# Supercritical $CO_2$ Power Cycle Development and Commercialization: Why $sCO_2$ Can Displace Steam

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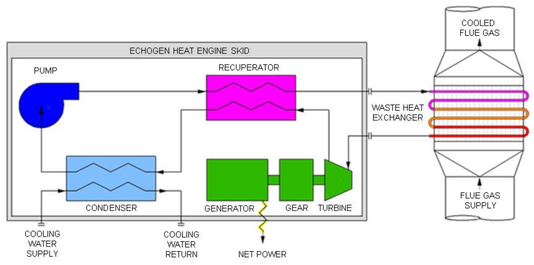
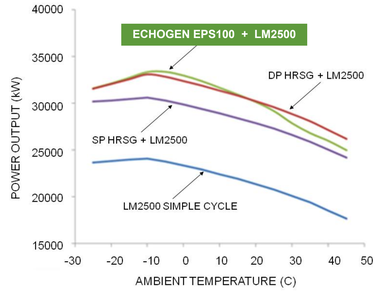
## The Echogen Cycle




- Innovative usable (waste) heat to power generation cycle using supercritical $CO_2$ ($sCO_2$) in a closed loop
- Large scale industrial, utility and marine applications, including concentrating solar power (CSP)

## Power vs. Ambient Temperature




- Echogen EPS100 performance is comparable to a double-pressure heat recovery steam system (DP-HRSG)
- An $sCO_2$ heat engine can provide up to 35% additional power output for stationary gas turbines

## Levelized Cost of Electricity (LCOE) – The Key Performance Metric

- LCOE accounts for all equipment, installation, operating, and maintenance costs over the lifetime of the system installation
- Expression for LCOE (USD $/kWh):

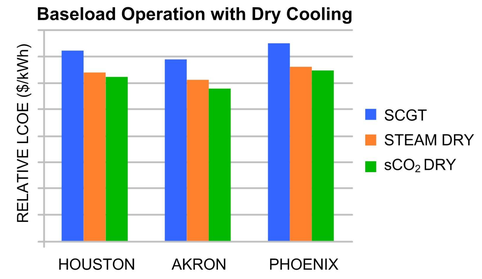
$$LCOE = (b \bullet C) / (P \bullet H) + f/h + OM/H + m \bullet OM(n, b)$$

*Where:*

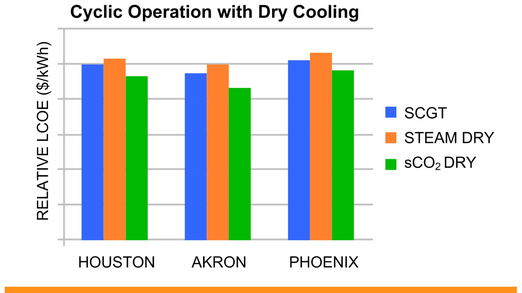
| | | |
|---|---|---|
| $b$ | = | Levelized carrying charge factor or cost of money |
| $C$ | = | Total plant cost (USD $) |
| $H$ | = | Annual operating hours |
| $P$ | = | Net rated output (kW) |
| $f$ | = | Levelized fuel cost (USD $/kWh) |
| $h$ | = | Net rated effciency of the combined cycle plant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

- LCOE analyses prepared for combined cycle gas turbine with steam or supercritical $CO_2$ heat recovery bottoming cycles
- Baseload operation: 8,000 hrs, 50 start/stops per year
- Cyclic operation: 3,500 hrs, 250 start/stop cycles per year
- Five system configurations studied at several price points for gas turbine fuel:
  - Simple cycle gas turbine (SCGT)
  - Combined cycle gas turbine (CCGT) with two-pressure HRSG bottoming cycle
  - Combined cycle gas turbine (CCGT) with Echogen EPS100 bottoming cycle
  - All combined cycles with wet-cooling (Steam wet and $sCO_2$ wet)
  - All combined cycles with dry-cooling (Steam dry and $sCO_2$ dry)

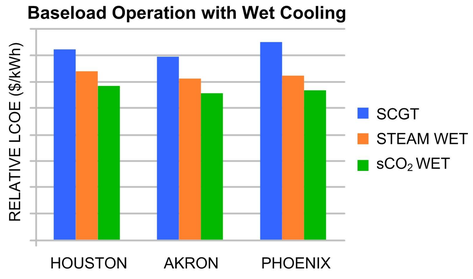
**Baseload Operation with Dry Cooling**



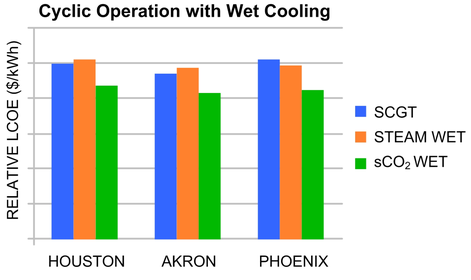

**Cyclic Operation with Dry Cooling**




**Baseload Operation with Wet Cooling**

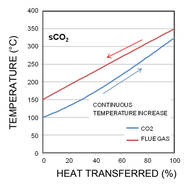


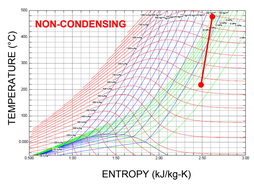

**Cyclic Operation with Wet Cooling**



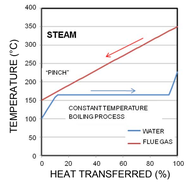

## The Advantages of $sCO_2$ Over Traditional Steam

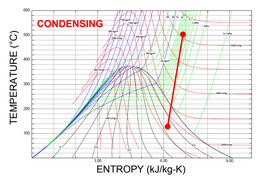
**$sCO_2$ – Higher Power Density with No Phase Change**



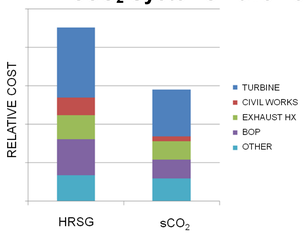




**Steam – Phase Change Limits Temperature and Cycle Efficiency**




**$sCO_2$ Systems Have Lower Installation and O & M Costs Compared to Heat Recovery Steam Systems**



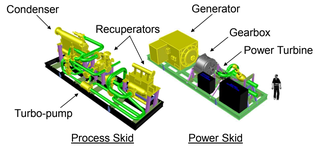

- Installed cost per kilowatt for Echogen EPS100 is up to 40% less compared to HRSG
- $sCO_2$ requires a smaller system footprint with reduced balance of plant requirements
- HRSG requires higher O & M costs for water quality and chemical treatment of feedwater supply and condensate return systems which adversely impact HRSG availability, hardware reliability, and ability to tolerate cyclic operation

## Echogen Heat Engines Are Currently in Test and Production

**250 kW Demonstration System Completed Field Tests at AEP in 2010-11, and is Now Beginning Endurance Testing**



**First Production Unit of the EPS100 6 to 8+ MWe System is Beginning Checkout Tests**

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## Conclusions

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

- Echogen EPS100 provides a 10 to 20% lower LCOE compared to traditional heat recovery steam for baseload and cyclic operation
- Lower installed cost for $sCO_2$ – smaller system footprint and reduced balance of plant requirements
- Lower O & M costs for $sCO_2$ – plant personnel not needed for water quality and treatment support functions typically found in a steam-based plants
- Growing trend to operate CCGT plants on as-needed, cyclic basis favors single-phase $sCO_2$ over steam – no hardware damage and premature life due to thermal fatigue and flow-assisted corrosion

**$sCO_2$ the clear solution for gas turbine heat recovery**

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