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INTEGRATED THERMAL ENERGY STORAGE AND BRAYTON CYCLE EQUIPMENT DEMONSTRATION (INTEGRATED TESTBED) PROJECT DESIGN BASIS

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Matt Carlson is currently the Project Chief Engineer for Capella and Principal Investigator for TESTBED working to deploy a first of a kind modular particle-sCO_2 concentrating solar power generation product. Before joining Heliogen Matt worked at Sandia National Labs for over a decade on space nuclear, terrestrial nuclear, and concentrating solar power systems including some of the first integrated sCO2 power systems and particle-sCO2 heat exchangers.

Amanda Gold received a Bachelor of Science from the University California Santa Barbara in Chemical Engineering and is PMP certified. Amanda has over 15 years of experience managing concentrated solar power (CSP) and photovoltaic power projects, including contract and scope development, schedule, budget, construction supervision, operation and maintenance plans and performance analysis. She currently works as the Project Manager of Heliogen's Capella Concentrated Solar Energy Project.

ABSTRACT

The Integrated Thermal Energy Storage and Brayton cycle Equipment Demonstration (Integrated TESTBED) project seeks to retire commercial-scale risks associated with the design, integration, and operation of a supercritical carbon dioxide ($sCO_{2)}$ power cycle and concentrating solar power (CSP) thermal energy storage (TES) system. This requires an understanding of commercial-scale collector system transient impacts on the TES system, the dynamics of heat exchange from the

TES to the power cycle, and the control and operation of the power cycle to accommodate various dispatch strategies.

In order to retire these risks, Heliogen has proposed to construct a 5 MWe CSP demonstration facility based on directly heated particle and sCO_2 technology. The receivers, primary heat exchanger, and power cycle will be deployed at a full commercial scale based on Heliogen's modular plant architecture to ensure actual system integration risks are validated during design, construction, and operation.

This work summarizes the design basis for the Integrated TESTBED project demonstration facility including a design target for capacity factor to support test operations, hours of storage, particle silo arrangement, centrifugal article receivers, a diffusion bonded particle-sCO_2 heat exchanger, and a 5 MWe (net) integrally geared sCO_2 recompression Brayton cycle.

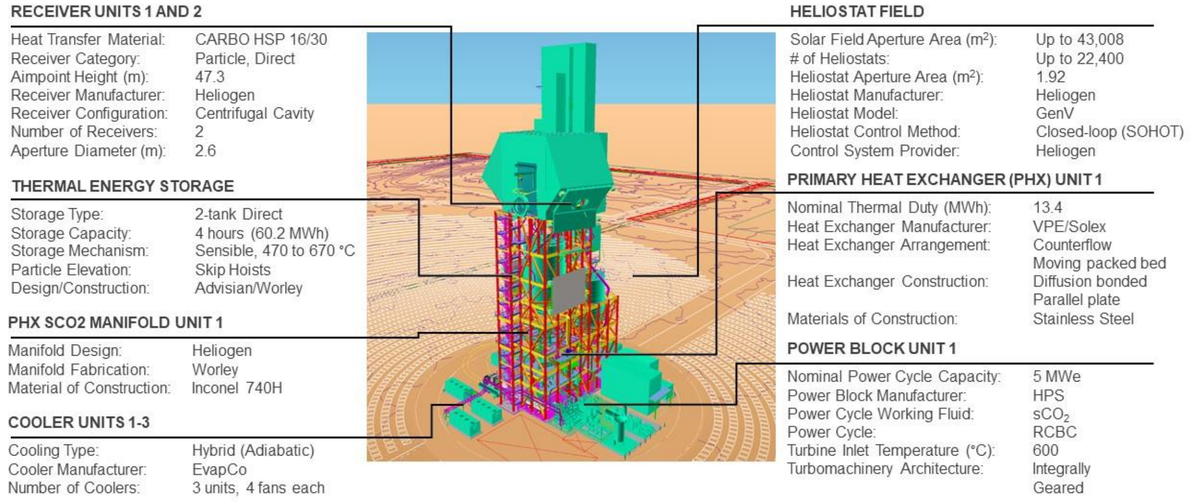
INTRODUCTION

Heliogen's Capella Concentrated Solar Energy Project (CSEP) project, encompassing the TESTBED project, aims to successfully demonstrate the following aspects of system integration typically found in a commercial concentrated solar plant:

1. Normal daily operation of the heliostat field.
2. Control of the solar flux into the receiver for safe operation by Heliogen's field control software.
3. Integration of Heliogen's centrifugal particle receiver and thermal energy storage (TES) technologies with a commercial scale particle heat exchanger (PHX) and a 5 MWe power generation system.

4. Demonstrate commercial operability targets, including transients, solar peak fluxes, start-up, ambient temperature ranges, and partial load operation informed by DOE TESTBED program targets.

To this end, this plant is designed for twenty-five years with 100,000 hrs. of operation and 18,750 and 7,000 start/stops for the charging and discharging equipment, respectively. By using up to 22,000 AI-controlled heliostats, sintered bauxite CARBO particles will be heated to a designed set point temperature of 675 °C by two particle receivers operating in parallel located in the central tower. These high-temperature particles will be used as both the heat transfer fluid (HTF) and thermal energy storage (TES) media throughout the system. Using a modular shell and plate particle heat exchanger (PHX), stored energy within hot particles will be transferred to a 5 MWe supercritical CO_2 (sCO_2) power generation system. In addition to the plant's continuous daytime operation CSEP will provide 4 hours of stored energy for operation of the power generation cycle independent from the solar energy input. The Capella plant configuration and subsystem specifications are summarized in Figure 1:



RECEIVER UNITS 1 AND 2

Heat Transfer Material:	CARBO HSP 16/30
Receiver Category:	Particle, Direct
Aimpoint Height (m):	47.3
Receiver Manufacturer:	Heliogen
Receiver Configuration:	Centrifugal Cavity
Number of Receivers:	2
Aperture Diameter (m):	2.6

THERMAL ENERGY STORAGE

Storage Type:	2-tank Direct
Storage Capacity:	4 hours (60.2 MWh)
Storage Mechanism:	Sensible, 470 to 670 °C
Particle Elevation:	Skip Hoists
Design/Construction:	Advisian/Worley

PHX SCO2 MANIFOLD UNIT 1

Manifold Design:	Heliogen
Manifold Fabrication:	Worley
Material of Construction:	Inconel 740H

COOLER UNITS 1-3

Cooling Type:	Hybrid (Adiabatic)
Cooler Manufacturer:	EvapCo
Number of Coolers:	3 units, 4 fans each

HELIOSTAT FIELD

Solar Field Aperture Area (m^2):	Up to 43,008
# of Heliostats:	Up to 22,400
Heliostat Aperture Area (m^2):	1.92
Heliostat Manufacturer:	Heliogen
Heliostat Model:	GenV
Heliostat Control Method:	Closed-loop (SOHOT)
Control System Provider:	Heliogen

PRIMARY HEAT EXCHANGER (PHX) UNIT 1

Nominal Thermal Duty (MWh):	13.4
Heat Exchanger Manufacturer:	VPE/Solex
Heat Exchanger Arrangement:	Counterflow Moving packed bed
Heat Exchanger Construction:	Diffusion bonded Parallel plate
Materials of Construction:	Stainless Steel

POWER BLOCK UNIT 1

Nominal Power Cycle Capacity:	5 MWe
Power Block Manufacturer:	HPS
Power Cycle Working Fluid:	sCO_2
Power Cycle:	RCBC
Turbine Inlet Temperature (°C):	600
Turbomachinery Architecture:	Integrally Geared

Figure1: Plant's key metrics and subsystem specifications

In the following sections, a general description of these subsystems and their interactions is provided.

RESULTS AND DISCUSSION

The plant can be divided into the following subsystems:

- Heliostat Field
- Particle Loop
- Tower
- Power Generation
- Balance of Plant (site)

A plant control system (PCS) oversees the operational status of the entire plant, translating the input signals to a corresponding action signal for the plant's related components and subsystems. The PCS also ensures proper coordinated control between different plant systems, such as the field control and turbine control systems, during state transition or emergency cases. The plant's subsystem interactions are visualized in the following block flow diagram in Figure 2.

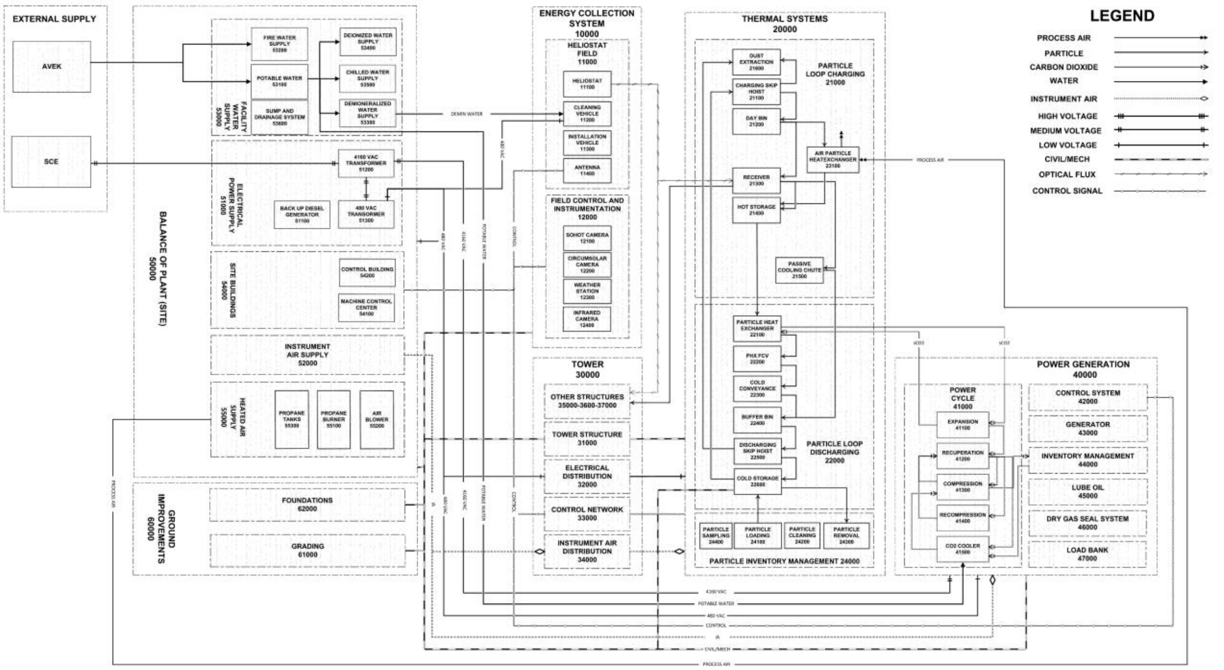


Figure 2: Block Flow Diagram visualizing the subsystem interactions.

Below is a list of the main components for various plant subsystems, along with a brief operational description for each.

HELIOSTAT FIELD: The heliostat field consists of up to 22,000 Generation 5 heliostats manufactured by Heliogen and controlled by a closed-loop heliostat tracking control system. Heliostat control cameras are located above and below the receivers to provide continuous automated calibration. Wireless distribution will be adopted for power (photovoltaic), control, and communication to the heliostats in the solar field. Two inputs are communicated to the Plant Control System (PCS) from the heliostat field including (1) the field's max available flux, Qmax (100% field capacity) at that point in time, which is calculated internally by the field control system based on the available solar direct normal irradiance DNI and its forecast and (2) the required time for transition between the current flux value and the particle receiver's requested one. The first interaction type limits the possible requested thermal duty demand from the particle CenRec receiver. Based on the field's response time limitation communicated through (2), a proper action set can be designed for various plant operation scenarios and mode transitions.

PARTICLE LOOP: This system consists of components that convert the input solar energy from the heliostat field to hot particles with a defined set temperature. The stored particles provide thermal energy to the power generation cycle through the particle heat exchanger. Based on functionality, the particle loop can be divided into charging and discharging subsystems. These two subssystems can operate independently or simultaneously, depending on the availability of solar radiation, current storage capacity, and other variables.

RECEIVER CHARGING SKIP HOIST: A single skip hoist system transfers cold particles (at 470 °C) from the cold storage silo to the receiver feed bin (day bin) at the top of the tower. The variable speed of the skip hoist enables control of the particle level inside the bin during different modes of operation. The discharge connections from the bin are as follows.

RECEIVER FEEDER BIN (DAY BIN): A bin at the top of the tower will receive the particles at a nominal temperature of 470 °C from the charging skip hoist system. During regular operation, the bin is designed to maintain a minimum level of particles and ensure a steady flow to each receiver. Two motorized flow control valves near the bin regulate the flow rate to each receiver to its nominal and start-up values. Load cells will be added to the day bin for periodic calibration of the feed control valves.

A bypass line for the two receivers has also been implemented which enables a direct connection between the day bin and the hot silo. Additionally, this bypass route allows for the supply of 470 °C particles directly to the heat exchanger's inlet hopper when needed.

RECEIVER (S): Centrifugal particle receivers comprise tilted rotating drums which spin fast enough to cause particles to form a film on the inner surface through centrifugal force. CARBO particles are fed to the back of the drum through a particle infeed accelerator constructed from an angled inlet pipe. Control over the drum rotational speed creates a stable film on the drum's inner surface resulting from the balance between gravitational and centrifugal forces. The film thickness is controlled by adjusting the particle mass flow rate and the drum's rotational speed for a fixed tilt angle. After achieving a uniform film, the solar flux is directed towards the front aperture from the heliostat field. As a result, the temperature of the particle film surface increases and is then equilibrated throughout the entire thickness of the film primarily through conduction and advection. The heated particles move in the axial direction of the drum with the help of gravity. Subsequently, the particles are collected in the receiver collector ring and transported to the hot storage via a chute. The receiver outlet temperature can be controlled by adjusting the solar flux or particle film thickness. The receiver control strategy aims to maximize energy collection. Thus, increasing the mass flow rate or input solar flux is used for temperature overshoot and undershoot control, respectively. During these transient cases, a control signal to the valve positioner or field control loop will be trimmed by the receiver particle outlet temperature deviation, ensuring the temperature remains within an acceptable range.

To avoid receiver thermal shock during daily startup the drum's surface is first heated to temperatures close to 470 °C using a low level of direct solar flux. Particles are then introduced from the feeder bin at low flow rates, and solar flux is increased to achieve the design ramp-up rate. After achieving the nominal outlet temperature, solar flux is increased to its maximum available level concurrent with the particle flow rate increase. The intermediate temperature particles generated during startup are used for warm-up of the downstream equipment, such as the particle heat exchanger, or rerouted to the bypass cooling chutes.

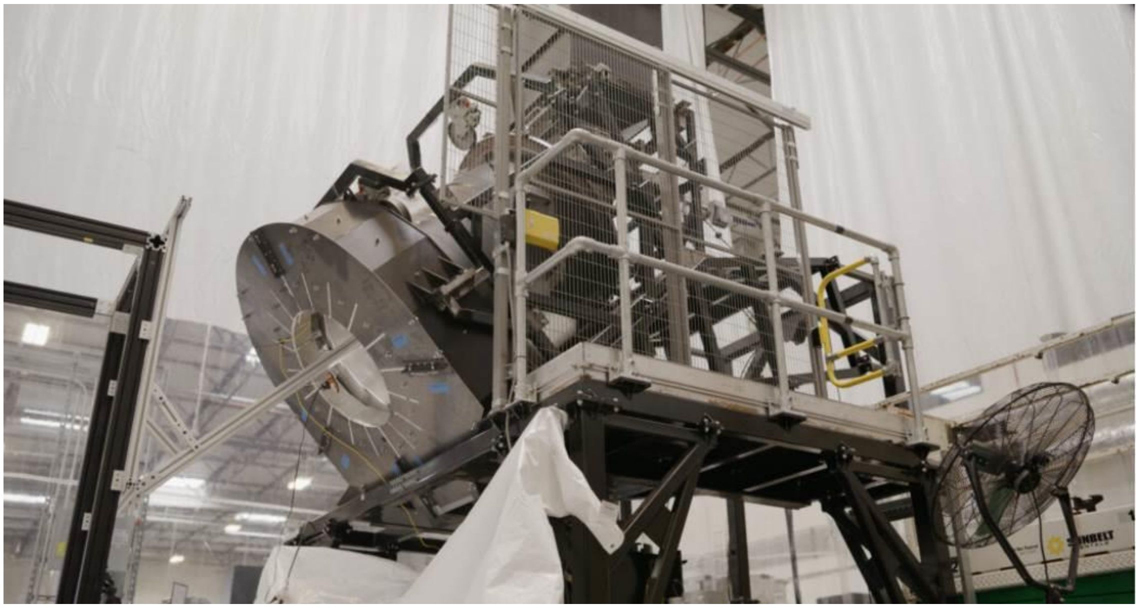


Figure 3: Centrifugal Particle Receiver

HOT SILO: The Hot silo is designed to store particles required for four hours of power generation at nominal conditions with an additional 10% margin. The discharge from each receiver and the chute from the air particle heat exchanger/feeder bin are directed toward the center of the silo.

Possible hot shocks are avoided by implementing multiple temperature sensors before the PHX discharge allowing for a rapid trip response where particle flow is stopped. Flow is then resumed when the particles have cooled. Additionally, because of the low particle side heat transfer coefficient, PHX cold shocks caused by a small drop in particle temperatures is not expected to be an issue. The mean metal temperature of the heat transfer plates within the PHX will track the sCO_2 flow temperature more closely than the particle temperature because the sCO_2-side heat transfer coefficient is much higher than the particle-side heat transfer coefficient.

Based on the chosen plant dispatch strategy, the hot particles produced during the first few hours of daily operation are not initially discharged through the PHX. Thus, before the power generation system's daily warmup, a pre-determined stored particle level shall be achieved within the silo. No direct flow control element is considered at the silo outlet. Thus, during discharge, the PHX inlet hopper is completely filled with particles (choke-fed), and the discharge rate is adjusted by the opening of control valves installed at the PHX outlet.

PRIMARY HEAT EXCHANGER: The primary heat exchanger (PHX) will be a diffusion-bonded shell and plate heat exchanger with etched microchannels on the sCO_2 (cold) media side. Diffusion-bonded shell and plate heat exchangers are known for their high thermal efficiency and higher operable pressures and temperatures owing to their strong, bonded plate construction. Their compact size is a significant advantage in space-constrained applications, and they require less maintenance with a reduced risk of leakage compared to traditional heat exchangers. These features, combined with customizable designs and environmentally friendly aspects due to high heat transfer efficiency and durability, make them ideal for the next generation of CSP applications. Vacuum Process Engineering VPE and Solex will design and fabricate the PHX consisting of three separate modules with one combined inlet hopper. Each module will be equipped with two outlet hoppers and flow control valves (6 in total) at the outlet. Six radiometric flow meters installed on two parallel screw conveyors at the PHX discharge measure the particle flow rate through each module.

During discharge, thermal energy is transferred from the hot particles to the power cycle's motive fluid (sCO_2) via the PHX plates. The 670 °C hot particles enter each PHX module and discharged 470 °C particles are then conveyed to the cold silo. Simultaneously, sCO_2 enters the PHX at 440.8 °C and 220 barA and exits at 600°C and 216 barA. While the PHX is designed for a thermal duty of 14.15 MW, it will nominally operate at 13.44 MW.

Due to the passive nature of mixing within the silo, time variation in particle inlet temperatures to the PHX will be unavoidable. However, this is expected to have minimal operational impact within acceptable bounds because the PHX mean metal temperature ramp rate limitation is not strongly correlated to the particle inlet temperature. The mean metal temperature is closely tied to the sCO_2 flow rate and temperature which is actively controlled with a fast response time to adapt to varying particle inlet temperatures. Minor variations in particle temperatures due to mixing will be accommodated for using the sCO_2 flow rate.

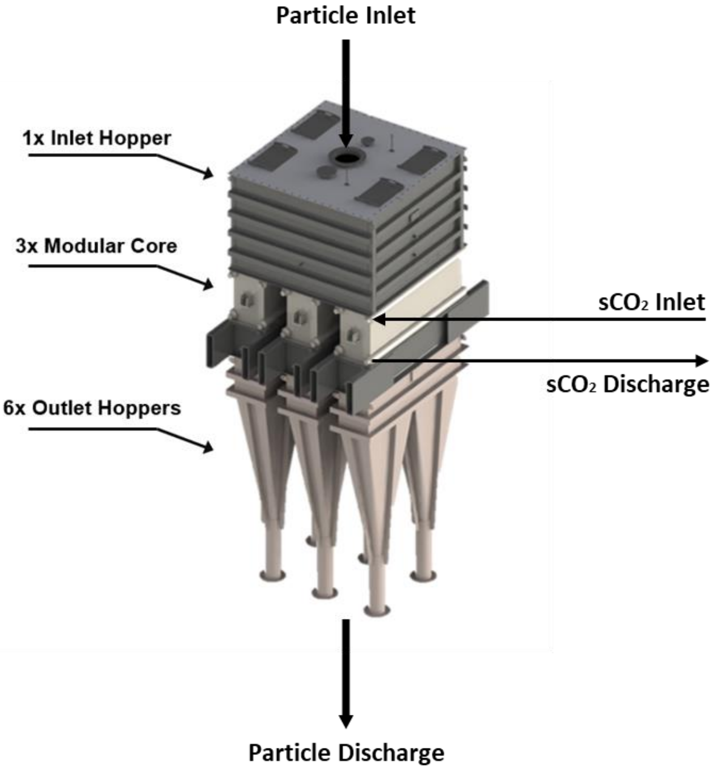


Figure 4: Diffusion Bonded Shell and Plate Particle-sCO_2 Heat Exchanger (image curtesy Vacuum Process Engineering)

DISCHARGE SCREW CONVEYOR (s): To transfer the discharged particles from the

PHX to a buffer bin, two inclined screw conveyors are utilized. Subsequently, the particles are loaded onto the discharging skip hoist from the bin and transferred to the cold silo. The conveyors' speed is adjusted based on the PHX discharge flow rate to prevent the backup of particles through the PHX modules and the conveyor shall be designed for the maximum flow rate. Additionally, radiometric flow meters are installed on the screw conveying system and calibrated based on the conveyor design.

DISCHARGING SKIP HOIST: Similar to the charging skip hoist, a single skip hoist system with a counterweight transfers the 470 °C particles from the PHX discharge buffer bin to the cold silo.

COLD SILO: A silo of equal size to the hot silo is planned to store 470 °C particles after they've exited the PHX. The cold silo discharge is connected to the receiver charging skip hoist loading system, while a second outlet is considered for future integration of a possible particle cleaning system. Temperature and level sensors will be installed on the cold silo, providing the existing particle level and temperature values at various silo heights.

PASSIVE COOLING CHUTES: Two bypass cooling chutes will be located between: 1) the outlet of the receivers and discharging skip hoist loading bin and 2) the cold silo inlet and the charging skip hoist loading point. In addition to the cooling capability, these chutes can function as bypass lines increasing the particle loop's operational flexibility. Transient particles with temperatures lower than 650 °C or higher than 835 °C cannot be fed to the primary particle heat exchanger PHX nor stored within the hot silo. Therefore, these particles must be diverted to cooling chute (1). Both chutes will be designed without insulation to naturally cool down these off-design temperature particles generated during the plant transient operation instances. After cooling to less than 470 °C particles will either be transferred to the cold storage silo or stored in the second cooling chute for further cooling to ambient temperature. These ambient temperature particles can then be used during startup. Further thermal analysis and cost optimization will determine each cooling chute's required length-to-diameter ratio and capacity.

Figure 5 below shows a simplified particle loop Process Flow Diagram, with main process lines highlighted in bold blue (470 °C) and bold red (670-675 °C).

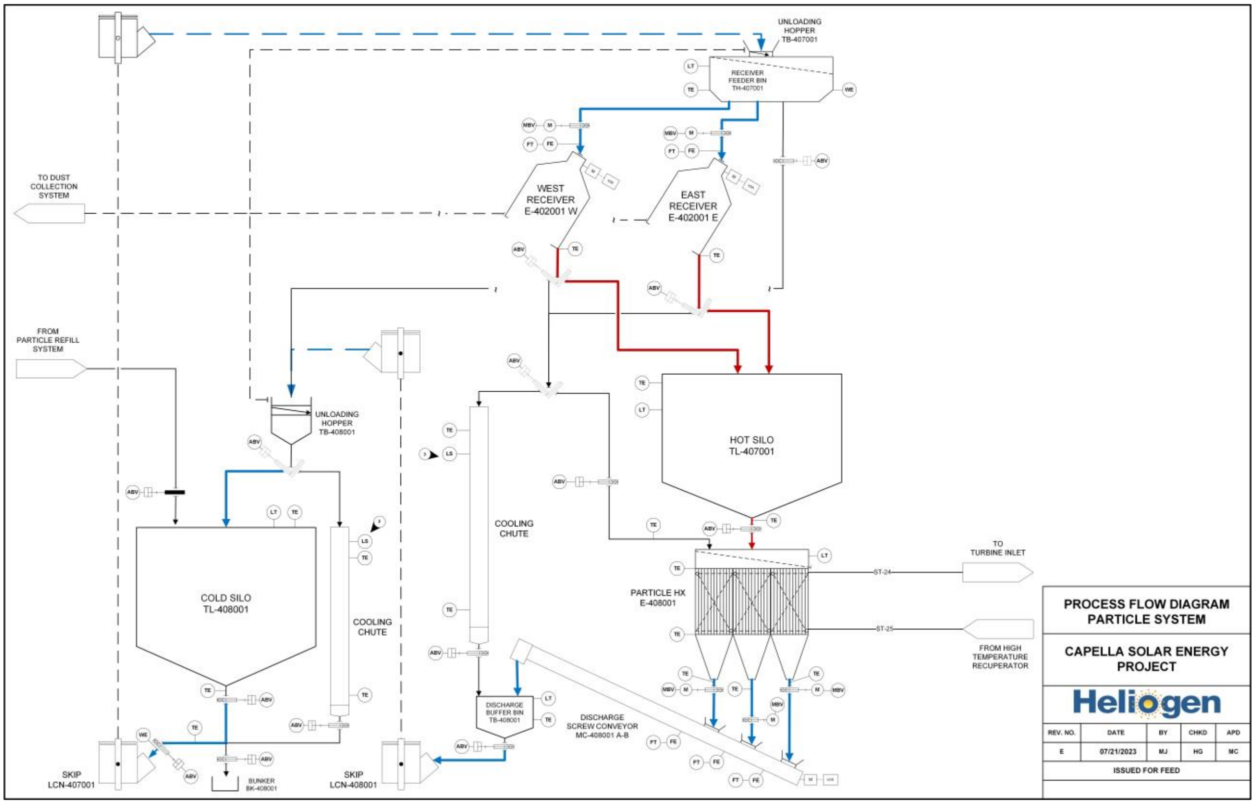
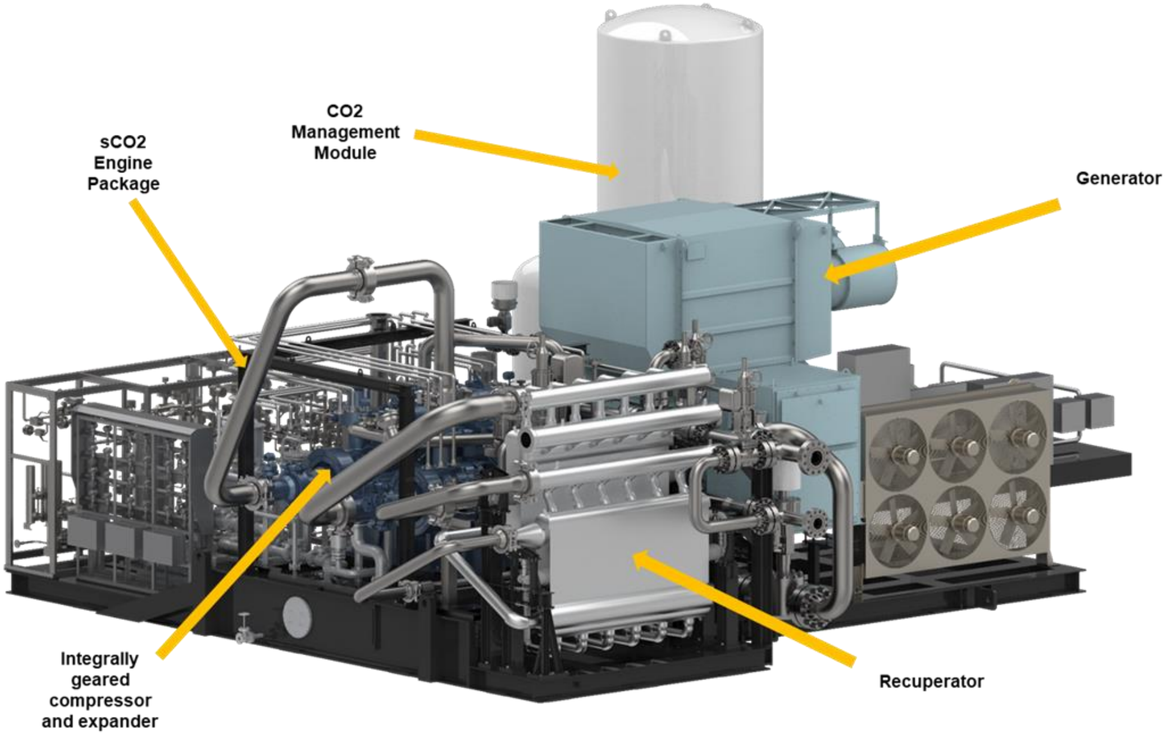


Figure 5: Simplified particle loop Process Flow Diagram (PFD) with main process lines highlighted in bold blue (470 °C) and bold red (670-675 °C).

POWER BLOCK: This recompression Brayton cycle provided by Hanwha Power System consists of the main components required for electricity generation using supercritical carbon dioxide (sCO_2) as a working fluid. After heating in PHX, high temperature sCO_2 is expanded within a two-stage radial turbine generating 5 MWe of net electric power. The exhaust sCO_2 is further cooled down by a heat recuperation system prior to compression in two parallel two-stage compression trains at different temperature conditions to maximize recuperation. An air-cooled heat exchanger is used for heat rejection before the low-temperature main compressor. Finally, the compressed sCO_2 flows back through the recuperators (cold side) and then back to the PHX inlet. These various components are assembled in three uncovered skids as shown in Figure 6.



3-D Rendition provided by PSM

Figure 6: Hanwha Supercritical CO_2 Power System Module Layout (image curtesy Hanwha Power Systems)

- **Heater (PHX):** Main heater to transfer the heat from the thermal energy storage system (TES) to the sCO_2 process fluid.
- **sCO_2 Core:** Integrally geared (IG) type compander (compressor – expander).
- **Recuperator:** Low temperature recuperator (LTR) and high temperature recuperator (HTR) to recover as much of the otherwise wasted energy within the cycle to maximize the overall system efficiency.
- **sCO_2 Inventory Management System:** To manage the pressure levels within the cycle, as well as charge and recover CO_2 from the cycle during transients.
- **Lube Oil System:** To lubricate the bearings and gears and minimize mechanical losses from the turbomachinery.
- **Dry Gas Seal System:** To monitor and protect the dry gas seals within the core machine.
- **Main Electrical Equipment:** Generator and its related equipment to connect to the electrical grid.
- **Pre-cooler (air cooled):** Three EvapCo adiabatic cooling units are used to cool the working fluid (sCO_2) to the required compressor inlet conditions. As shown in Figure 6, these units are designed as V-configuration induced draft gas coolers equipped with 4 VFD controlled fans. These fans are utilized with an air pre-cooling system, depressing the dry bulb temperature using wetted fibrous pads to minimize the water use.

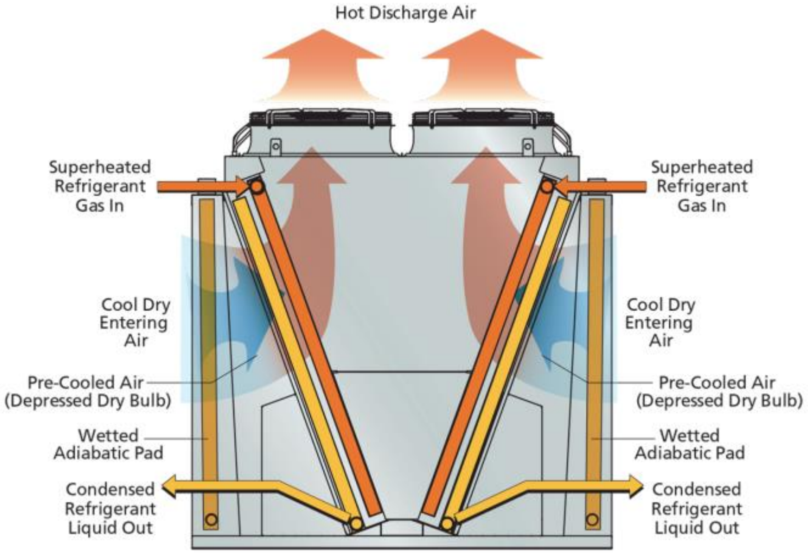


Figure 7: EvapCo Adibatic Cooling Unit's Configuration (image curtesy Evapco Dry Cooling)

This power generation unit is designed to have the performance characteristics specified in Table 1.

Table 1: Power Block Key Metrics and Design Specifications

sCO_2 Inlet Condition	Unit	Expander
Mass Flowrate	kg/s	66.2
Pressure	barA	216
Temperature	C	600
sCO_2 Discharge Condition	**Unit**	**Expander**
Pressure	barA	220
Temperature	C	400
Net Power	kWe	5000
Voltage Frequency	Volts	4160 (60 Hz, 3 Phase)

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