, diesel, other reciprocating engine, boiler, or other industrial heat source. The heated $ScCO_2$ passes through a turbine where the waste heat is converted into mechanical shaft work to produce electricity. A recuperator recovers a portion of the residual heat while the remainder is discharged from the system through a water or air-cooled condenser. Operating conditions maintain the CO_2 in a supercritical condition during the heat recovery and power generation portion of system cycle, and as a subcooled liquid at the pump inlet. The Echogen technology can provide integrated power, heating and cooling through a flexible system architecture which can be configured for power, co-generation or tri-generation.

Over a two-year time period, Echogen successfully advanced its technology from initial concept to product prototypes. Prototype 1 (5 kW) (2008), based on NASA technology, was an absorption heat pump using CO_2 and carrier fluid, and reduced to practice our approach to power generation. Prototype 2 (5 kW) (early 2009) utilized pure CO_2, proved that a supercritical cycle heat engine could be built for commercial application, and established a development pathway for first product units. A 15 kW engineering unit was designed and built in 2009 to initially qualify the CO_2 turbine design and scale-up for future commercial-scale systems. Having achieved the milestone of delivering positive net power output during initial testing, the 15 kW system currently provides a "wet rig" capability as an engineering lab-based system to enable quick-turn evaluation of proposed configuration and/or controls changes for field systems development and optimization.

The Advantages of Supercritical CO_2

A key advantage of the Echogen technology is the use of supercritical CO_2 as a working fluid for heat recovery and power generation. A supercritical fluid is a substance at a temperature and pressure above its critical temperature and pressure. The critical point represents the highest temperature and pressure at which the substance can exist as a vapor and liquid in equilibrium. As shown in Figure 2, above its critical point of 87.76°F at 1,070 psi (30.98°C at 73.78 bar), carbon dioxide is a supercritical fluid and adopts properties midway between a gas and a liquid.

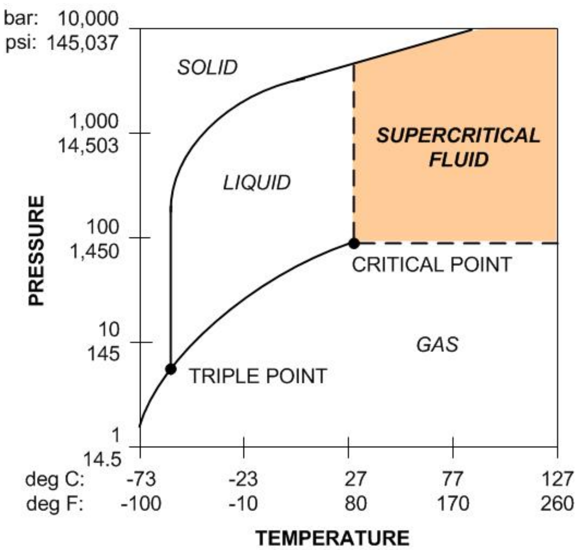

Figure 2: *Carbon dioxide pressure versus temperature (PT) phase diagram.*

Carbon dioxide as a working fluid for power generating cycles has many advantages. It is inexpensive, non-flammable, and abundant in nature. Due in part to its relative high working pressure, a carbon dioxide system can be built that is much more compact than systems using other working fluids.

The high density and volumetric heat capacity of CO_2 with respect to other working fluids makes it more *energy dense* meaning that the size of all system components can be considerably reduced without losing performance – including the turbine, pump, and heat exchangers (2-4). Dostal (5) compares CO_2 turbines to steam-based turbomachinery and indicates that CO_2 turbines are very compact and highly efficient with simpler, single casing body designs while steam turbines usually require multiple turbine stages (i.e., high, medium and low-pressure) and associated casings with a corresponding increase in systems packaging complexity for additional inlet and outlet piping.

Carbon dioxide more effectively captures waste heat from sources that have an approximately constant heat capacity, such as turbine exhaust or other gases. This is due to the character of its heat capacity in the supercritical region which provides superior matching to the heat source temperature profile compared to the boiling process utilized with other working fluids such as steam or organic working fluids used in Organic Rankine Cycle (ORC) systems. The so-called *pinch point* (see Figure 3) occurs during the constant-temperature phase change of subcritical fluids, and limits the maximum fluid temperature, and thus cycle efficiency in other waste heat recovery technologies. This phenomenon is not encountered in the heat exchange process with

CO_2 due to its single-phase characteristics well above the critical point (6,7), thus permitting a higher fluid temperature to be achieved for the same heat source.

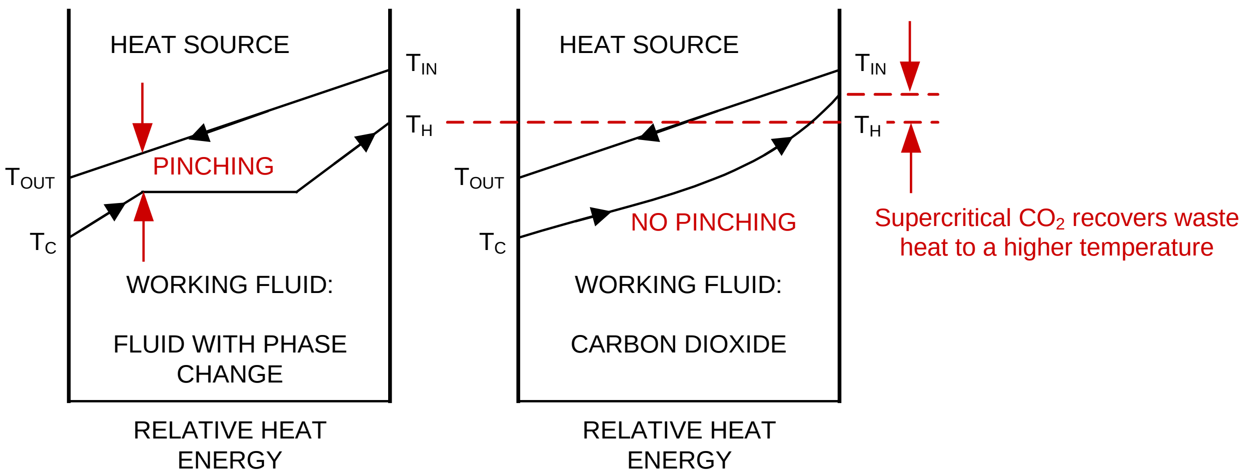

Figure 3: *Comparison of waste heat exchanger operation between a thermal source and different working fluids shows the advantages of using supercritical CO_2 as a working fluid for power generation from waste heat. Source: derived from Refs. (6, 7).*

Technology Comparison

A brief comparison of working fluids currently used commercially for power generation through heat recovery is shown in Table 1. Unlike steam-based systems that require condensate control and conditioned water for steam generation to prevent scaling, corrosion and fouling of system piping and components, CO_2 is a clean, non-scaling, non-fouling working fluid, and provided it is maintained in a dry condition, it is non-corrosive as well. Also, due to the boiling heat exchange process, a typical steam-based heat recovery system requires multiple stages (e.g. economizer, boiler and superheater) and multiple pressures to efficiently extract heat from the source. Effective management of stresses in the large steam drums often is a limiting factor in steam system design, particularly for cyclic operation. The single-phase heat transfer process of CO_2 permits simpler, more robust construction of the waste heat exchanger. Proper management of the startup process also gives CO_2 a much shorter potential heat-up and time to power than typical steam-based systems.

Table 1: *Comparison of Power Generating Cycles for Waste Heat Recovery*

Parameter	ECHOGEN ScCO$_2$ Power Cycle	Organic Rankine Cycle	Steam Rankine Cycle
Source Temp Range (F)	400 to greater than 1,200	180 to 550	650+

Working Fluid	Supercritical carbon dioxide	HCFC, HFC or volatile hydrocarbons	Treated water
Working Fluid Attributes	Non-corrosive, not-toxic, non-flammable, thermally stable	Limited temperature range, flammable	Requires treatment to reduce corrosion & mineral deposition

ORC heat recovery systems use various hydro-chloro-fluoro-carbon (HCFC) refrigerants such as R245fa (1,1,1,3,3-pentafluoropropane) and hydro-fluoro-carbons (HFCs), or light hydrocarbons such as n-pentane and isobutene, or toluene. The HCFC and HFC fluids have limited temperature capability due to their thermal decomposition to highly reactive hydrochlorides and hydrofluorides. The high global warming potential of these fluids has led to regulatory pressure to phase these fluids out of production and use. Hydrocarbon working fluids present significant flammability hazards. For both classes of fluids, direct heat exchange from a high temperature source is generally avoided by use of an intermediate heat transfer fluid loop, which adds significant installation cost to ORC systems. The heat transfer fluids also have upper temperature limits in the 572 to 662 F (300 to 350 C) range, which limits the maximum working fluid temperature to lower operating temperatures. For higher temperature applications, the temperature limit of the heat transfer fluid then requires use of a diverter and bypass stack to accommodate continued operation of the main process when the heat recovery system is not operating. Due to the superior thermal stability and non-flammability of CO_2, direct heat exchange from high temperature sources is possible, permitting higher working fluid temperature (and thus higher cycle efficiency). With proper material selection and heat exchanger design, the $ScCO_2$ system is also capable of “dry-running,” where the main process can operate uninterrupted when the heat recovery system is not operating, thus eliminating the diverter and bypass stack.

Figure 4 compares the power output for a standalone LM2500 power generation turbine compared to the power output of the LM2500 integrated with various heat recovery technologies. The analysis was conducted using published performance data for the gas turbine, the competing waste heat recovery technologies, and an Echogen utility-scale system currently under development. Modeling results show that compared to steam-based and Organic Rankine Cycle systems, the Echogen Cycle delivers higher performance, exceeding the output of single-pressure Heat Recovery Steam Generators by a factor of 1.13 and comparable ORC systems by a factor of 1.48. The Echogen heat engine technology is a smaller and lower cost waste heat recovery solution compared to traditional power generation technologies such as steam turbines, heat recovery steam generators and ORC systems. As a platform technology, it is easily scalable from 250 kW to greater than 50 MW to support the widest possible variety of industrial and utility applications. Echogen heat engines are thermal source agnostic, meaning a wide range of heat sources are suitable for energy conversion to electricity. The thermal engines work at operating temperatures from 400 F to greater than 1,200 F (204 C to greater than 650 C) and conditions where other devices cannot operate, enabling a greater amount of waste energy to be recovered and transformed to electricity or process heat.

Field Testing at American Electric Power

As shown in Figure 5, Echogen completed the design and fabrication of a 250 kW system in late 2009, and the system was installed during 2010 at the American Electric Power (AEP) Walnut Test Facility located in Groveport, OH for beta testing.

The 250 kW system skid measures only 10 x 12 x 20 ft (width x height x length) and weighs less than 49,000 lbs which allows for highway and truck transport without special Department of Transportation (DOT) permits. Located within the skid are all of the components previously described in Figure 1 including the main system pump, recuperator, condenser, system controller, turbo-alternator and power electronics. For convenience of testing, the flue/exhaust gas to CO_2 waste heat exchanger was replaced by a heat transfer fluid to CO_2 heat exchanger. A slave natural gas-fired system is used to heat and circulate the heat transfer fluid. Water is supplied to the condenser using a conventional cooling tower and circulation pump.

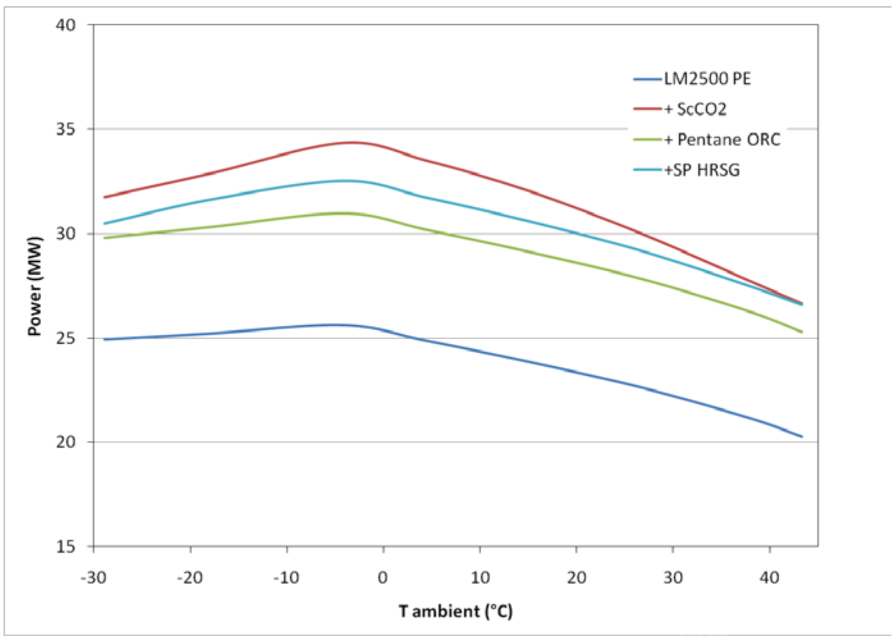

Figure 4: *System performance model for an Echogen utility scale heat engine integrated to a LM2500 power generation turbine compared to competing waste heat recovery technologies.*

As part of the AEP Dolan Technology Center, the Walnut Test Facility provides unique research and testing services for various distributed energy resources. Testing can be conducted on generation, energy storage, and power quality devices in the 100kW to 1.5MW scale. Previous testing by others at this AEP facility has included microturbines, fuel cells, advanced batteries, renewable powered equipment, power electronics, and other related equipment, including communications, protection and control equipment and components. Devices may be tested singularly or in combination with other devices and may operate with or without connection to the electric power grid. Interconnection to the AEP distribution system is through a 13.8 kV tap point capable of handling devices up to 1.5MVA and is provided with separate bi-directional metering to distinguish power used by the facility from power that could be exported. The test site includes a low voltage switchgear, metering and protection, low and medium voltage transformation, 250 psi nominal natural gas supply, and onsite water supply for cooling and other needs. Standards based and custom testing are performed using best practices and protocols developed over the 30-year history at AEP's Dolan Laboratory.

System testing has successfully progressed through several test phases including initial checkout, shakedown and part load characterization of key system components. During testing, the 250 kW thermal engine has achieved net power output with 80 days of operation and over 85 turbine starts. In future commercial installations, the actual net system power output from the 250 kW thermal engine will range between 200 to 300 kW depending on the size and temperature of the

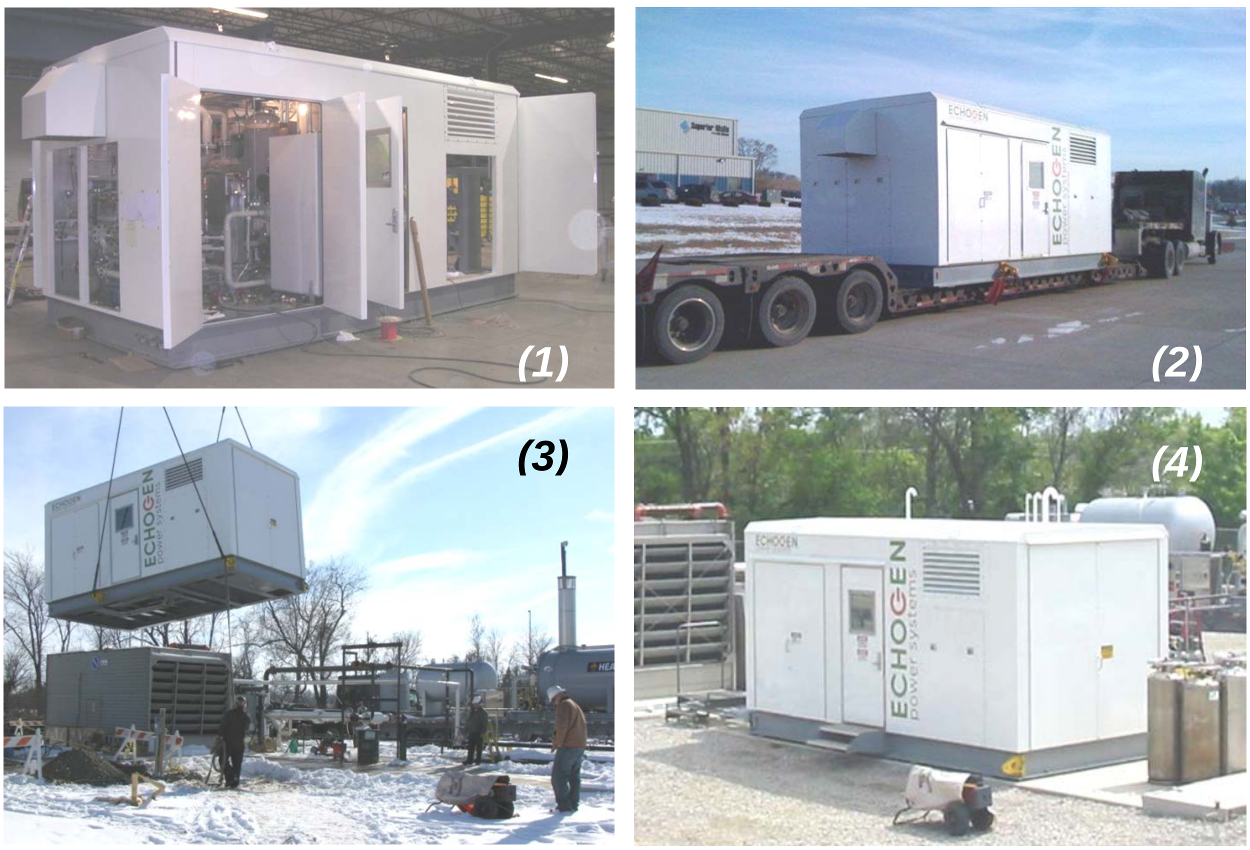

***Figure 5: Field testing of the Echogen 250 kW demonstration system** – (1) the system skid completed factory assembly and checkout with our systems integration partner, (2) was shipped by truck to the AEP Dolan Technology Center test site (Groveport, OH), where (3) the system was installed, and (4) has achieved net power output during field testing in 2010.*

heat source, and condenser water temperature. Specific tests were conducted to check out system controls for fully automated start/stop, alarm, shutdown, process adjustment, and power grid synchronization. Performance data collected during characterization testing included temperature, pressure and mass flowrate data to calculate heat transfer effectiveness and pressure drop for all heat exchangers, system pump, turbine, and electrical generation performance, and measurement of auxiliary loads. Net power has been successfully exported to the AEP test grid. Test results have been compared to cycle model calculations to verify actual versus predicted performance. In general, measured system and component performance has been within expectations. The results of these comparisons have provided confidence in prediction capabilities for system optimization, off design point operation, and system sizing and component scale-up for planned multi-megawatt class thermal engines for utility scale applications.

Testing for the remainder of 2011 will include further system optimization. After test completion at AEP later this year, the thermal engine is scheduled to be redeployed to a customer facility for long term durability and reliability tests. For this testing, a finned tube waste heat exchanger, installed in the customer's exhaust duct, will be used for heat input to the cycle.

Conclusion

The Echogen $ScCO_2$ cycle holds great promise in providing a flexible, efficient, low cost system for waste heat recovery from a wide variety of applications. Initial testing of the 250kW scale unit has demonstrated that the component and system performance is in line with expectations. The results of this program have been used to guide the initial design of a multi-megawatt scale system for use in large industrial and power generation applications.

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Stephen Hostler, Ph.D. is a Lead Engineer for Echogen Power Systems. He has been involved with all aspects in the development of the Echogen power generation technology since 2007. Dr. Hostler is the Program Manager leading field testing of the 250 kW thermal engine at AEP.

Edward Zdankiewicz is a Lead Engineer for Echogen Power Systems. He has been involved with all aspects in the development of the Echogen power generation technology since 2007. Mr. Zdankiewicz has over 30 years experience in product and business development for process systems equipment and controls for international markets involved in regenerative power generation, water reclamation, environmental monitoring and control.

David Klapp is a Research Engineer at the American Electric Power's Dolan Technology Center since 2004. He is also Test Site Manager for the AEP Walnut Test Facility. Mr. Klapp's research work includes testing and failure analysis of utility system components and development of power electronics systems for distributed grid applications. Prior to AEP, Mr. Klapp conducted research on composite insulators and the detection of dielectric breakdown in power electronics systems at the Clarkson High Voltage Lab, Clarkson University.

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