Presented at Power-Gen India & Central Asia 2012,
19-21 April, 2012, Pragati Maidan, New Delhi, India

Supercritical CO_2 Power Cycle Developments and Commercialization: Why sCO_2 can Displace Steam

Michael Persichilli, Alex Kacludis, Edward Zdankiewicz, and Timothy Held [(a)]

Echogen Power Systems LLC
365 Water St.
Akron, OH 44308 U.S.A.
www.echogen.com

ABSTRACT

The U.S. DOE estimates that 280,000 MW discharged annually in the U.S. as *waste heat* could be recycled as usable energy to provide 20 percent of U.S. electricity needs while slashing GHG by 20 percent and saving USD $70-150B per year on energy costs. Waste heat can be considered as the other green energy because it is a renewable energy equivalent resource that improves energy efficiency from existing fossil fuel usage, while reducing grid demand by converting the recovered heat into usable electricity, heating and/or cooling. While various sources of independent data suggest that this waste heat recovery opportunity is valued at over USD $600B for the U.S. market, similar large opportunities exist worldwide.

Echogen Power Systems LLC (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; the Thermafficient® Heat Engine converts waste heat to power using a breakthrough supercritical CO_2-based power cycle.

Compared to organic and steam-based Rankine Cycle 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, lower capital and operating costs. The Levelized Cost of Electricity (LCOE) is calculated at an average USD $0.025 per kWh for the CO_2-based heat engine and averages at USD $0.065 per kWh for a complete combined cycle gas turbine system utilizing the supercritical CO_2 heat engine for bottom cycling.

This paper presents an exemplary trade study comparison between the CO_2 and steam-based heat recovery systems. An update is also provided for the Echogen 250 kW demonstration thermal engine which completed initial testing at the American Electric Power's research center during 2011. Also presented is current status of long term testing with this system at a commercial district heating organization, and a multi-megawatt heat engine that will be installed at a U.S. customer host site during 2013.

(a) Presenting author.

INTRODUCTION

Concerns about energy affordability, energy security, and greenhouse gas emissions have heightened interest in the potential for energy efficiency because it offers a largely untapped energy resource for the economies of the world. *Usable (waste) heat to power* is a leading application area for energy efficiency that can address this growing need. This paper presents an exemplary trade study of two heat recovery technologies that can capture and convert these energy sources: *heat recovery steam generation and Echogen's supercritical CO_2 based heat to power cycle.*

Usable (waste) heat to power – the existing market opportunity

Repurposing usable (waste) heat to power represents a critical component of addressing global energy stability and security. The *International Energy Outlook 2011 Report* (1) estimates that the United States consumed 100.1 quadrillion BTU (quads) of energy in 2008 which is projected to increase 0.5 percent annually to 114.2 quads by 2035. Comparable energy consumption estimates for India, China and the non-OECD Asia region are summarized in Table 1.

Table 1: *Total Primary Energy Consumption by Region (from Ref. 1)*

Region	Energy Consumption by Region (quadrillion BTU)		
	2008 (Historical)	2035 (Projected)	Average Annual Percent Change (2008-2035)
Non-OECD Asia	**137.9**	298.8	**2.9**
China	86.2	191.4	3.0
India	21.1	49.2	3.2
Other	30.7	58.2	2.4
United States	**100.1**	114.2	**0.5**

According to the U.S. Department of Energy (DOE), U. S. industry alone consumes approximately 32 quadrillion BTUs (quads) of energy per year, almost one third of all energy used in the U. S., of which 280,000 MWh lost as waste heat may be recoverable and repurposed as useable energy, while slashing GHG emissions by 20 percent and saving USD $70-150B per year on energy generation costs (2). Similar opportunities exist for India, China and the rest of the Non-OECD Asia region.

Energy-intensive manufacturers such as steel, glass, cement, chemicals, glass, aluminum and pulp/paper, oil & gas, etc. often experience slim profit margins in the U.S. and reducing operating costs through reductions in energy consumption can help them gain a competitive edge. For example, a steel company with typical profit margins that cuts energy spending by $66,000 (e.g. by converting waste heat into electricity) would have to increase total sales by $1,000,000 in order to achieve the same financial impact.

While 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 estimates the global installed base for industrial gas turbines at 46,455 units consisting of 21 percent (9,755 units) aeroderivative, 46 percent (21,370 units) light frame units, and the remaining 33 percent (15,330 units) as large frame turbines (3). The large frame units (e.g. above 120 MWe size) are typically installed for utility-scale power generation and are usually configured for combined cycle service with large heat recovery steam generators for bottom cycling. The small to medium size gas turbine markets are typically sold as simple cycle units because of the difficulties and economics in scaling down steam systems for combined cycle service. The small to medium gas turbine market makes sense for other bottom cycling technologies such as the supercritical CO_2 based power cycle which can deliver smaller, more economical solutions for bottom cycling. We estimate that a 10 percent market share to install Echogen heat engines as a bottoming cycle on existing and new 20-120 MWe, simple cycle GTs projected over the next five years would be an opportunity estimated at more than $3B.

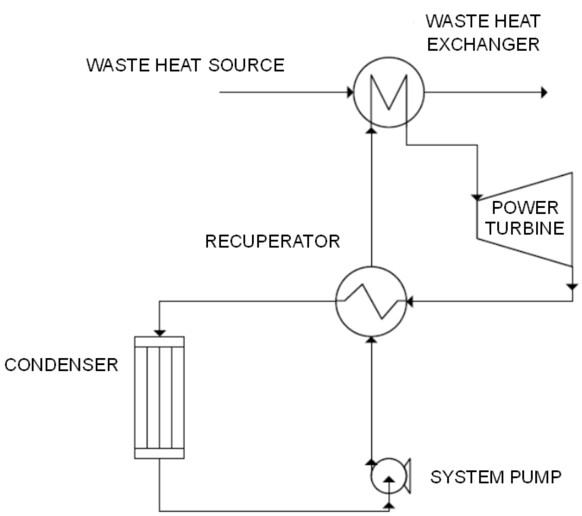
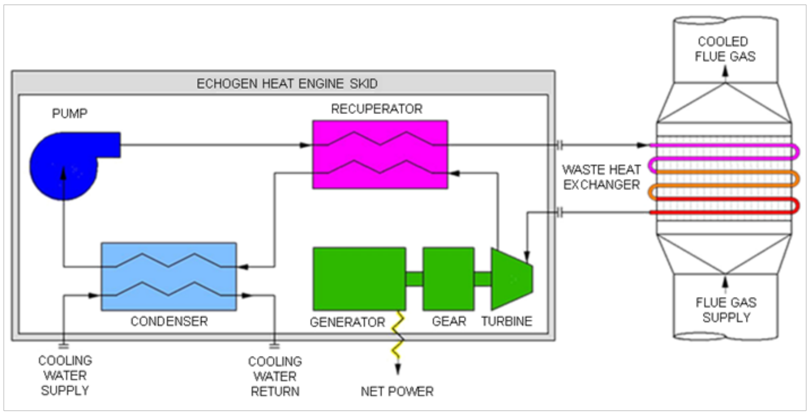


Figure 1: *Simplified process flow diagram for the Echogen heat engine.*

ECHOGEN'S UNIQUE TECHNOLOGY

Echogen is currently commercializing a waste (useable) 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 Echogen heat engine consists of five main components: exhaust and recuperator heat exchangers, condenser, system pump, and power turbine (Figures 1 and 2). Ancillary components (valves and sensors) provide system monitoring and control. Heat energy is introduced through an exhaust heat exchanger installed into the exhaust stack of a gas turbine or the furnace or flue gas exhaust of an industrial process, or other external heat sources with 200^{o}C to greater than 540^{o}C operating temperature range (400^{o}F to greater than 1000^{o}F). Echogen's technology can provide integrated power, heating and/or cooling through a flexible system architecture, that can be configured for power, co-generation or tri-generation. The useable energy can be generated from the turbine exhaust heat without burning fuel or producing resultant emissions which will provide the added benefit of reducing greenhouse emissions while improving overall energy efficiency.

The sCO_2 heat engine is a platform technology scalable from 250 kWe to greater than 50 MWe to support the widest possible variety of industrial and utility scale applications. The Echogen technology is thermal source agnostic, meaning that it is suitable with a wide range of heat sources for energy recovery with efficiencies up to 30 percent. Our patent-pending thermal engines can transform significant amounts of waste heat into electricity for applications ranging from bottom cycling in gas turbines, stationary reciprocating engine gensets, industrial waste heat recovery, solar thermal, geothermal, and hybrid alternatives to the internal combustion engine (4-6).



Cycle Description:

- Liquid CO_2 pumped to supercritical pressure
- Internal system heat recycled at recuperator
- Turbine exhaust or industrial waste heat added at waste heat exchanger
- High energy sCO_2 expanded at power turbine drives generator
- Generator produces electrical power to customer specifications

Figure 2: *The Echogen Cycle is a compact, high-efficiency solution for exhaust heat to power from large scale industrial and utility applications including concentrating solar power.*

Advantages of supercritical CO_2 over steam

Supercritical CO_2 is an ideal working fluid for closed-loop power generation applications. It is a low-cost fluid that is non-toxic, non-flammable, non-corrosive and readily available. The high fluid density of sCO_2 enables extremely compact turbomachinery designs. Figure 3 compares Echogen's 10 MWe CO_2 turbine, which is being designed for commercial service, to a commercially available 10 MWe steam turbine. Supercritical 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

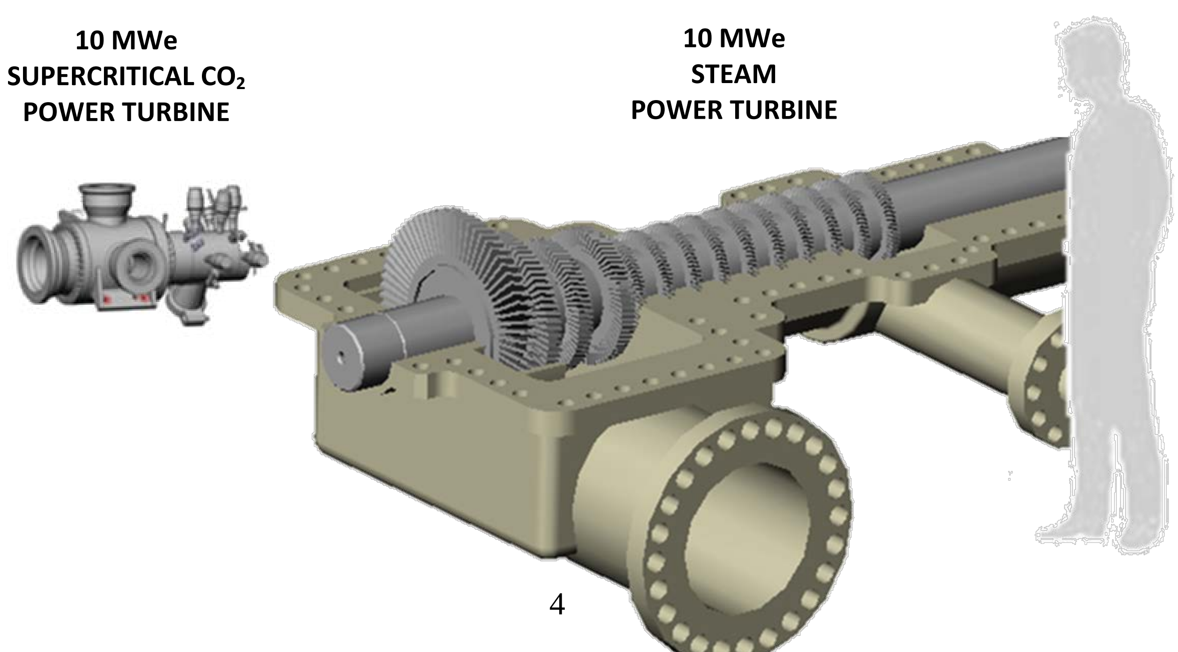


Figure 3: *Echogen's 10 MWe sCO_2 power turbine compared to a 10 MWe steam turbine.*

corresponding increase in systems packaging complexity for additional inlet and outlet piping (7, 8). For example, the power turbine for the large-scale Echogen supercritical carbon dioxide heat engine uses a 0.24-meter (9.5-inch) turbine impeller to produce enough electrical power for approximately 8,000 homes.

The high density of sCO_2 on both sides of a recuperating heat exchanger for service in an Echogen heat engine permits the use of highly compact, microchannel-based heat exchanger technology. A comparison of the physical layout and weight for a shell and tube versus a highly compact heat exchanger of comparable overall heat duty is summarized in Table 2.

Table 2: *Comparison of Shell & Tube and Highly Compact HX Technologies*

Recuperator Type	Dimensions (m) [in]	Weight (kg) [lbs]
Shell & Tube	4-shells, 0.25 dia. x 6.09 lg. [10 dia. X 240 lg.]	7,711 [17,000]
Highly Compact Microchannel	0.58 x 0.58 x 0.58 [23 x 23 x 13]	969.78 [2,138]

Carbon dioxide also more effectively captures waste heat from sources that have an approximately constant heat capacity, such as turbine exhaust or other hot 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.

As shown in Figure 4, the so-called *pinch point* occurs during the constant-temperature phase change from water into steam which limits the maximum fluid temperature, and resulting cycle efficiency for steam-based waste heat recovery and power generation technologies. This

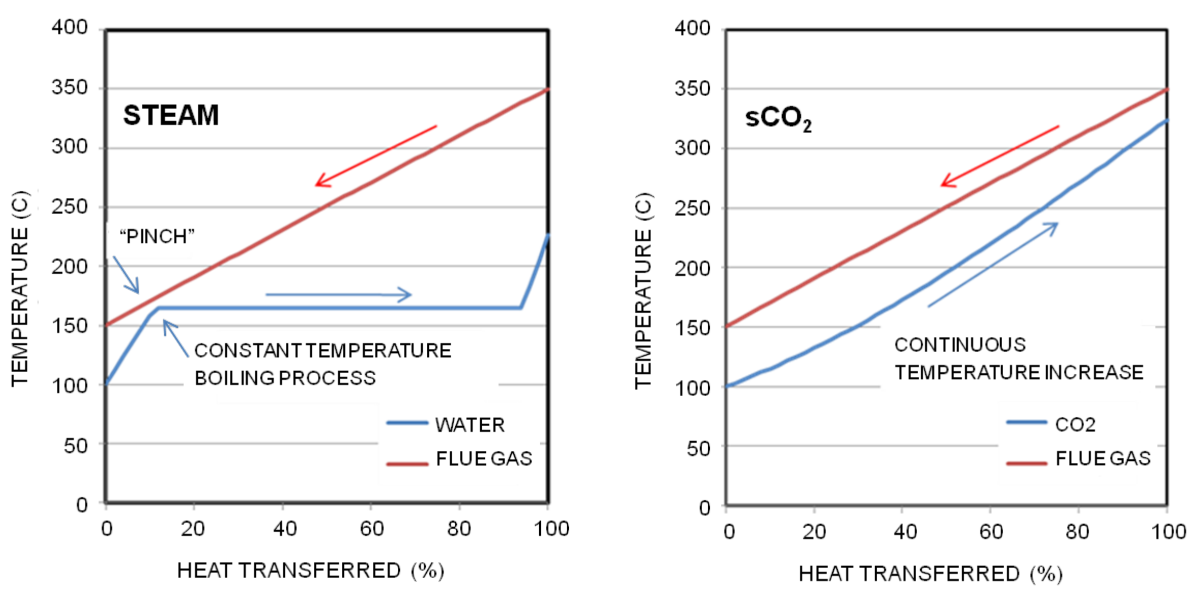


Figure 4: *Unlike steam (left), supercritical CO_2 (right) is a single-phase fluid during heating in the exhaust heat exchanger resulting in higher fluid temperatures and cycle efficiencies.*

phenomenon is not encountered in the heat exchange process with supercritical CO_2 due to its single-phase characteristics well above the critical point, which permits a higher fluid temperature to be achieved for the same heat source. The boiling process in steam systems limits the maximum fluid temperature and requires multiple pressures (e.g., double and triple-pressure HRSG systems) to achieve close approach to the exhaust or flue gas temperature. The Echogen Cycle enables single phase heat transfer resulting in improved heat exchanger effectiveness while reducing exhaust heat exchanger size and cost (9, 10).

The single phase nature of supercritical CO_2 allows for the design of simple, single phase, single pressure exhaust heat exchangers with low gas-side pressure drop. 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 sCO_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.

EXEMPLARY SYSTEM TRADE STUDY

Echogen is currently building the EPS100, a 6 to 8+ MWe thermal engine (depending upon the size of the heat source), which is designed for large industrial, fuel-fired utility and concentrating solar thermal utility applications. The EPS100 uses supercritical CO_2 and incorporates a patent-pending, advanced power cycle that maximizes utilization of exhaust thermal energy by reducing the exhaust temperature to a minimum practical limit. The EPS100 thermal engine will be used for the exemplary system trade study.

Heat recovery steam generators

Heat recovery steam generators (HRSGs**)** are water to steam boilers which capture or recover waste heat from the exhaust of a combustion turbine, fuel-fired reciprocating engine as a combined cycle or fuel-fired duct burner to create steam (11). In a combined cycle plant, this steam is expanded through a turbine for conversion into mechanical, and then electrical power.

HRSGs consist of four major components: evaporator, superheater, economizer and water preheater. The evaporator consists of banks of tubes are mounted in the exhaust stack where gases at 427°C to 650°C (800°F to 1,200°F) heat the tubes. Water is pumped and circulated through the tubes and can be held under high pressure to temperatures of 188°C (370°F) or higher to produce steam. HRSG's are typically found in combined cycle power plants or at other steam-intensive industries such as pulp and paper processing and chemical processing. Numerous suppliers exist globally that offer HRSG hardware and turnkey systems as part of their larger product offerings in power generation and pollution abatement.

Modular HRSGs are categorized by the number of pressure levels – either single pressure or multi-pressure. Single pressure HRSGs have only one steam drum and steam is generated at single pressure. A *double-pressure HRSG* (DP-HRSG) system consists of a low pressure (LP) section and high pressure (HP) pressure section. Each section has a steam drum and an evaporator section where water is converted to steam. This steam then passes through superheaters to further raise the temperature and pressure past the saturation point. The added complexity of multiple pressure HRSG systems is necessary to achieve higher steam temperature, and therefore cycle efficiency, due to the "pinch" phenomenon depicted in Figure 3. However, this improvement comes at a significantly increased complexity and cost derived from the multiple heat exchangers required for the multiple pressure systems.

A comparably sized, double-pressure HRSG will be used in the exemplary trade study because its performance closely matches the Echogen EPS100 heat engine.

System performance comparisons

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 5). All cases shown below for the EPS100 heat engine assume an evaporatively-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. The Echogen system can also increase net power production from heat in gas turbine exhaust. For example, net power on 20-50 MWe gas turbines can be increased by up to 30%.

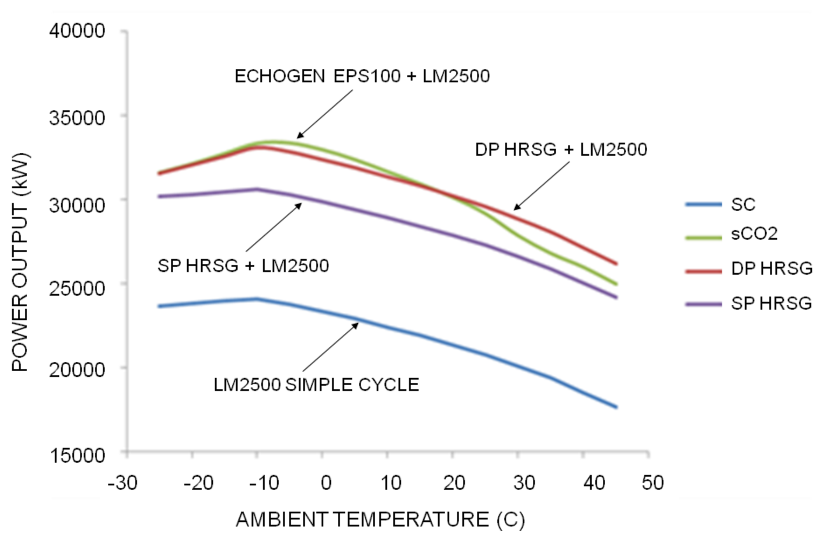


Figure 5: *Power out versus ambient temperature -- Echogen's EPS100 heat engine performance is comparable to a double-pressure heat recovery steam system. The simple cycle LM2500 gas turbine (SC) is shown for reference.*

Smaller system installation footprint

Due to the compact equipment set and reduced auxiliary support equipment required, sCO_2 systems can be installed in a much smaller footprint than can comparable steam-based systems. Figure 6 compares the overall site installation for a DP-HRSG versus a sCO_2 heat engine, both sized to produce 8 MWe additional electrical power configured as a bottoming cycle to a stationary gas turbine. The overall site installation footprint for an Echogen heat

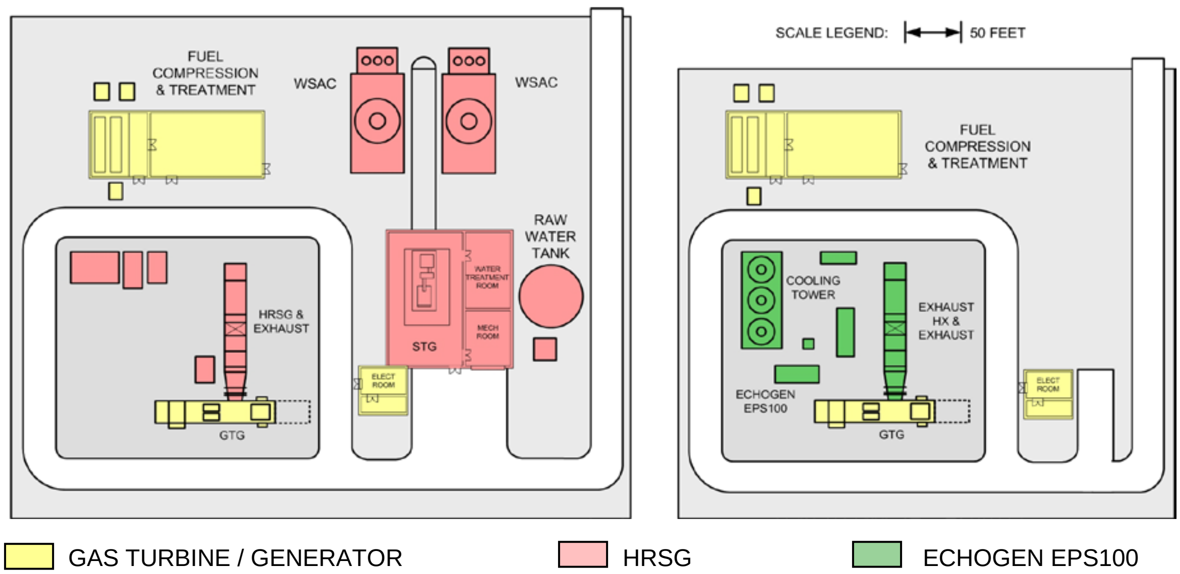


Figure 6: *The Echogen EPS100 heat engine requires a smaller installation footprint compared to a heat recovery steam system for gas turbine heat recovery.*

engine to a gas turbine is less than two-thirds of a steam system / HRSG plant.

The EPS100 sCO_2 heat engine is delivered on two truck-shippable skids plus an off-skid CO_2 storage tank. Footing and foundation requirements are similar to those typically used for industrial environments. The exhaust heat exchanger is modular, with components that are also truck-shippable and can be field-erected quickly. The technology is ideal for simple cycle retrofits due to its small footprint and rapid, flexible installation.

Lower installed and O & M costs

A detailed cost estimate of a fully-installed 6 to 8+ MWe sCO_2 system has been compared to a similar double-pressure steam system (Figure 7) utilizing GT-PRO/PEACE (12). The lower installed cost is a function of the simplicity of the sCO_2 system, its smaller footprint, and reduced auxiliary system requirements. Note that many of the component costs are based on actual purchased hardware costs accumulated during the ongoing fabrication of the prototype 6 to 8+ MWe system (see later section). Installation costs are based on a study performed by an independent EPC that has

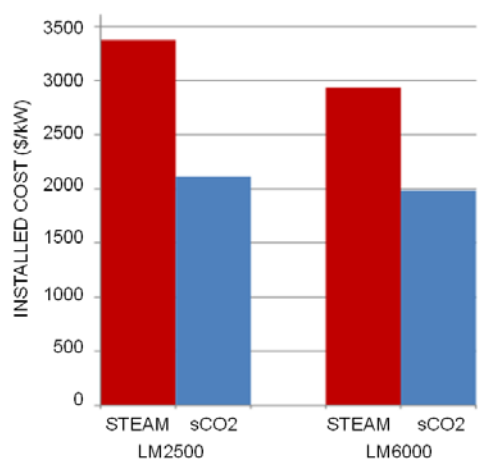


Figure 7: *Installed cost per kilowatt for Echogen EPS100 is up to 40% less compared to heat recovery steam.*

performed numerous small gas turbine simple and combined cycle installations.

The sCO_2 power cycle is a compact, closed loop system requiring minimal operational and maintenance support. Operation and Maintenance (O&M) costs are projected to be significantly lower for the sCO_2 system compared to the steam system. For HRSG systems, a large com-ponent of O&M cost is water quality and associated chemical treatment for feedwater supply and condensate return systems which can adversely impact system availability, hardware reliability and its ability to tolerate peaking (cycling) operation (13-16). By contrast, CO_2 is a clean, non-scaling, non-fouling, and provided it is maintained in a dry condition, it is non-corrosive with the associated lesser maintenance costs. Consequently, the number of personnel required to maintain a sCO_2 system will be greatly reduced because technicians will not be needed for water quality and treatment support functions typically found in a steam-based power plant.

Finally, the growing trend to operate CCGT plants on an as-needed, cyclical basis can cause severe HRSG hardware damage and premature life due to thermal fatigue and flow-assisted corrosion in boiler and superheater tube bundles. Cyclical operation can also cause turbine blade erosion due to water droplet carryover in the low-pressure stage of the condensing steam turbines which are typically installed with HRSGs for power generation.

Because supercritical CO_2 is a single-phase working fluid, it does not require the heat input for phase change from water to steam and does not create the associated thermal fatigue or corrosion associated due to two-phase flow within the system components. The compact equipment set and advanced controls give the EPS100 a fast startup time (approximately 20 minutes to full power), enabling application in peaking duty.

Levelized Cost of Electricity – the key performance metric

Ultimately, the levelized cost of electricity (LCOE) is the most important parameter for comparison because it appropriately accounts for all equipment, installation and operating/maintenance costs over the lifetime of the system installation. Based on the approach described by Can Gulen (17), we have calculated the LCOE for several different equipment configurations, using a 22 MWe LM2500 stationary gas turbine as the primary power generator with either a steam or sCO_2-based heat recovery system on the turbine exhaust:

- Simple cycle gas turbine (SC)
- Combined cycle gas turbine (CCGT) with two-pressure HRSG bottoming cycle and wet-cooling (Steam wet)
- CCGT with two-pressure HRSG bottoming cycle and air (dry) cooling (Steam dry)

- CCGT with Echogen EPS100 bottoming cycle and wet cooling (sCO2 wet)

- CCGT with Echogen EPS100 bottoming cycle and dry cooling (sCO2 dry)

The expression for LCOE is:

$$LCOE = (\beta \cdot C)/(P \cdot H) + f/\eta + OM/H + \mu \cdot OM(v,b)$$

Where:

β = Levelized carrying charge factor or cost of money
C = Total plant cost (USD $)
H = Annual operating hours
P = Net rated output (kW)
f = Levelized fuel cost (USD $/kWh)
η = Net rated efficiency of the combined-cycle plant (LHV)
OM = Fixed O&M costs (USD $/kW-yr)
(v,b) = Variable O&M costs for baseload operation (USD $/kWh)
μ = Maintenance cost escalation factor (1.0 for baseload operation)

The levelized carrying charge factor was calculated based on a 4 percent nominal discount rate (18) as recommended by the US DOE EERE office for 2010-2011, and a 20-year equipment lifetime. Plant cost was the owners total cost estimated for a US market by GT-PRO/PEACE for SC and CCGT, and comparable estimates for the sCO_2 plant.

To calculate total net rated output (*P·H*), performance models were run using three different sets of climate design conditions from the ASHRAE database to represent a range of annual outdoor conditions typically found in the U.S.: temperate (Akron OH), hot with low relative humidity (Phoenix, AZ), and hot with high relative humidity (Houston, TX). Two different duty cycles were also assumed, “baseload” (8,000 hours, 50 start/stop cycles per year), and a once per day cyclic operation (3,500 hours, 250 start/stop cycles per year). The startup time of each system was also accounted for by derating the system output during initial operation. Operation and maintenance costs were calculated based on reduction in personnel costs due to lower head count required on site, and elimination of boiler feedwater treatment costs. Periodic top-off of CO_2 due to seal and other fugitive leakage was included, but has a minimal impact on operating costs.

Several models were prepared assuming natural gas fuel costs for the gas turbine ranging from USD $5.50/MCF to USD $3.50/MCF to better understand the impact of fuel cost on overall plant performance and resulting LCOE. The modeling results are presented in Figure 8 for baseload operation (8,000 hours per year) and in Figure 9 for peaking (cyclic) operation (3,500 hours per year, one start/stop cycle per day).

Note that Figures 8 and 9 are for the total plant, including both the gas turbine and sCO_2 engine power outputs and costs. A similar analysis can be undertaken for the sCO_2 engine in isolation, in which only the output and costs are used in the LCOE calculation. In these calculations, the LCOE of the sCO_2 engine ranges from USD $0.019 to 0.031 per kWh for baseload operation, and USD $0.047 to 0.075 for cyclic operation. In all cases, the incremental power of the sCO_2 system is being produced at a significant discount relative to the output of the gas turbine. In comparison, the steam-based HRSG LCOE ranges from USD $0.036 to 0.043 for baseload, and USD $0.105 to $0.126 for cyclic operation. The lower LCOE of the sCO_2 system makes for an economically superior solution for both baseload and cyclic operation (Figure 10).

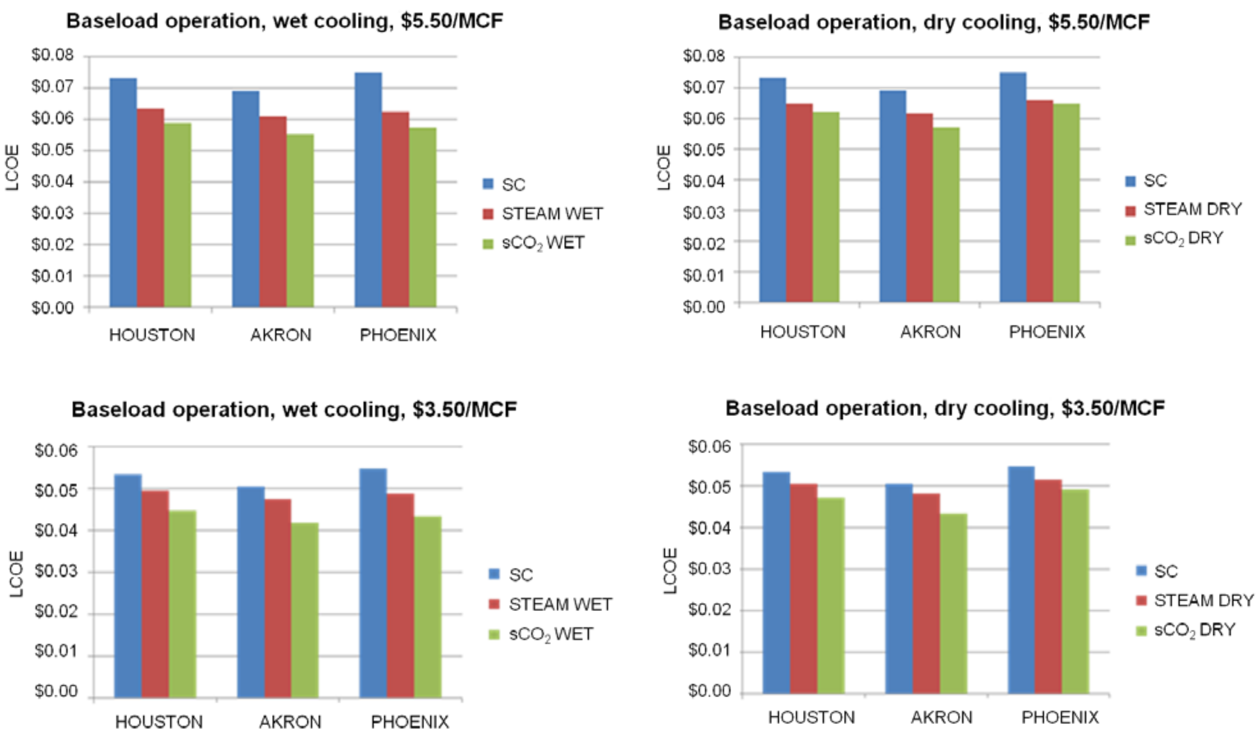


Figure 8: *Baseload operation using an Echogen EPS100 for bottom cycling results in a 10 to 20 percent LCOE improvement compared to a simple cycle GT or CCGT with a steam bottoming cycle under wet-cooled conditions, and 4 to 15 percent LCOE improvement for dry-cooled cases.*

High output power + low cost + low O&M cost = low LCOE

- The sCO_2 cycle provides a 10 to 20% lower LCOE compared to traditional heat recovery steam for baseload and cyclic operation
- Lower installed cost for the sCO_2 system is due to its smaller system footprint and reduced balance of plant requirements
- Lower O & M costs for sCO_2 are possible because plant personnel are not needed for water quality and treatment support functions typically found in steam-based plants
- The growing trend to operate CCGT plants on an as-needed basis favors single-phase sCO_2 over steam due to no hardware damage and premature life due to thermal fatigue and flow-assisted corrosion

Figure 10: *The lower LCOE of the sCO_2 system makes for an economically superior solution for both baseload and cyclic operation compared to heat recovery steam systems.*

ECHOGEN HEAT ENGINE STATUS

Echogen Power Systems is currently entering the product introduction and customer demonstration phase of commercialization through several parallel initiatives.

During the AEP test program conducted from April 2010 through April 2011 (Figure 11), eight turbo-alternator configurations were evaluated (4, 5). Test data was collected to calculate and compare predicted versus actual isentropic, aerodynamic, fluid power and grid power performance. In general, actual performance was found to be slightly better than predicted values (Figure 12). Results were used to define design features for power turbine improvements which include increasing rated power output from 250 kWe to 400 kWe. Two configurations of new power turbine hardware are currently in fabrication and will begin long term endurance testing during the next deployment of the demonstration system.

Figure 11: *Initial testing of the Echogen 250 kWe demonstration system was completed during mid-2011 at the American Electric Power (AEP) Dolan Technology Center (Groveport, OH U.S.A.).*

The heat engine is currently being installed at Akron Energy Systems (Akron, OH), a municipal district heating utility, located close to Echogen's corporate offices. Site design was completed by Echogen's engineering team during mid-2011. Installation of the balance of plant hardware is now underway with system commissioning scheduled for April 2012 (Figure 13). Long term endurance testing will provide the opportunity to operate the system with supercritical

CO_2 running at ambient operating conditions which will vary with weather and seasonal changes and with duty cycles similar to what future commercial systems will experience in customer installations. Testing will also provide long term performance data on all system components.

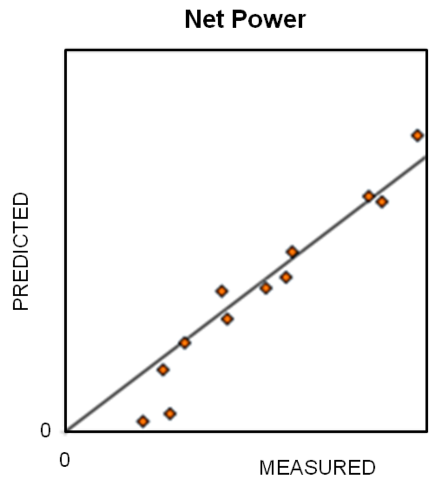


Figure 12: Measured vs. predicted net power output for the 250 kWe demonstration heat engine at AEP.

As previously discussed in this paper, the EPS100 system completed detailed design in 2011 and is currently in fabrication. Initial systems checkout testing will be conducted at a New York based turbo-machinery test facility provided by Echogen's strategic partner, Dresser-Rand Corporation, and will be installed at a customer host facility for field testing in 2013.

Figure 13: The 250 kWe heat engine will begin long term endurance testing at the Akron Energy Systems district heating facility (Akron, OH U.S.A) during 2Q 2012.

OTHER sCO_2 PROGRAMS

During late 2011, Echogen completed a 6-month, Phase I SBIR project under contract to the U.S. Navy NAVSEA Electric Ship Office. The project explored the feasibility of using Echogen's thermal engine technology to improve efficiency and reduce fuel consumption for marine power generation modules. Study results indicate that an Echogen heat engine can potentially reduce fuel consumption for propulsion and service power turbines by over 20 percent within the extremely tight packaging volume constraints found on Naval surface ships. In a related project, Echogen completed preliminary designs of systems for gas turbine inlet chilling for power augmentation in which exhaust heat-driven power generation can produce significant additional power gains for both marine and land-based applications. Detailed planning for a follow-on Phase II prototype design and test program with the U.S. Navy is currently underway.

In 2011, Echogen, as part of a team led by the Lawrence Berkeley National Laboratory (LBNL), was notified that they received a USD $5 million, 3-year team award from the U.S. DOE Geothermal Technology Office (19). Echogen's USD $3.7 million sub-award will be used to develop and demonstrate a thermal engine that produces electricity from circulating CO_2 in deep geothermal formations. A side benefit of the circulation of CO_2 is that a fraction remains sequestered within the geological formation. Phase 1 activities are well underway and include developing the conceptual and preliminary design for the geothermal-driven heat engine.

Program Phases 2 and 3 will involve the detailed design, fabrication, installation and testing of the heat engine at the SECARB Cranfield Geothermal Field located in Cranfield, MS U.S.A.

Echogen has conducted system design studies to define requirements for sCO_2 heat engines that can operate with full dry cooling for applications where cooling water is not available. The sCO_2 power cycle has the ability to operate totally *water-free* making it a very attractive selection as the power block for emerging concentrating solar power (CSP) applications.

CONCLUSIONS

The systems trade study presented shows that sCO_2 technology can displace steam for bottom cycling on gas turbines by providing higher output power with lower installed cost and lower O&M costs which can reduce LCOE by up to a 10 to 20 percent. Performance of the sCO_2 heat engine for converting heat to power from furnace and flue gas exhaust for large-scale industrial applications will produce similar savings. In comparison to heat recovery steam generators, the higher energy density of sCO_2 reduces system component size and cost, and provides significant advantages regarding system efficiency, footprint, and ease of installation. Echogen's sCO_2 heat engine technology is *transformational* because it uses CO_2 to:

- Generate electricity from useable (waste) heat without burning fuel or producing resultant emissions
- Reduce reliance on grid delivered power for industrial applications and provide insulation from fluctuating retail electricity costs
- Offset new energy production with recovered energy, reducing associated greenhouse emissions by improving overall energy production efficiency

The sCO_2 heat engine is a platform technology scalable from 250 kWe to greater than 50 MWe to support the widest possible variety of industrial and utility scale applications. The Echogen technology is thermal source agnostic, meaning that it is suitable with a wide range of heat sources for energy recovery with efficiencies up to 30 percent.

REFERENCES

1) U.S. Energy Information Administration (EIA), *International Energy Outlook 2011*.

2) BCS, Inc. 2008, "Waste Heat Recovery – Technology and Opportunities in U.S. Industry," U.S. DOE Industrial Technologies Program.

3) Anon., "The Industrial Gas Turbine Global Maintenance Market," Forecast International, Dec. 2009.

4) Echogen Power Systems LLC 2012, *Supercritical CO_2 Heat Engines for Power Generation – Combined Cycle Gas Turbine (CCGT) and Concentrating Solar Power (CSP) Useable (Waste) Heat to Power*: Echogen Power Systems LLC.

5) Persichilli, M., Held, T., Hostler, S., and Zdankiewicz, E., "Transforming Waste Heat to Power through Development of a CO_2-Based-Power Cycle," presented at 16th International Symposium for Compressor Users and Manufacturers, St. Petersburg, Russia; 08-10 June 2011.

6) Persichilli, M., Held, T., Hostler, S., Zdankiewicz, E., and Klapp, D., "Transforming Waste Heat to Power through Development of a CO_2-Based-Power Cycle," presented at Electric Power Expo 2011, Rosemount, IL U.S.A; 10-12 May, 2011.

7) Dostal V., Drsicoll. M., and Hejzlar, P., "A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors," MIT-ANP-TR-100, The MIT Center for Advanced Nuclear Energy Systems; 10 Mar 2004.

8) Wright, S., "Mighty Mite - A Turbine That Uses Supercritical Carbon Dioxide Can Deliver Great Power from a Small Package," *Mechanical Engineering*, Jan 2012; pp. 40-43.

9) Chen, Y. et.al, "Theoretical Research of Carbon Dioxide Power Cycle Application in Automobile Industry to Reduce Vehicle's Fuel Consumption," *Applied Thermal Engineering*, 25 (2005) 2041–2053.

10) Chen, Y., et.al, "Carbon Dioxide Cooling and Power Combined Cycle for Mobile Applications," Div. of Applied Thermodynamics and Refrigeration, Dept. of Energy Technology, Royal Institute of Technology, Brinellvagaegen 60, Stockholm, Sweden.

11) Ganapathy, V., "Heat-Recovery Steam Generators: Understand the Basics," *Chemical Engineering*, Aug 1996, pp. 32-45.

12) GT-PRO/PEACE software; www.thermoflow.com; 2012.

13) Sampson, D., "Fleetwide Standardization of Steam Cycle Chemistry," *Power Magazine*; 15 Mar 2006.

14) Cotton, I. and Kolarick, J., "HRSG Water-side Reliability – Design and Operating Considerations," PowerGen 94, Dec 1994.

15) Weed, R., "Changing Boiler Water Treatment Needs in High-Pressure Heat Recovery Steam Generators," presented at Annual International Water Conference 1999, Pittsburgh, PA; 18- 19 Oct 1999.

16) Starr, F., "Background to the Design of HRSG System and Implications for CCGT Plant Cycling," *Power Plant Operation Maintenance and Materials Issues (OMMI)*,Vol. 2 (1).

17) Can Gulen, S., “A More Accurate Way to Calculate the Cost of Electricity,” *Power Magazine*; 01 Jun 2011.

18) Anon., “NIST Updates Discount Rates for Federal Life-Cycle Cost Analyses,” U.S. Department of Energy, Energy Efficiency and Renewable Energy (EERE), http://www1.eere.energy.gov/femp/news; 15 Mar 2010.

19) Progress Release: “Department of Energy Awards More Than $11 Million to Advance Innovative Geothermal Energy Technologies,” U.S. Department of Energy, Energy Efficiency and Renewable Energy (EERE), http://apps1.eere.energy.gov/news/progress; 24 Jun 2011.