A Low Carbon Supercritical CO_2 Power Cycle / Pulverized Coal Power Plant Integrated with Energy Storage:
Compact, Efficient and Flexible Coal Power

ECHOGEN
power systems

Project Execution Plan

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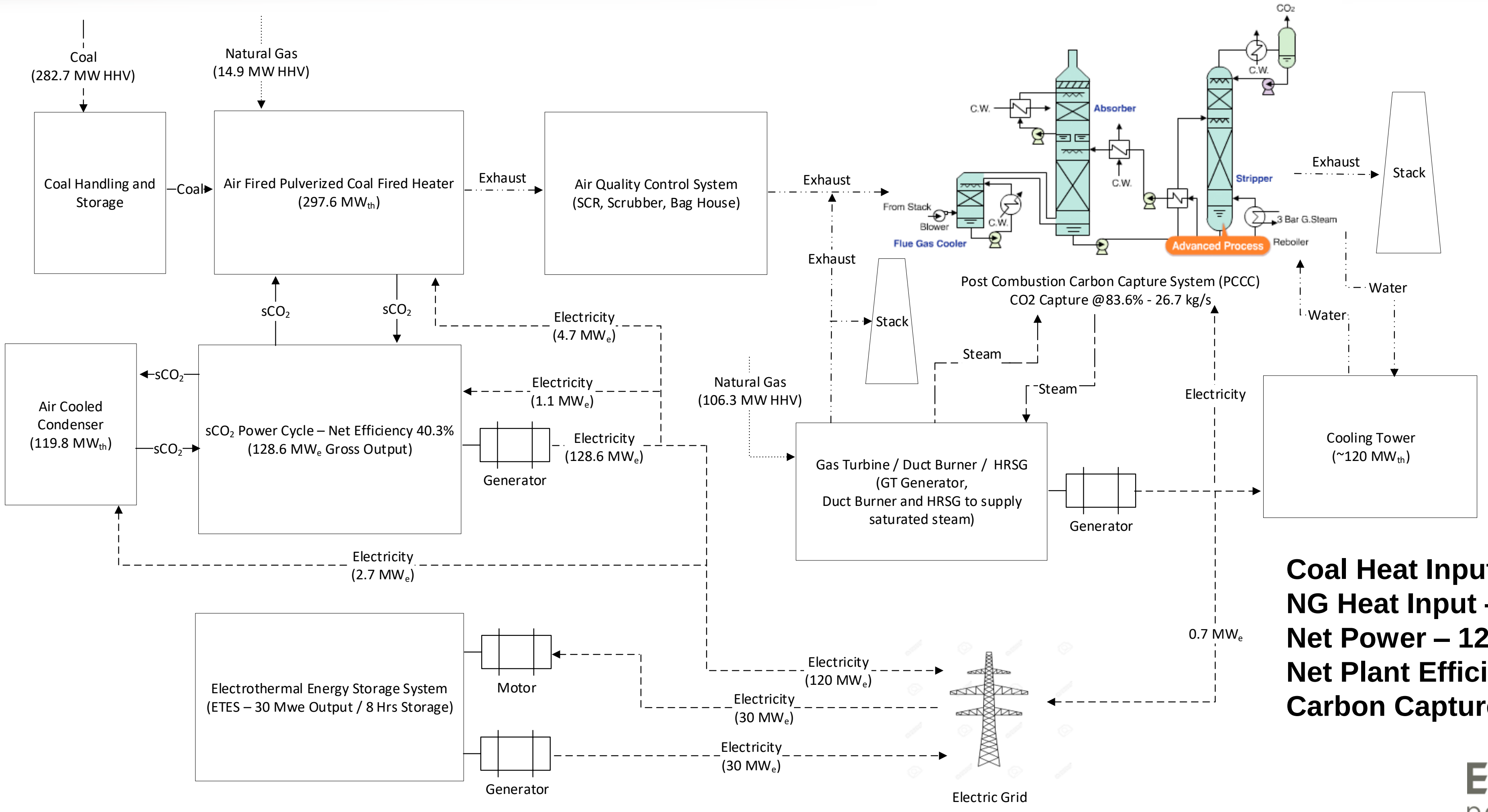
March 4, 2020

Plant Overview – Block Flow Diagram



Coal Heat Input – 282.7 MW_{th}

NG Heat Input – 121.2 MW_{th}

Net Power – 120.7 MW_e

Net Plant Efficiency – 29.9%

Carbon Capture Efficiency – 83.6%

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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 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)

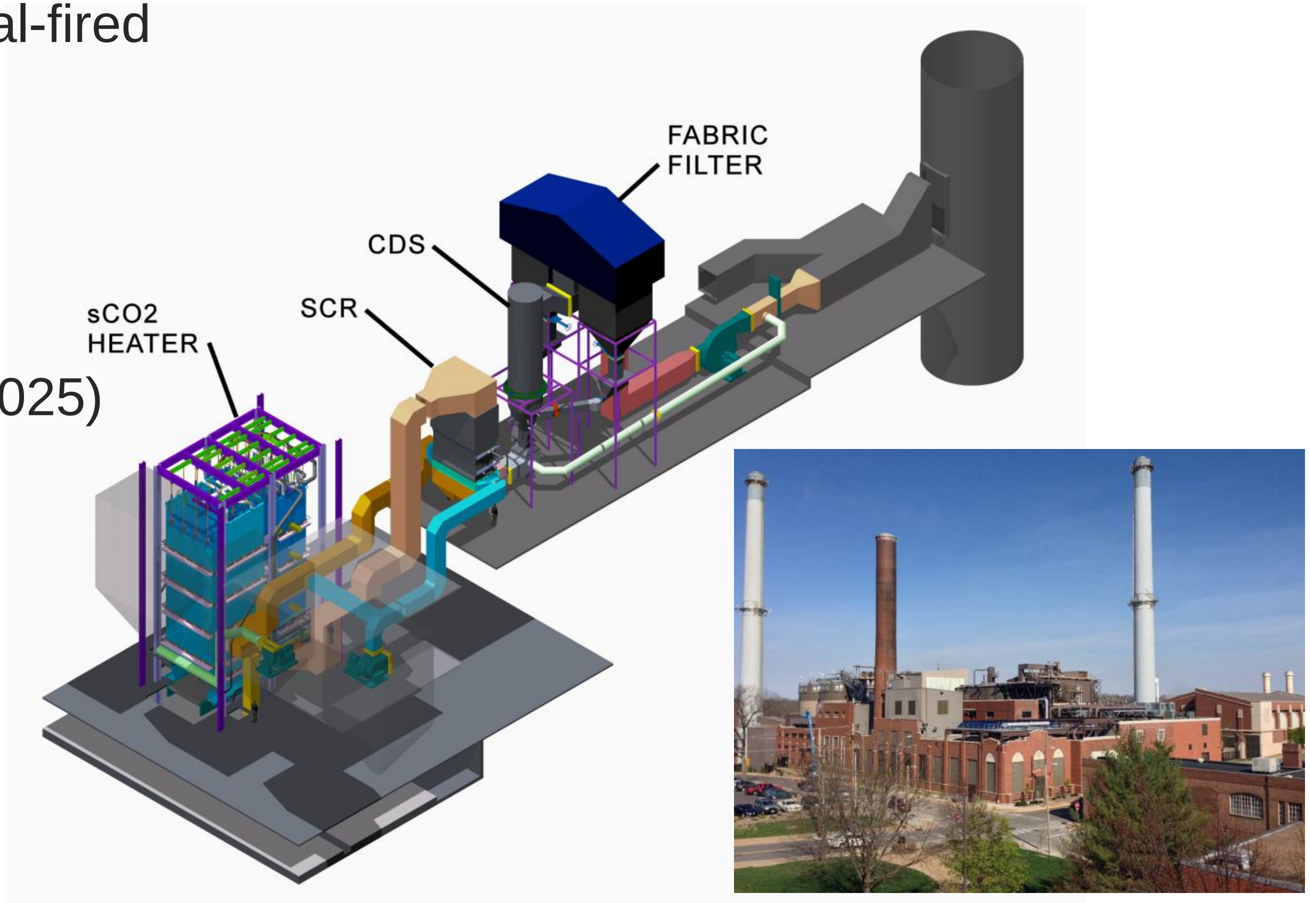
Echogen – Program lead, power cycle

CDM Smith – EPC

EPRI – TEA, industry voice

MU – Host site

RileyPower – Coal-fired heater, AQCS



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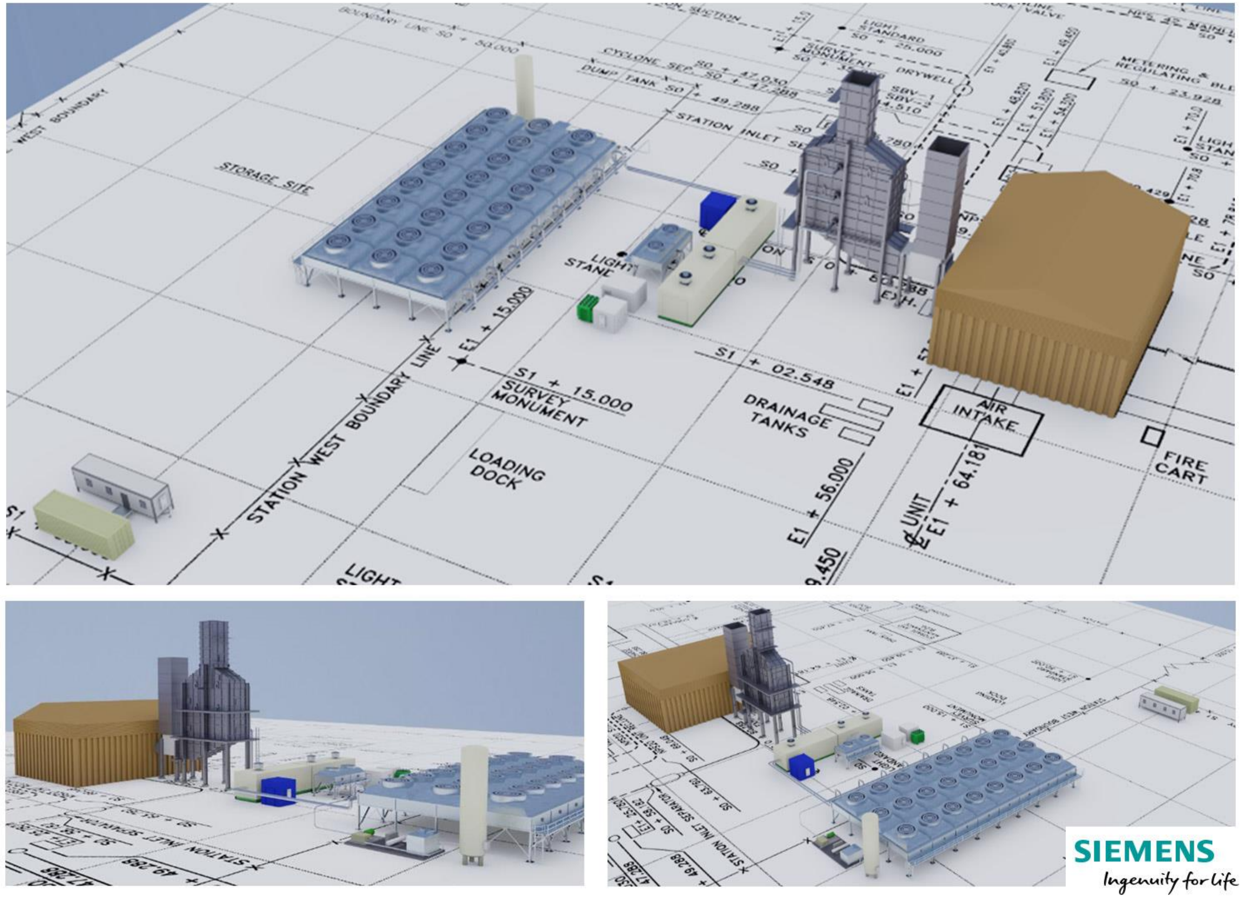
TransCanada / Siemens project - sCO_2 Commercial Deployment

- 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

Supercritical CO2 Pilot Project - Concept Plan



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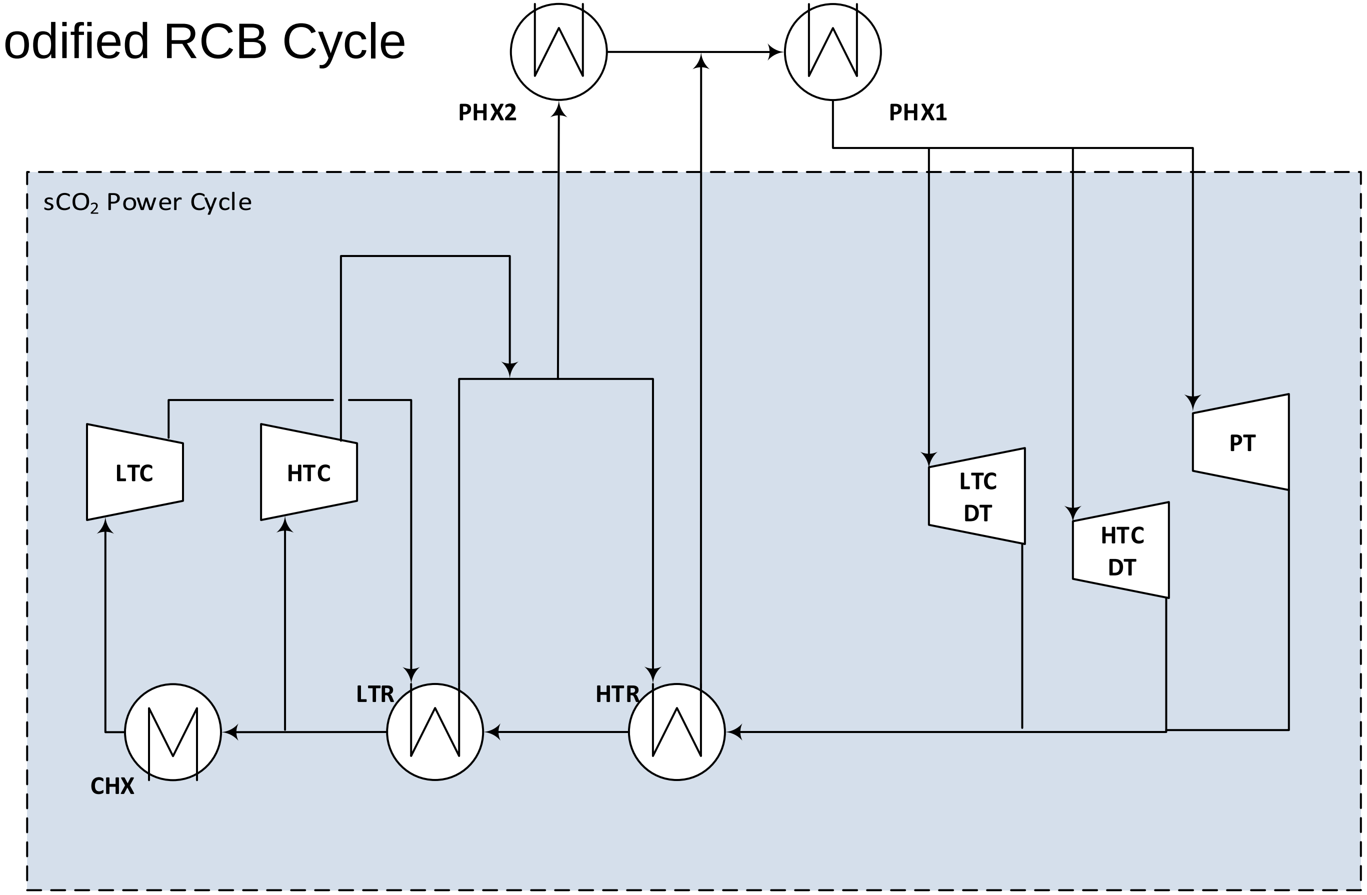
https://www.tcenergy.com/stories/2019/2019-02-28-capturing-the-power-of-hot-air/

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.

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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

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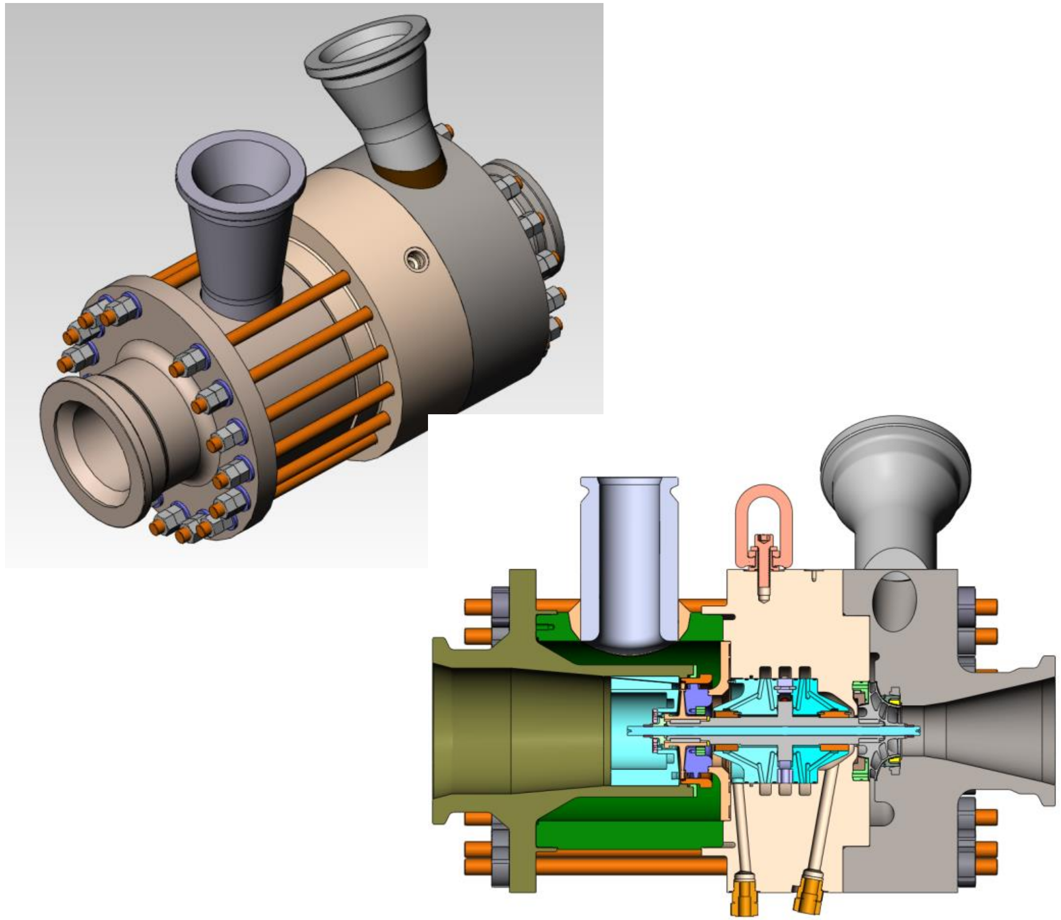
High and Low Temperature Compressors (HTC & LTC)

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)



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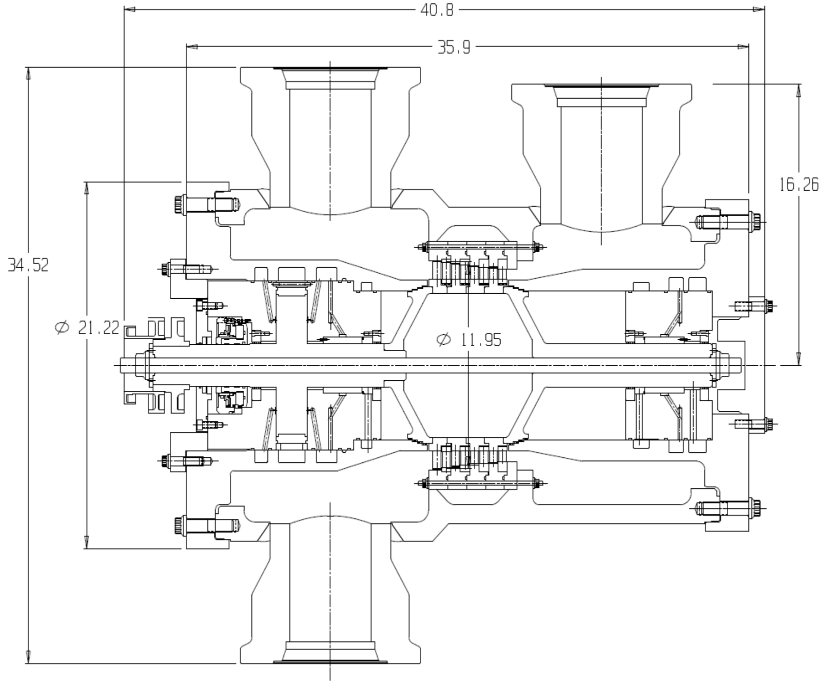
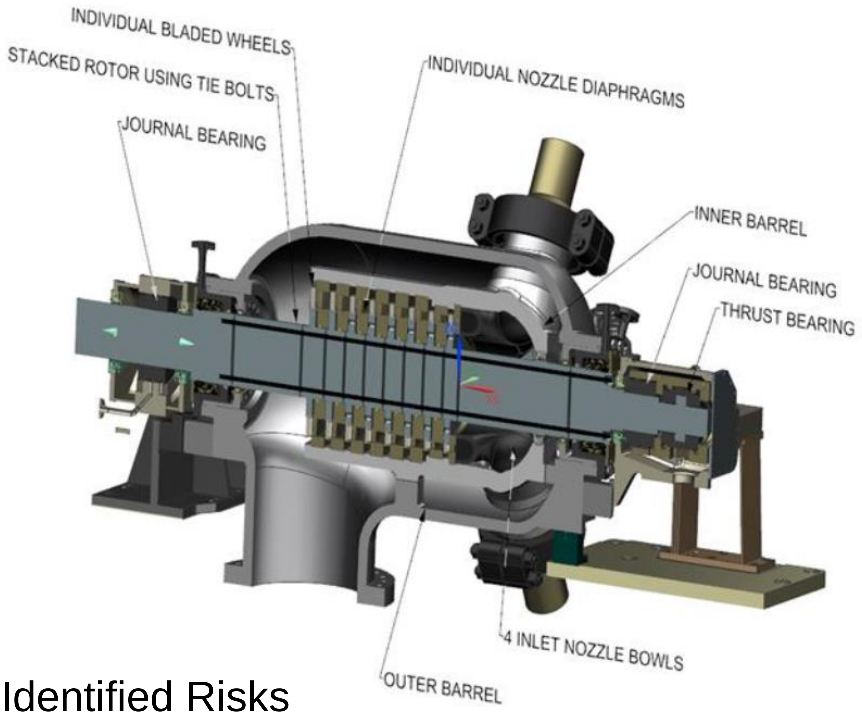
Power Turbine (PT)

LSP Power Turbine Design



- 3 or 4 stage axial design
- T_{in} = 600°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

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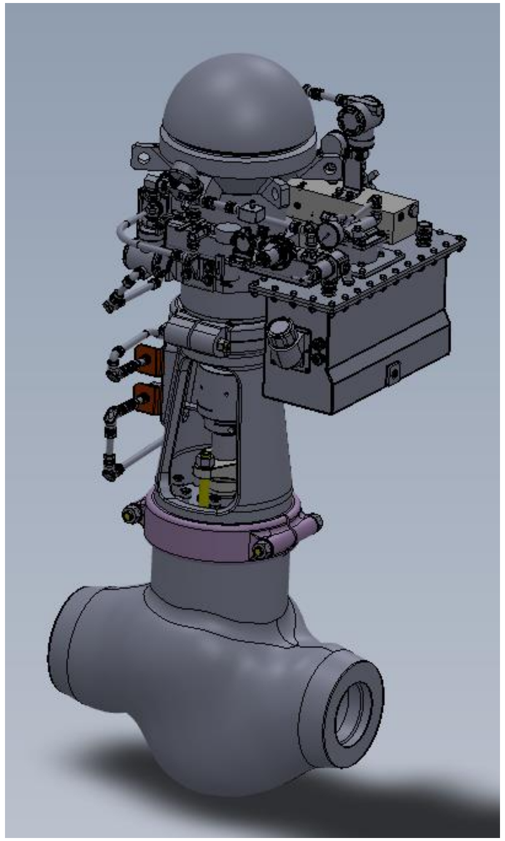
High Energy Turbine Valves (TSV)



- 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


[1]

[1]Marion, J., Kutin, M., McClung, A., Mortzheim, J., Ames, R.; "The STEP 10 MWe sCO2 Pilot Plant Demonstration", ASME Turbo Expo 2019

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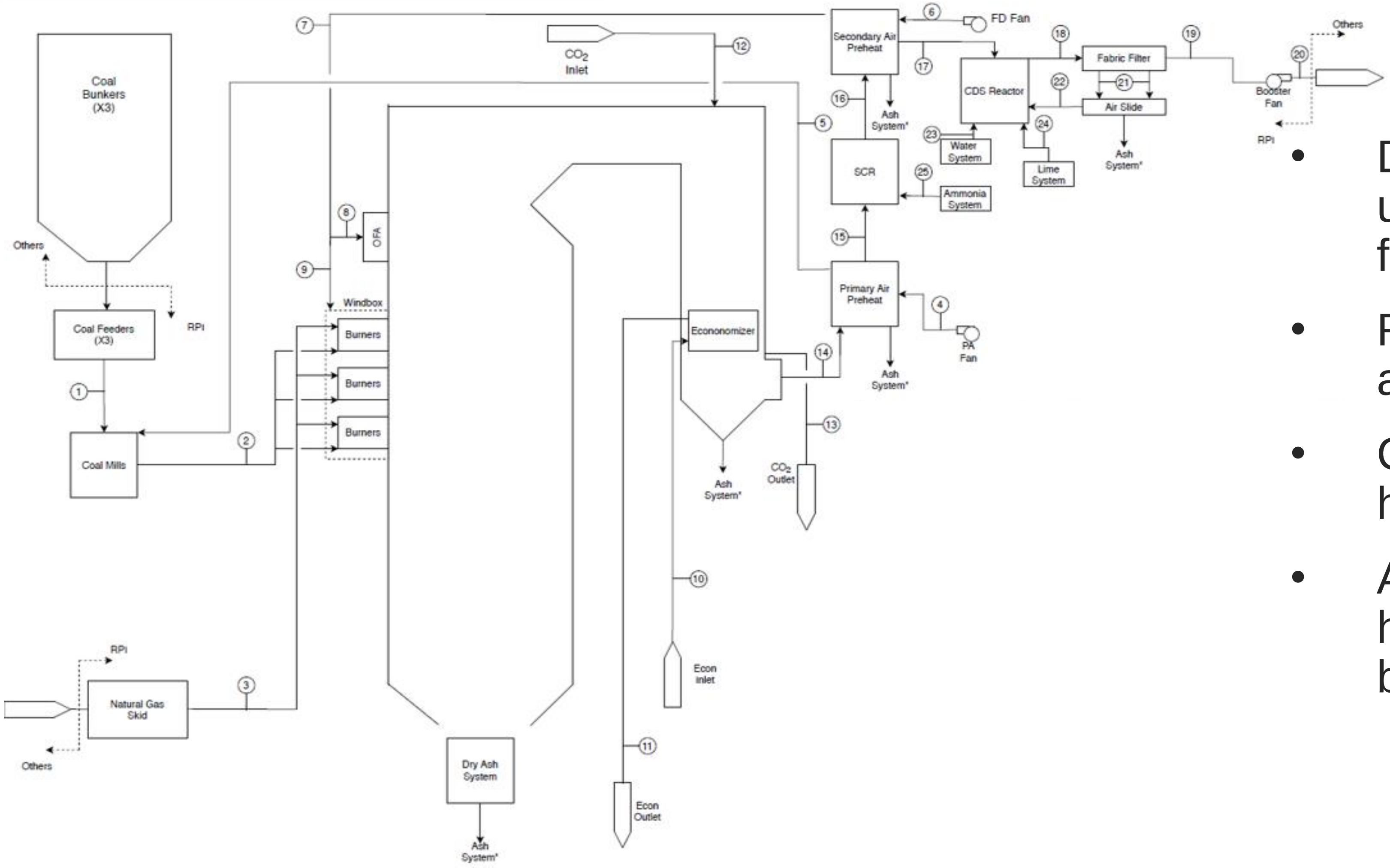
Air Fired PC Heater - Overview



- Designed similarly to a traditional utility steam boiler (CO_2 is utilized for wall cooling)
- Radiant furnace for combustion and final CO_2 heating (to 700°C)
- Convection pass for initial CO_2 heating – PHX2
- Air delivery system, AQCS, ash handling, fuel delivery and burners commercially available

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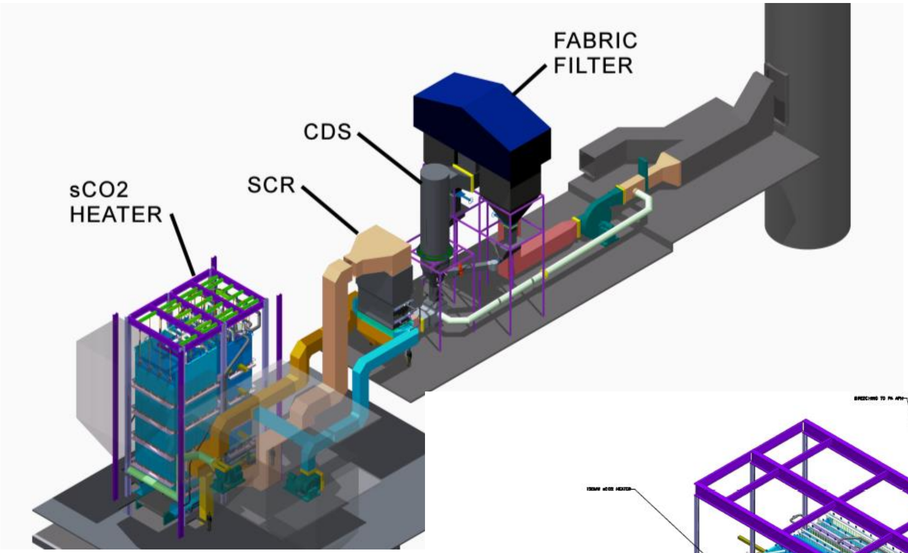
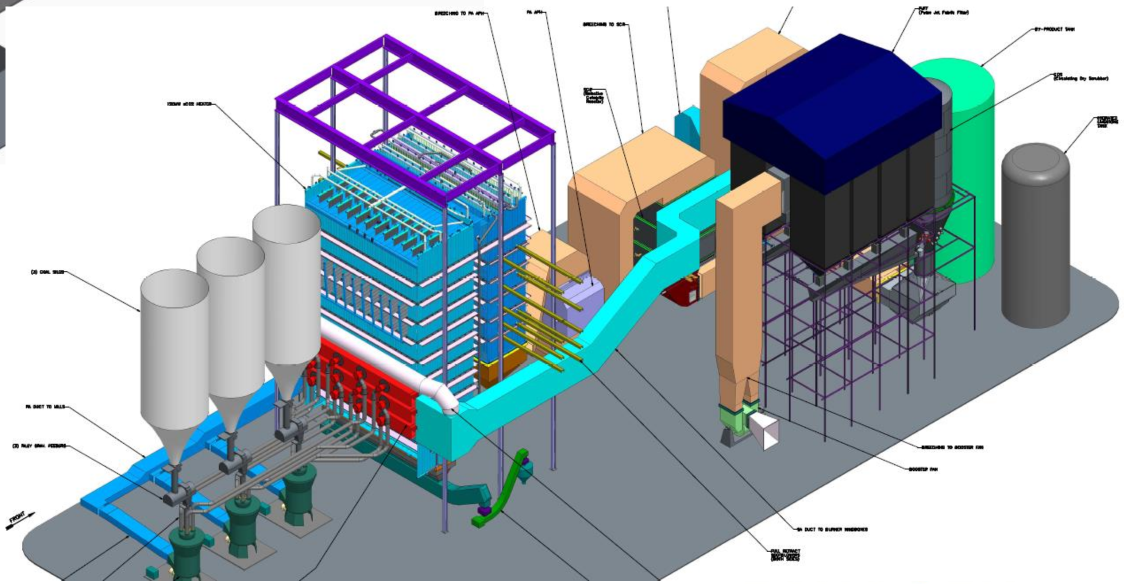
Fired Heater Risk Mitigated - LSP

- Operational
  - Design does not use traditional attemperation for CO_2 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 CO_2 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

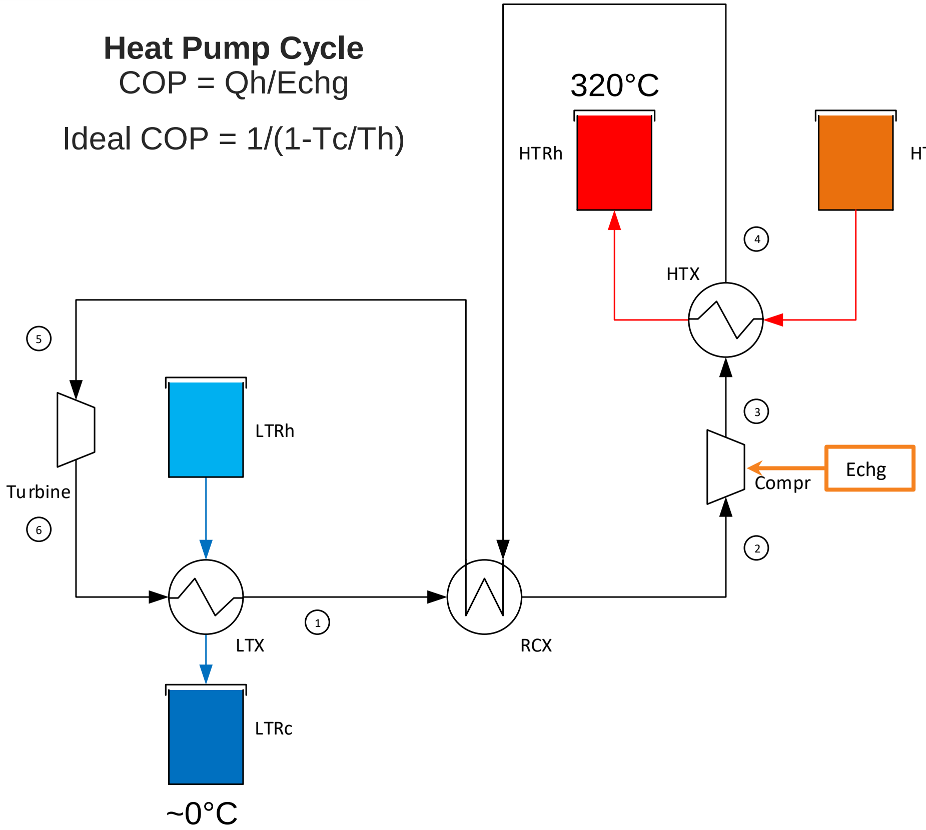




Electrothermal Energy Storage Overview

Heat Pump Cycle
COP = Qh/Echg

Ideal COP = 1/(1-Tc/Th)

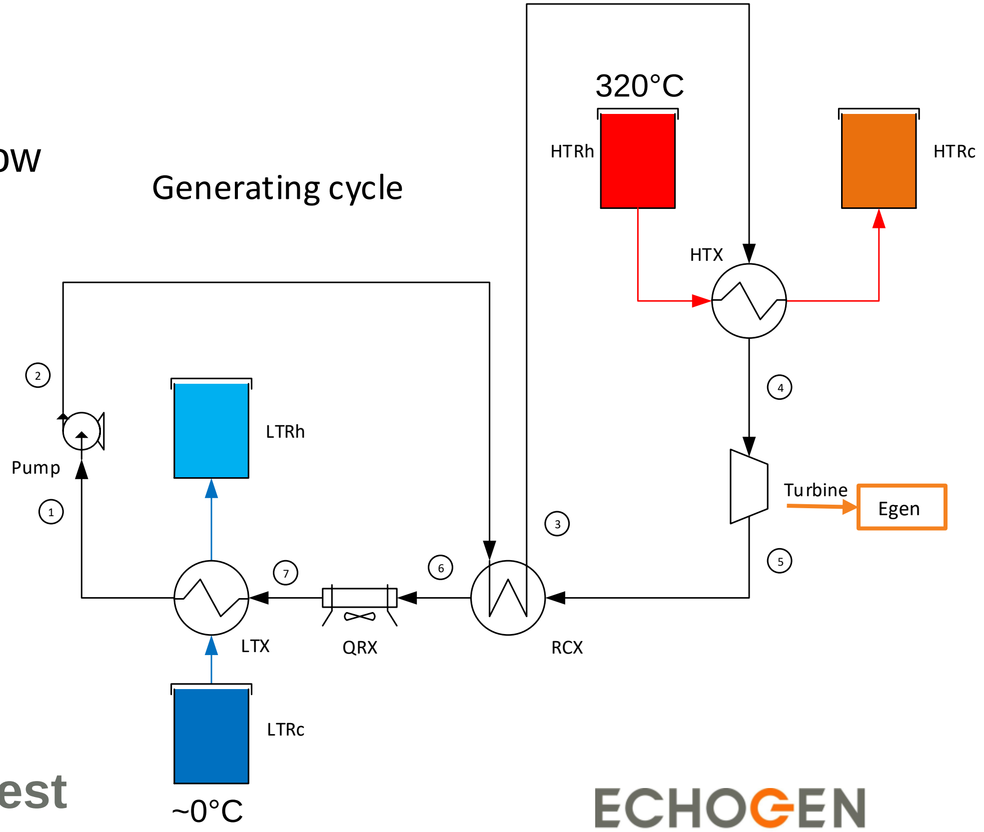


CO2 based ETES system

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

Power Cycle
Efficiency = Egen/Qh

Ideal efficiency = 1-Tc/Th



Overall Process
RTE = Egen/Echg

= COP x Efficiency

Ideal cycle RTE = $COP_{Carnot} \times \eta_{Carnot}$ = 100%

Non-ideal processes result in RTE ~60%, even at modest temperature ratio

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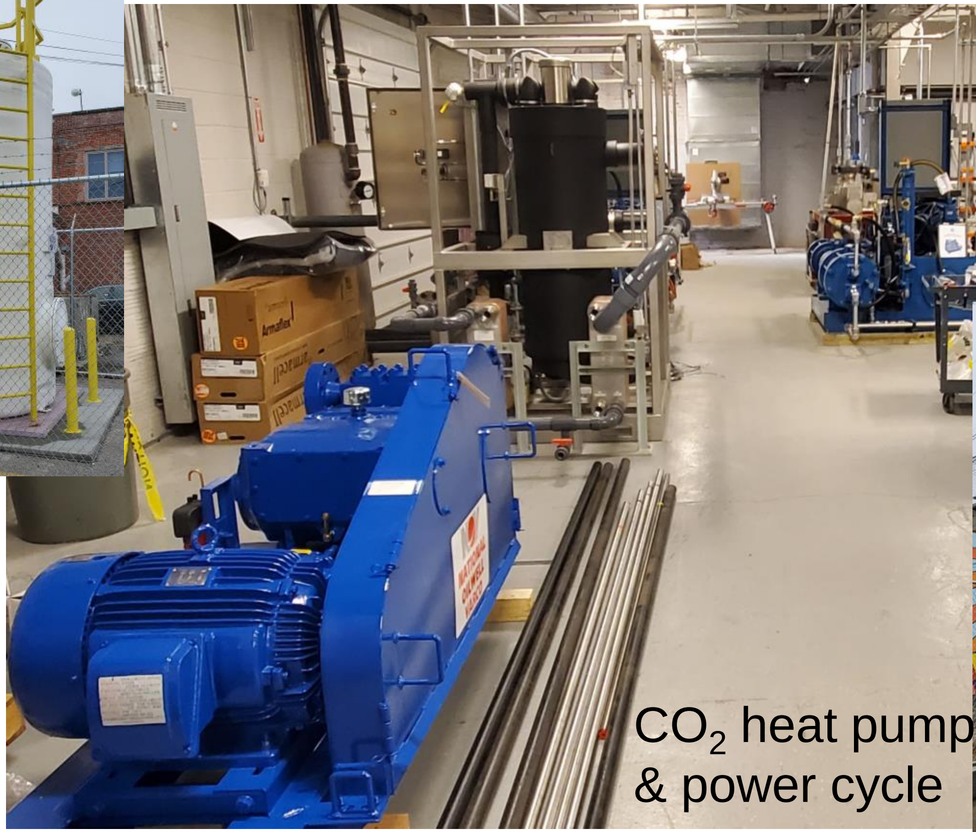
ARPA-E DAYS Program – ETES Proof of Concept

~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

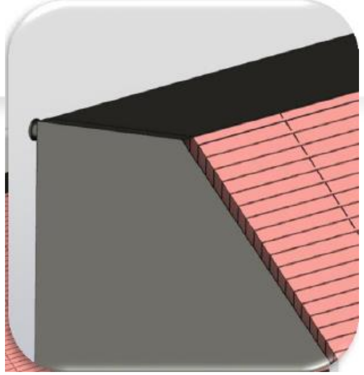
Primary developmental focus:

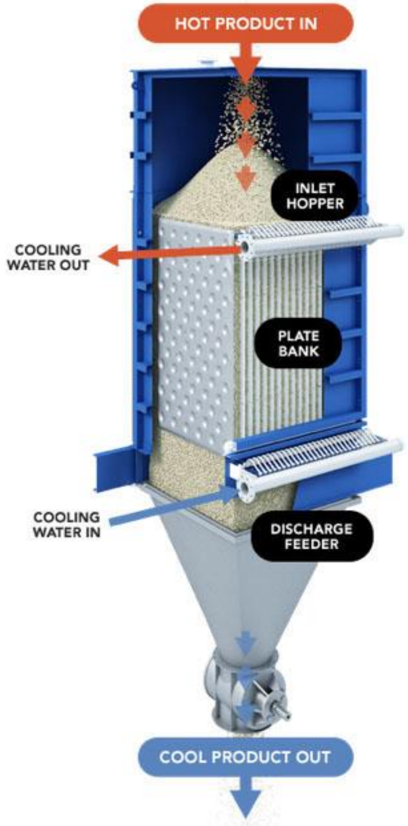
- HTSR and heat exchanger (TRL 4)
- LTSR performance (TRL 4)
- Operation and controls

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)

Westinghouse



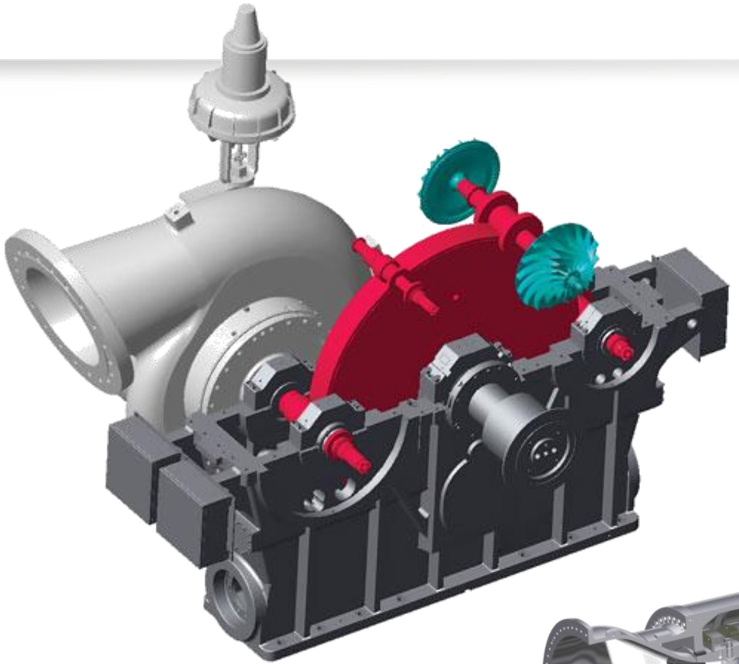


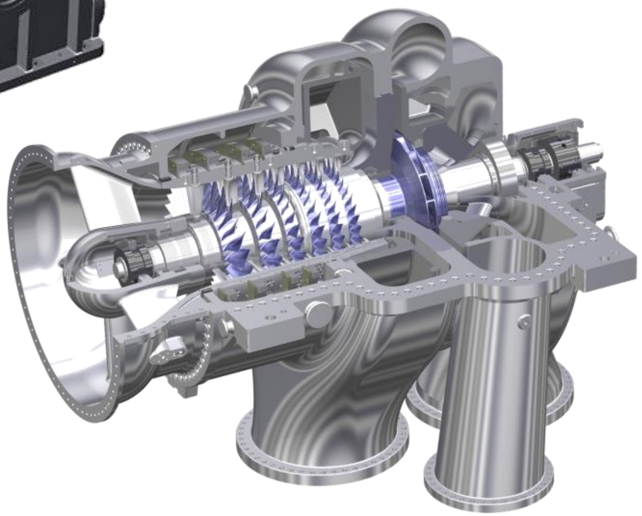
Solex MBHE

TU Wien FBHE

Charge compressor

- 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





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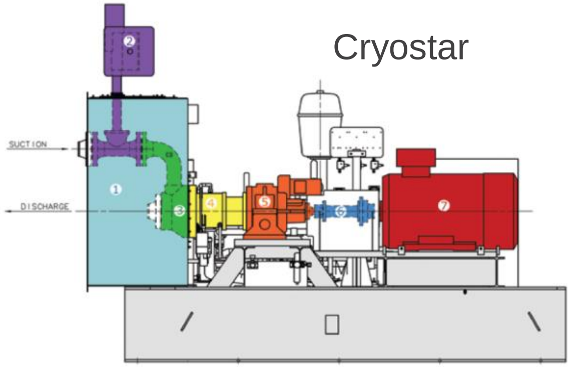
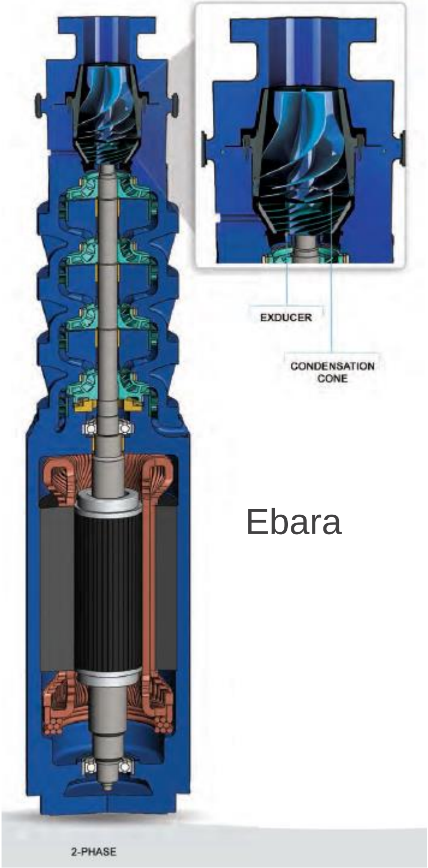
Charge cycle hydraulic turbine

- Similar to LNG expanders used in liquefaction
- Pressure, power within experience range
- Multiple manufacturers
  - Cryostar
  - Ebara
  - Flowserve

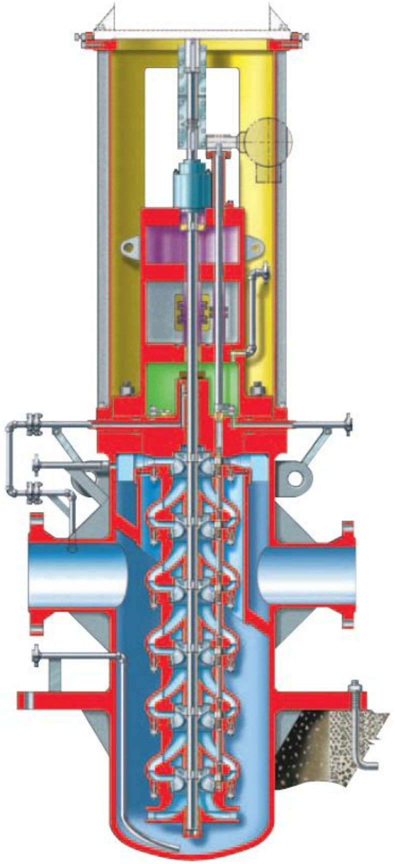


Cryostar



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

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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, CO_2 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 projects[1]
  - Political and public perception of funding coal projects

[1] https://www.banktrack.org/page/list_of_banks_which_have_ended_direct_finance_for_new_coal_minesplants

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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

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Detailed Design Plan and Timeline

Months	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
System																								
sCO2 Power Cycle Detailed Design	Preliminary Design (FEED)									Detailed Design														
Power Turbine		Preliminary Design								Detailed Design														
High Temperature Compressor		Preliminary Design								Detailed Design														
Low Temperature Compressor		Preliminary Design								Detailed Design														
High Energy Valves		Preliminary Design								Detailed Design														
ETES System	Preliminary Design (FEED)									Detailed Design														
Fired Heater	Preliminary Design (FEED)									Detailed Design														
Air Quality Control System			Preliminary Design (FEED)							Detailed Design														
Post Combustion Carbon Capture System	Preliminary Design (FEED)									Detailed Design														
Plant Engineering (Piping, Foundations, Buildings, Steam Supply)			Preliminary Design (FEED) Conclusion - Notice To Proceed										Detailed Design											
Site Permitting Scenario 2 or 3							Permitting (No Netting)																	
Site Permitting Scenario 4																	Permitting (Netting)							

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

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