Pre-FEED – Technology Gap Analysis

A Low Carbon Supercritical CO_2 Power Cycle / Pulverized Coal Power Plant Integrated with Energy Storage:

Compact, Efficient and Flexible Coal Power

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Project Partners

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1. Equipment Summary and Technology Gap Analysis

The PC/sCO$_2$/ETES power plant makes extensive use of proven technologies to limit technical risk and provide a clear path to commercialization. An inventory of key plant components and subsystem is shown in Table 1, along with an identification of commercial availability.

Table 1 Key plant components TRL summary

Subsystem	Component	Availability	TRL	Source
	Non-commercial components			
Power cycle				
	130 MW$_e$ power turbine	Scale-up from 100 MW	6	Siemens
	30 MW HT compressor	Scale from 4 MW	4	Barber Nichols
	18 MW LT compressor	Scale from 3 MW	5	EPS100, Barber Nichols
	Operation and control	Scale from 10 MW	4	Echogen
	High temperature turbine stop valve	Scale from 10 MW	4	Flowserve, Baker Hughes
Primary heat exchanger				
	Heat exchanger design	Scale from 10 MW	3	LSP
Energy storage system				
	Charging system turbine	Derivative	6	Ebara, Flowserve, Cryostar
	Generating system turbine	Scale-up from 10 MW	6	EPS100, Barber Nichols
	High-temp. exchanger (sand-to-CO_2)	Derivative	6	Solex
	Low-temperature reservoir	Derivative	6	Liquid Ice, BAC
	Commercial components			
Power cycle				
	15 MW LT compressor (alternate)	Liquid pump	9	Sulzer, Flowserve
	Recuperators	Commercial	9	Heatric, VPE
	Water-cooled cooler	Commercial	9	Heatric, VPE
	High temperature materials	Commercial	9	Special Metals, Haynes
	All others	Commercial	9	Various
Pulverized coal and natural gas combustor				
		Commercial	9	Riley Power
Primary heat exchanger				
	High-temperature materials	Commercial	9	Special Metals, Haynes
Emissions control system				
	NOX reduction catalyst	Commercial	9	Riley Power
	SO2/HCl scrubber	Commercial	9	Riley Power
	Particulate management (baghouse)	Commercial	9	Dustex or equivalent
Carbon capture system				
		Commercial	9	Mitsubishi
Energy storage system				
	Charging system compressor	Commercial	9	Siemens, Hanwha, etc.
	Recuperators	Commercial	9	Heatric, VPE
	High temp. exchangers (liquid-to-CO_2)	Commercial	9	Heatric, VPE
	Low-temp. exchangers	Commercial	9	Tranter, Alfa Laval
	High-temp. reservoir	Commercial	9	Silo or tank manuf.
	Generating system pump	Liquid pump	9	Sulzer, Flowserve

The components and subsystems that are not directly commercially available are discussed further, along with the technical development and risk abatement activities that are in place or planned.

Non-Commercial Components and Subsystems

130 MW_e power turbine

The sCO_2 power turbine is a modest scale-up of the 100 MW_e, 730°C inlet temperature turbine designed by Siemens during the DOE-funded "High-Efficiency Thermal Integration of Closed Supercritical CO_2 Brayton Power Cycles with Oxy-Fired Heaters" project[1] (DE-FE0025959). The turbine features a dual barrel design due to the high turbine inlet temperature with an axially-split outer barrel. A technology gap and risk assessment analysis were conducted by Siemens during the program. The two highest ranking risks were:

1) Rotating blade failure due to high unsteady/alternating stresses due to fluid density and pressure.
2) Materials long-term compatibility with sCO_2.

The identified risk mitigation strategy for these two items was:

1) Detailed transient CFD and forced response analyses to assess alternating stresses and update design as necessary.
2) Review literature to select best candidate materials and perform additional material compatibility testing, if required.

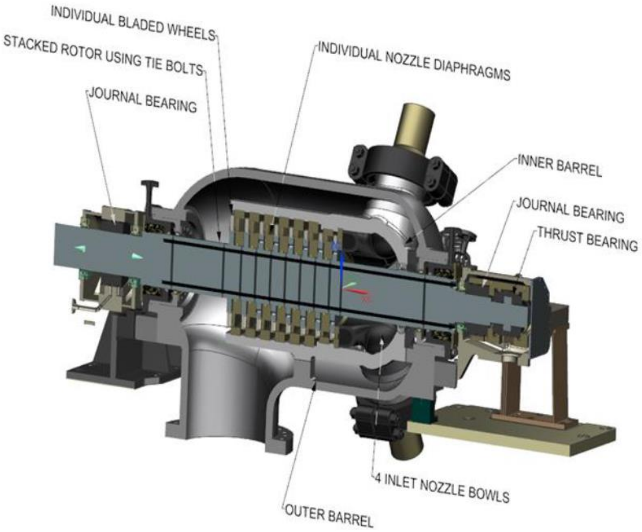

Figure 1: Siemens-designed 100 MW_e sCO_2 turbine (from DE-FE0025959).

Both these risk mitigation activities would be initiated at the next stage of the design process, which would occur once funding were assigned to develop the Coal FIRST system. We anticipate that Siemens or another OEM would be contracted to perform the design and fabrication of the power turbine.

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[1] Jason D. Miller et al., "Comparison of Supercritical CO_2 Power Cycles to Steam Rankine Cycles in Coal-Fired Applications," in *Proceedings of ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition* (Charlotte, North Carolina, USA: American Society of Mechanical Engineers, 2017), GT2017-64933; Andrew Maxson et al., "High-Efficiency Thermal Integration of Closed Supercritical CO_2 Brayton Power Cycles with Oxy-Fired Heaters," 2017; Andrew Maxson et al., "Integration of Indirect-Fired Supercritical CO_2 Power Cycles with Coal-Based Heaters," in *The 6th International Symposium - Supercritical CO_2 Power Cycles* (Pittsburgh, Pennsylvania, 2018).

18 MW Low Temperature Compressor (LTC)

The LTC compresses CO_2 from the water-cooled heat exchanger (CHX) outlet to the low-temperature recuperator (LTR) high-pressure inlet. The fluid properties at the LTC inlet are high density and low compressibility—very similar to an incompressible fluid. Thus, the operating characteristics of the LTC are similar to that of a liquid CO_2 pump. Echogen has previously designed, built and successfully tested the equivalent of a 3 MW LTC in their EPS100, which would require a relatively modest scaling to 18 MW for the current program.

Alternatively, the fluid properties are sufficiently liquid-like that Echogen has approached pump suppliers such as Sulzer, Flowserve and Ebara regarding the use of a conventional barrel-case style pump for LTC service. Provided sufficient suction margin is provided, this approach also appears feasible. The predicted isentropic efficiency of these pumps ranged from 76-84% at the design point, which is similar to the predicted and measured EPS100 compressor/pump performance (78-82%).

30 MW High Temperature Compressor (HTC)

Sometimes called the "bypass compressor" or "re-compressor", the HTC compresses CO_2 from the low-pressure outlet of the HTR to the high-pressure outlet of the LTR (effectively bypassing the LTR and CHX). The HTC operates over fluid conditions that are intermediate between the liquid-like properties at the LTC inlet and true ideal gas properties. The primary design path for the Coal FIRST HTC is a scaled version of a turbine-driven compressor that is being designed for the Large-Scale Pilot program, which in turn is a derivative of the LTC design.

Alternate designs are also being considered. At these conditions, the compressor could also be an industrial-style barrel-case or integrally-geared multistage design. As these are commercial devices, the technical risk of this approach is low. However, typical isentropic efficiency values of these compressors are in the 80-82% range, vs the predicted 86.4-87.3% range for the high-speed single-stage design. The efficiency of the power cycle would be approximately 1-2 percentage points lower with the industrial compressor design than the high-speed approach.

High temperature turbine stop valve

The turbine stop valve (TSV) is a key component to the sCO_2 power cycle. It is exposed to the highest CO_2 temperature and pressure and must close quickly in response to system trip signals, such as the loss of generator load, to avoid a power train overspeed situation. Echogen has successfully demonstrated a Flowserve high-speed TSV in their EPS100 testing at lower CO_2 temperature. The work in cast valve bodies discussed below also applies to the TSV, and Baker Hughes is developing a CO_2 TSV for the STEP program. In addition, the work that the AUSC program has conducted includes steam TSV development work that is directly relevant here. Much of the necessary development in this area consists of code modifications to permit the use of advanced materials such as Haynes 282 and Inconel 740H at the temperatures used herein.

Operation and control

Echogen has extensive experience in the operation and control of single turbo-compressor sCO_2 power cycles through its EPS100 development and test program[2]. The RCB cycle has one unusual feature relative to most existing Rankine and Brayton cycles—the use of two compressors in parallel. The first (and to date only) operating RCB configuration was the Sandia loop. In their experience, starting the two compressors represented operating challenges, and required simultaneous starting of the LTC and HTC to avoid driving the compression system into surge. While this process could be used here, analysis of the Sandia configuration shows that the starting challenges could have also been resolved through the use of

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[2] Timothy J. Held, "Initial Test Results of a Megawatt-Class Supercritical CO_2 Heat Engine," in *The 4th International Symposium - Supercritical* CO_2 *Power Cycles* (Pittsburgh, Pennsylvania, 2014).

independent bypass (or “anti-surge”) and isolation valves and controls, such as are planned for the current project. In addition, the transient modeling simulations that have been developed for the LSP and current projects allow for detailed operability modeling throughout the start and other operating modes.

In Echogen’s previous design studies and simulations, the heat source has most frequently been natural gas-fired combustion turbine (CT) exhaust for combined-cycle applications. The differences between that heat source and the coal-fired heater are two-fold. First, the heat source time constants are very long in both cases, but for the CT exhaust the sCO_2 cycle had no control over the heat source, while for the coal-fired system the heat source firing rate can be controlled by the sCO_2 cycle. Second, the heat source temperature for the coal-fired case is much higher than the CT exhaust, thus requiring continuation of CO_2 flow following a system trip in order to maintain primary heat exchanger material temperatures to stay within limits. Echogen is experienced in developing and executing Failure Modes, Effects and Criticality Analysis (FMECA) processes that are used to develop response plans for all foreseen failure modes.

We do not expect that the presence of the post-combustion carbon capture system will have a significant effect on the operation and control of the power cycle. Similarly, the planned implementation of the energy storage system allows for less maneuvering of the main power plant, with little to no effect on the main power plant control system.

Primary heat exchanger

The PHX has two technology development requirements. The materials used for the heat exchanger tubes and other components are already addressed in the “Materials, piping, tubing and valves” section above. The same materials are used in steam boilers, thus reducing the risk of unexpected problems with fire-side corrosion.

Due to the high working temperatures and pressures of the fluid, RPI has elected to design the majority of the heater components using Inco 740H. This material is a nickel-based alloy and has excellent strength in this operating region. This material is substantially more expensive than traditional tube materials, such as stainless steels, but allows for workable tube thicknesses and diameters.

The heat transfer design of the PHX is relatively challenging due to the higher volumetric flow rate required for an sCO_2 power cycle for the same power rating as a steam Rankine cycle. In addition, the lower pressure ratio of the sCO_2 cycle increases its sensitivity to pressure drop in the PHX relative to a steam Rankine cycle. The simultaneous management of the pressure drop, and heat transfer design requires an integrated cycle-level optimization process. Echogen and Riley Power are presently collaborating in the LSP program including development and refinement of this optimization process. The learnings from that program will directly impact the design process for this program.

The LSP program is presently in the Front-End-Engineering-Design (FEED) phase of the program and RPI has completed the preliminary design of the coal fired – sCO2 heater. The FEED study will be completed in August of 2020, and a competitive down select of projects will be undertaken by the DOE for Phase III awards with announcements expected October of 2020. Detailed design of the fired heater (power cycle and balance of plant) will commence in January 2021, with material procurement and fabrication beginning in the 2nd quarter. Commissioning of the system is expected to begin in January 2023, with full load operation beginning in June. With operational data being available in 2023 to support the design of the commercial scale fired heater, a 2030 commercial deployment is easily achievable and could be as soon as 2026 if financing becomes available.

The proposed heater design is based on a traditional utility scale steam boiler, with a furnace and a separate convective backpass. The element design of the backpass is a series of serpentine elements, designed to be fully drainable. These elements are stringer supported, with the coldest fluid cooling the stringers to provide maximum strength. Economizer elements are in-line with the primary convective elements and can share the same stringers for support.

Economizer tubes are finned to maximize heat transfer and minimize the amount of material required. Bare tube economizers may be considered following additional fuel analysis to reduce potential for ash buildup and soot-blowing requirements. Due to the lower working temperatures of the economizer elements, these will be fabricated of a stainless alloy to reduce overall project cost.

RPI anticipates no significant issues with the fabrication of the convective elements, though care will be taken to ensure welding procedures and heat treatment as adequate for the Inco 740H materials.

The furnace and backpass walls are CO_2 cooled, and will be the highest temperature components of the heater. Tube size and spacing has been selected to match known fabrication standards, but RPI has not fabricated membrane walls using Inco 740 materials. This will require additional development, to ensure the panels can be effectively welded without significant warping or cracking. Field welds for this material will be minimized, due to the strict welding requirements.

To improve overall efficiency and maximize radiant absorption, RPI is including platens in the upper section of the furnace. These platens are fully drainable and are on wide spacing to prevent issues with ash bridging due to the high metal temperatures, as well as maximizing the radiant exposure. RPI does not anticipate issues with fabrication of these elements.

Because of the relatively large volumetric flow rates require, large diameter piping for headers may be required to maintain the low target pressure drop. RPI currently plans to use Inco 740, though this is under review for possible cost reduction. The high pressures will require thick walls for all of these components, and fabrication and welding will need to be closely monitored for this material.

Energy Storage System

The electro-thermal energy storage (ETES) system is a new technology that Echogen is developing in part through DOE ARPA-E funding. Many of the key components are commercially available or are derivatives of those developed for sCO_2 power cycles. Echogen is presently designing a 10 MW_e, 8-hour ETES demonstration plant that is anticipated to be in operation in the 2022-time frame. This demonstration plant will provide significant risk abatement for the ETES system proposed here.

Charging system turbine

The turbine in the charging cycle is a hydraulic turbine, where the liquid “flashes” to vapor near the turbine exit. Although CO_2 turbines of this type are not commercially available, in the last 25 years, hydraulic turbines have been introduced into the natural gas liquification process and are regularly employed to improve the overall process efficiency[3]. Initial discussions with Ebara Turbine indicate that the charging system turbine is a relatively simple modification to their product line, thus reducing the risk for this component.

Generating system turbine

The turbine is a derivative of the sCO_2 power cycle turbines described above. The inlet temperature of 300°C is modest, allowing for low-cost materials of construction.

High temperature reservoir and heat exchangers

Three alternative reservoir and heat exchanger technologies are being developed for the ETES system. One, discussed below, is a commercial system. The non-commercial alternatives are described here.

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[3] Hans E Kimmel and Simon Cathery, “Thermo-Fluid Dynamics and Design of Liquid-Vapour Two-Phase LNG Expanders,” in *Gas Processors Association-Europe, Technical Meeting, Advances in Process Equipment,* (Paris, France, 2010).

One approach uses a stationary concrete thermal mass[4] as the thermal storage medium while using a much smaller quantity of HTF (Duratherm HF) as an intermediate medium between the CO_2 and concrete. As with the commercial approach, the heat exchanger between the HTF and CO_2 is a conventional PCHE. The concrete thermal masses include cast-in fluid passages, enabling direct-contact heat transfer between the HTF and concrete. The HTF tanks, pumps and controls are all commercially available components. Echogen is partnered with Westinghouse Nuclear under ARPA-E program DE-AR0000996 to conduct design and techno-economic optimization of the concrete-based solution.

Another approach uses silica sand as both the heat transfer and storage medium. The storage containers would be conventional concrete silos or dome structures[5]. The sand transport process is a combination of conventional and high-temperature conveyors[6]. The heat exchanger between CO_2 and sand is planned to be either a moving-bed heat exchanger (MBHE)[7] or fluidized bed heat exchanger (FBHE)[8]. The MBHE is a commercially-available technology[9], although not at the pressures required for CO_2-based power cycles—however, development work on a CO_2-capable MBHE is underway under two DOE-funded programs, for CSP applications[10] and Echogen's ETES program in partnership with Solex Thermal Sciences under DE-AR0000996. The FBHE is based on well-known heat transfer principles and design methods from fluidized bed combustion. Echogen is also partnered with TU Wien on DE-AR0000996.

At the conclusion of the first phase of DE-AR0000996, scheduled for mid-year 2020, Echogen will down-select between the concrete- and sand-based high-temperature reservoirs to test in their laboratory-scale (200 kWth) ETES system. Following successful lab-scale testing in 2021, Echogen plans to scale the high-temperature reservoir to the 10 MW_e demonstration plant for further design validation testing. The concrete/HTF system is inherently modular and thus freely scalable. The two sand solutions also are modular in nature, in that multiple heat exchangers in parallel are frequently employed in industrial applications.

Low-temperature reservoir (LTR) and heat exchangers

Similar to the high-temperature reservoir, Echogen is evaluating two different LTR configurations, both using water-ice phase change as the reservoir material. The first, lower-risk approach is to use a stationary

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[4] Cory Stansbury, Energy storage device, US PTO US 2018/0372423 A1, filed May 15, 2018, and issued December 27, 2018.

[5] Benjamin Davis, "Holcim New Zealand Cement Terminal," *Shotcrete Mag.* 19, no. 1 (2017): 26–30.

[6] "The Magaldi Superbelt Conveyor | Magaldi Group," accessed January 9, 2020, https://www.magaldi.com/en/about-us/the-magaldi-superbelt-conveyor.

[7] Pedro Isaza, W. David Warnica, and Markus Bussmann, "Thermal Performance and Sizing of Moving Bed Heat Exchangers," in *ASME 2014 International Mechanical Engineering Congress and Exposition*, (Montreal, Quebec, Canada: American Society of Mechanical Engineers, 2014); Philipp Bartsch and Stefan Zunft, "Heat Transfer in Moving Bed Heat Exchangers for High Temperature Thermal Energy Storage," in *SOLARPACES 2016: International Conference on Concentrating Solar Power and Chemical Energy Systems* (Abu Dhabi, United Arab Emirates, 2017).

[8] K Schwaiger et al., "SandTES-A Novel Thermal Energy Storage System Based on Sand," in *21st International Conference on Fluidized Bed Combustion,* (Naples, Italy, 2012); Martin Haemmerle et al., "Saline Cavern Adiabatic Compressed Air Energy Storage Using Sand as Heat Storage Material," *Journal of Sustainable Development of Energy, Water and Environment Systems* 5, no. 1 (March 2017): 32–45.

[9] "Solex Thermal Sciences | Energy Efficient Heat Exchanger Technology," Solex Thermal Sciences, accessed January 9, 2020, https://www.solexthermal.com/.

[10] Clifford K Ho et al., "Evaluation of Alternative Designs for a High Temperature Particle-to-SCO_2 Heat Exchanger," in *Proceedings of the ASME 2018 12th International Conference on Energy Sustainability* (Lake Buena Vista, Florida, USA: ASME, 2018).

ice-on-coil thermal reservoir[11] with either direct heat transfer to and from CO_2 in embedded heat exchangers, or by using a separate HTF system to transfer heat between the LTR and CO_2. The second approach uses an ice slurry generator (ISG) to create a fluid ice/water mixture that can be stored in a separate tank and pumped similarly to a liquid up to approximately 30% ice fraction, which is the storage system design target[12]. The advantage of this approach is that the heat exchanger scaling is decoupled from the storage medium and containment, which improves the scalability of the LTR. ISGs are commercially available, but generally using conventional F-gas and similar refrigerants[13]. Echogen is partnered with Liquid Ice Technologies, a commercial provider of ice slurry generators, to develop a prototype CO_2-based ISG as part of DE-AR0000996. A down-selection to the final configuration based on a full techno-economic analysis and the results of the ARPA-E program testing will be made in mid-2021.

Because the slurry formation process is different from the melting process, a separate low-temperature heat exchanger is used during the generating process. Provided that the ice particle size within the slurry is appropriately maintained, conventional plate-based heat exchangers can be used with slurries[14].

Commercial Components and Subsystems

Recuperators and CHX

These heat exchangers are all of the "Printed Circuit Heat Exchanger" (PCHE) type[15]. The developer and first supplier of PCHEs is Heatric, a division of Meggitt, who has supplied them to the oil and gas industry for over 40 years. Additional suppliers, such as Vacuum Products Engineering (VPE) and CompRex have recently entered the market, helping to diversify the supply chain and provide pricing competition. Echogen and others have used PCHEs from Heatric and VPE in sCO_2 power cycles at scales up to 10 MW_e. Heat exchangers of these types are extremely modular, and thus scalability is straightforward.

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[11] Michael Rutberg et al., "Thermal Energy Storage," *ASHRAE Journal* 55, no. 6 (June 2013): 62--66.

[12] Michael Kauffeld, Masahiro Kawaji, and Peter W. Egolf, eds., *Handbook on Ice Slurries—Fundamentals and Engineering* (International Institute of Refrigeration, 2005)

[13] Michael Kauffeld and Sebastian Gund. 2019. "Ice Slurry – History, Current Technologies and Future Developments." *International Journal of Refrigeration* 99:264–271.

[14] Beat Frei and Tahsin Boyman, "Plate Heat Exchanger Operating with Ice Slurry," in *PCM.2003 Phase Change Material and Slurry, Scientific Conference and Business Forum*, (Yverdon, Switzerland, 2003).

[15] Renaud Le Pierres et al., "Impact of Mechanical Design Issues on Printed Circuit Heat Exchangers," in *Supercritical* CO_2 *Power Cycle Symposium* (Boulder, Colorado, 2011).

Materials, piping, tubing and valves

Extensive studies of material compatibility with CO_2 have been conducted by Oak Ridge National Laboratory (ORNL)[16], University of Wisconsin Madison (UWM)[17] and others[18]. Echogen has direct contact with the researchers at these and other labs. In general, CO_2 does not create unique corrosion problems with most commonly used piping and heat exchanger materials in the temperature ranges they would normally be used due to their material strength and creep properties. At the highest temperatures used in this project (700-730°C), appropriate materials have been developed under the auspices of the Advanced Ultra Super-Critical (AUSC) steam development program[19] and their performance with CO_2 verified in ORNL testing.

A key remaining development activity is the qualification of Haynes 282 as a cast material for components such as valve bodies. This work is presently being performed under the STEP program[20]. Echogen has discussed the use of the combined turbine throttle/stop valve with GE and has received a favorable response to extending their development work to this program.

Note that Echogen has worked with Haynes and Special Metals on previous programs, including the use of Inconel 740H in the high-temperature sCO_2 heater developed under the DOE-funded TCES program, "sCO_2 Power Cycle with Integrated Thermochemical Energy Storage Using an MgO-Based sCO_2 Sorbent in Direct Contact with Working Fluid" (DE-EE0008126).

Fuel systems

RPI proposes using Atrita ® pulverizers. These are standard components and are widely used for smaller scale plants.

The firing system be designed with dual fuel burners, capable of achieving full load on pulverized coal and natural gas. These are standard RPI designs and are deployed in multiple existing utility boilers. These burners will provide fuel flexibility throughout the life of the unit.

RPI has extensive experience designing and supplying natural gas combustion systems, and will include a pressure regulating skid, as well as double block and bleed skids for each burner. The natural gas system will meet all standards, such as NFPA 85.

Emissions control system

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[16] B.A. Pint, R.G. Brese, and J.R. Keiser, "Supercritical CO_2 Compatibility of Structural Alloys at 400°-750°C," in *NACE Corrosion 2016 Conference and Expo*, 2016; Bruce A. Pint, Kinga A. Unocic, and James R. Keiser, "Effect of Impurities on Supercritical CO_2 Compatibility," in *Proceedings of 3rd European Supercritical CO_2 Conference* (Paris, France, 2019).

[17] Jacob Mahaffey et al., "Effect of Oxygen Impurity on Corrosion in Supercritical CO_2 Environments," in *The 5th International Symposium - Supercritical* CO_2 *Power Cycles* (The 5th International Supercritical CO_2 Power Cycles Symposium, San Antonio, Texas, 2016); Kumar Sridharan et al., "Corrosion of Candidate Alloys in High Temperature Supercritical Carbon Dioxide," in *Supercritical* CO_2 *Power Cycle Symposium* (Boulder, Colorado, 2011).

[18] Julie D Tucker et al., "Supercritical CO_2 Round Robin Test Program," in *The 6th International Symposium - Supercritical CO_2 Power Cycles* (Pittsburgh, Pennsylvania, 2018).

[19] Paul S Weitzel, "A Steam Generator for 700 C to 760 C Advanced Ultra-Supercritical Design and Plant Arrangement: What Stays the Same and What Needs to Change," in *The Seventh International Conference on Advances in Materials Technology for Fossil Power Plants* (Waikoloa, Hawaii, 2013).

[20] Marion et al., "The STEP 10 MW_e SCO_2 Pilot Plant Demonstration," in *The 6th International Symposium - Supercritical CO_2 Power Cycles* (Pittsburgh, Pennsylvania, 2018).

The emissions controls for this plant are conventional and are commercially available. Riley Power will supply the emission control system for this plant.

RPI is a leading supplier of SCR technology and has a wide install base on standard units. The design of this unit will meet all RPI standards for flue gas flows and temperatures and will utilize standard catalysts to achieve the target emissions.

RPI has multiple installed circulating dry scrubbers (CDS), across a range of boiler sizes. This unit will achieve the target emissions values, using a proven technology. As a Dry scrubber, all water injected into the system is converted to vapor, eliminating the need for slurry systems and other water handling equipment that would be seen on a traditional wet scrubber.

A fabric filter is an integral part of the CDS system. The operating conditions for the fabric filter are typical, and this equipment will be sourced from a well-known vendor such as Dustex or equivalent. Air slides will also be utilized for ash and byproduct recirculation. RPI has developed a pneumatic conveyor, which will be used to transport ash from the fabric filter to the CDS reactor.

CO_2 capture system

The PCCC system for this plant is a commercial product from Mitsubishi, a partner in this program.

ETES components: Charging system compressor

The compressor is a key component of the charging heat pump cycle. The operating conditions are conventional for a non-intercooled industrial gas compressor, and several commercial suppliers can provide equipment that meets the specification requirements. At the approximately 30 MW_e power rating of this program, the compressor would likely be of the integrally-geared type [21]. Commercial suppliers of this type of compressor have indicated that single compressors of up to 50 MW_e are within the current range of their product line. Echogen has had direct discussions with both Siemens and Hanwha for similar compressor applications

Generating system pump

The pump inlet conditions are subcritical, with a true liquid CO_2 phase. The operating conditions are well within the capability of commercial pump suppliers such as Sulzer and Flowserve, both of whom have provided quotations for Echogen on similar projects.

Recuperator

The operating conditions for the recuperator are similar to those used in the sCO_2 power cycle—thus the same comments as provided in the previous section also apply here.

High temperature reservoir and heat exchangers

The lowest technical risk HTR is a two-tank system using a conventional heat transfer fluid (HTF, such as Duratherm HF, Therminol or DowTherm) as both the heat transfer and thermal storage medium. The heat exchanger for this system would be a conventional PCHE, similar to the recuperator and CHX heat exchangers described above. The storage containers are conventional insulated oil tanks. The capital expense of this approach is the highest of the three alternatives.

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[21] Christian Wacker and René Dittmer, “Integrally Geared Compressors for Supercritical CO_2,” in *The 4th International Symposium - Supercritical* CO_2 *Power Cycles* (Pittsburgh, Pennsylvania, 2014).