A Low Carbon Supercritical CO₂ Power Cycle / Pulverized Coal Power Plant Integrated with Energy Storage: Compact, Efficient and Flexible Coal Power

March 4, 2020
Plant Overview – Block Flow Diagram

Coal Handling and Storage

Air Fired Pulverized Coal Fired Heater (297.6 MWth)

Air Quality Control System (SCR, Scrubber, Bag House)

Post Combustion Carbon Capture System (PCCC)
CO2 Capture @83.6% - 26.7 kg/s

Air Quality Control System

Stack

Air Cooled Condenser (119.8 MWth)

sCO2

Gas Turbine / Duct Burner / HRSG

[GT Generator, Duct Burner and HRSG to supply saturated steam]

Cooling Tower (~120 MWth)

Coal Heat Input – 282.7 MWth
NG Heat Input – 121.2 MWth
Net Power – 120.7 MWe
Net Plant Efficiency – 29.9%
Carbon Capture Efficiency – 83.6%
Technology Development Overview

• sCO2 Power Cycle
  • EPS100 Waste Heat Recovery – 8.5 MWe commercially available power cycle
  • Large-Scale Pilot program
  • STEP facility component development

• Coal Fired Heater
  • Large-Scale Pilot program

• ETES System
  • ARPA-E DAYS
  • 10 MW / 8-hour Pilot plant under development

• Post Combustion Carbon Capture, AQCS, Gas Turbine-HRSG, Process Cooling
  • Commercially available components – all TRL 9
Large-Scale Pilot Program – US DOE-Funded Project
Award: DE-FE0031585

- 10 MWe large-scale pilot plant using coal-fired combustor with $\text{sCO}_2$ power cycle
- Mizzou CHP plant host site
- Phase I feasibility study complete
- Phase II (FEED study) in process
- Phase III – Build and Operation (2021-2025)
  - Program lead, power cycle
  - EPC
  - TEA, industry voice
  - Host site
  - Coal-fired heater, AQCS
TransCanada / Siemens project - sCO$_2$ Commercial Deployment

- Announced by TransCanada in March 2019
- EPS120 (uprated EPS100) on an RB211
- Partially-funded by ER Alberta
- TC investigating potential for 25-30 additional WHRUs in Western Canada

sCO2 Power Cycle - Overview

Modified RCB Cycle

- System uses parallel compressors - EPS100 uses single compressor
- System designed for higher temperatures than EPS100, 600-700°C versus 400-500°C
- Only one two-compressor system operated to date – Sandia test loop
- Operational challenges include heat source thermal management during start-up, shutdown and ramping.
High and Low Temperature Recuperators (HTR & LTR)

- Commercially available from several suppliers
  - Heatric - provided PCHEs for EPS100 at lower operating temperatures
  - VPE – supplied lab scale PCHEs up to 600°C to Echogen (performance tests have been completed)
  - Both suppliers are engaged in the LSP program
- Presently TRL – 9 commercially available component even for “higher temperature” Coal FIRST plant
High and Low Temperature Compressors (HTC & LTC)

Low Temperature Compressor (18 MW)
- Fluid Conditions similar to liquid pump
- 2.5 MW hermetically sealed design tested (EPS100)
- Conventional barrel case pump feasible if sufficient NPSH margins

High Temperature Compressor (31 MW)
- Fluid conditions between ideal gas and liquid
- Primary design path: scaled version of LSP turbine driven compressor (3.6 MW)
- Alternate design path: barrel style or Internally-geared compressor multistage designs commercially available (lower efficiency)
Power Turbine (PT)

- 3 or 4 stage axial design
- $T_{in} = 600^\circ C$
- Based on STEP Conceptual Design

Coal FIRST Baseline
Siemens 100 MW 730°C Turbine

Identified Risks
- Blade failure risk – high unsteady alternating stresses
- Material compatibility with CO2
High Energy Turbine Valves (TSV)

- Flowserve TSV has been demonstrated at lower temperatures (485°C)
- ASME Code approved material – Inconel 740H
  - Not castable, requires forged valve bodies (very expensive)
- Haynes 282 – Code qualification underway
  - Castable material – potential for cost reduction
- High budget risk – low/moderate technical risk
- Flowserve and GE suppliers being considered for LSP – nickel alloys being considered

Air Fired PC Heater - Overview

- Designed similarly to a traditional utility steam boiler (CO₂ is utilized for wall cooling)
  - Radiant furnace for combustion and final CO₂ heating (to 700°C)
  - Convection pass for initial CO₂ heating – PHX2
  - Air delivery system, AQCS, ash handling, fuel delivery and burners commercially available
Fired Heater Risk Mitigated - LSP

- Operational
  - Design does not use traditional attemperation for CO2 temperature control – relies on firing rate (NG co-firing for trim) and excess air.

- Design
  - Furnace heat flux profile – LSP program is stoker fired furnace, Coal FIRST plant is Air Fired PC. Both units are CO2 wall cooled designs. Verification of radiant heat transfer models
  - Empirically-based margins in tube wall design due to better understanding of furnace heat flux profiles through LSP testing
  - Ability to meet low pressure drop requirement (compared to steam boiler) – flow distribution
Electrothermal Energy Storage Overview

CO2 based ETES system

- Leverages sCO2 power cycle development
- Modest temperatures allow for low cost materials

Overall Process
RTE = \frac{E_{gen}}{E_{chg}} = \text{COP} \times \text{Efficiency}

Ideal cycle RTE = \text{COP}_{\text{Carnot}} \times \eta_{\text{Carnot}} = 100\%

Non-ideal processes result in RTE \sim 60\%, even at modest temperature ratio
ARPA-E DAYS Program – ETES Proof of Concept

~200 kWth system, including both charging and generating cycles

Initial build
- 2-tank heat transfer fluid HTR
- Ice slurry LTR
- Complete July - 2020

BP 2
- Build and test sand or concrete HTR system
- Complete July - 2021

Primary developmental focus:
- HTSR and heat exchanger (TRL 4)
- LTSR performance (TRL 4)
- Operation and controls
High temperature heat exchanger and reservoir

• Version 1: Heat transfer fluid with PCHE heat exchangers
  • Commercially-available products
  • Lowest risk, but higher-cost

• Next versions being designed and evaluated under ARPA-E program:
  • Concrete + HTF (Westinghouse)
  • Sand + MBHE (Solex)
  • Sand + FBHE (TU Wien)
• 5-50 MWe – Commercially Available
  • Integrally-geared (IG) compressor
  • Multiple suppliers (Siemens, Hanwha, Howden, Atlas Copco…)
• 50+ MWe
  • Parallel IG compressors
  • Developing large axial compressor technology with Barber-Nichols, University of Cincinnati & Notre Dame
Charge cycle hydraulic turbine

- Similar to LNG expanders used in liquefaction
- Pressure, power within experience range
- Multiple manufacturers
  - Cryostar
  - Ebara
  - Flowserve
**ETES 10 MW / 8-hour Pilot Plant**

- Pilot plant utilizes low risk components
  - Commercial charge compressor
  - Scaled EPS100 turbomachinery for generating cycle
  - 2 – Tank heat transfer fluid HTSR with commercial PCHE for HTX
  - ISG or ice on coil solution for LTSR and LTX
  - 2-year program to operation from funding release (Expected operation late 2022)
  - Will bring ETES system to TRL 7

- Roadmap for lower cost, higher performance technology
  - Advanced HTSR/HTX (ARPA-E Days)
  - ISG (ARPA-E), passive slurry generation (TBD)
  - Hydraulic Turbine (vendor development – derivative design)
  - Pilot system provides testbed for technology improvement
Technology Developers

Echogen’s current commercial partnerships include Siemens (Oil and Gas) and GE (Marine) in Waste Heat Recovery Applications

Power Cycle
Turbomachinery
- Barber Nichols, Inc.
- Siemens
- Printed Circuit Heat Exchangers
- Vacuum Process Engineering
- Heatric
- High Energy Valves
- Flowserve and GE (LSP)

ETES
Thermal Reservoirs and HX
- Concrete HTSR
  Westinghouse Electric Corp.
- Sand Fluidized Bed HX
  Technische Universität Wien
- Sand Packed Moving Bed HX
  Solex Thermal Science
- Ice Slurry Generator
  Liquid Ice Technologies

Turbomachinery
- Siemens / Barber Nichols, Inc.
- Ebara, Flowserve, Cryostar
- High Energy Valves
  - Flowserve and GE (LSP)

Plant Systems
Fired Heater and AQCS
- Riley Power, Inc.

High Temperature Materials
- Special Metals Company
- Haynes International, Inc.

Post Combustion Carbon Capture
- Mitsubishi Heavy Industries

EPC
- Louis Perry and Associates, A CDM Smith Company
Project Financing Requirements and Challenges

• What would be required for securing financing?
  • Minimize technical risk – pilot operation of equipment will be required
  • Minimize financial risk – well defined revenues (long term PPA, CO2 credit/revenue with high likelihood of certainty such as 45Q)
  • EPC contractor to provide a full project wrap

• What are the biggest challenges?
  • Many banks have forsworn providing capital for coal projects¹
  • Political and public perception of funding coal projects

¹https://www.banktrack.org/page/list_of_banks_which_have Ended_direct_finance_for_new_coal_minesplants
Permitting Scenarios

- **Scenario 1 – Non-Attainment Area**
  - Subject to more rigorous air quality standards, Public backlash would be high
  - This would make permitting almost impossible – AVOID

- **Scenario 2 and 3 – Greenfield and Brownfield Site (Netting not available)**
  - New Construction > 250 MMBtu/hr Heat source or 100 tons of any criteria
  - PSD and BACT would be required
  - 12 – 18 months for construction permitting
  - Would trigger PSD, public notice mandatory (potential to slow down 12 months or more)
  - Oversight by EPA

- **Scenario 4 – Brownfield Site using Netting (replacing present emissions source with lower one)**
  - Using this method for LSP permitting at University of Missouri
  - 6 – 9 months for construction permitting
  - State has more autonomy in issuing permits
Approach to Site Selection

• Heavily dependent on project financing
  • Well defined revenue stream – Long Term PPA and CO2 credit/revenue
  • Enhanced Oil Recovery for CO2 revenue – Petra Nova Model

• Avoidance of plants in Non-Attainment Areas
  • Permitting would be near impossible

• Through EPRI’s support several US utilities have committed funds to LSP
  • AEP and Southern Company are supporting Echogen’s LSP program
  • Others have expressed interest in the program
  • Leverage existing relationships to determine potential interest in US based site

• International market
Detailed Design Plan and Timeline

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Assumes Notice to Proceed at FEED conclusion (Performance and Cost Determined)