Hanwha Power Systems

sCO2 Power System

– Industrial Waste Heat Recovery Applications

March 1, 2023

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Note: WHR - Waste Heat Recovery

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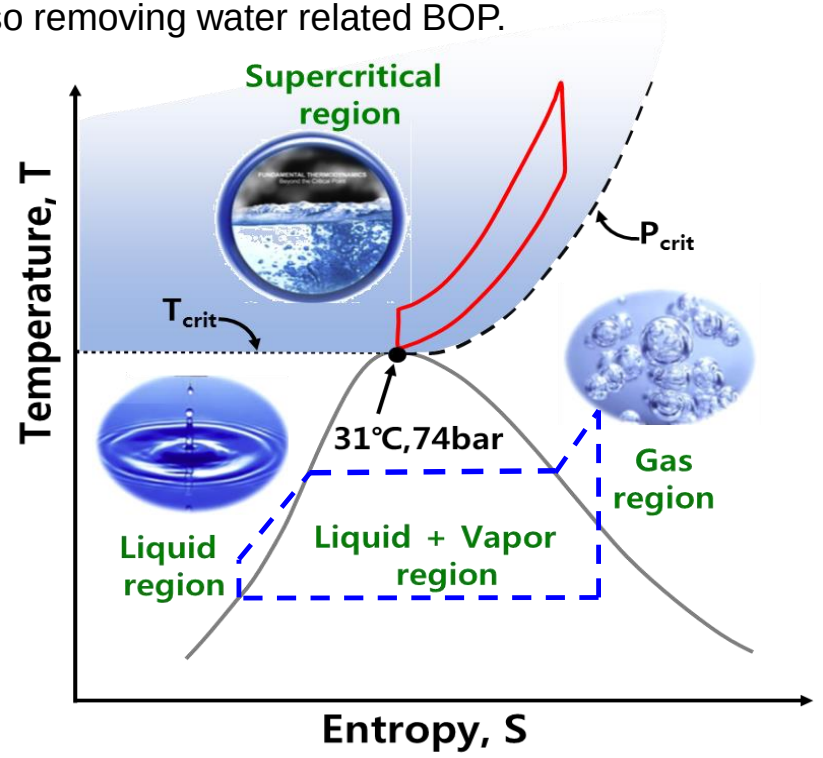
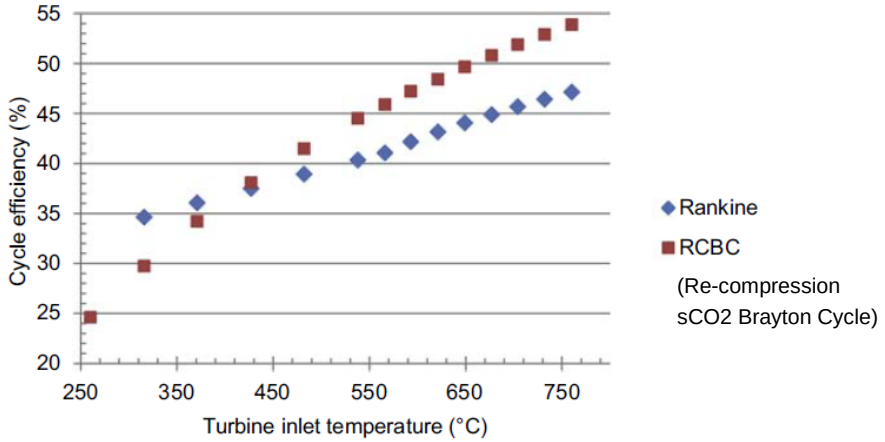
Concept & Advantages of Supercritical Carbon Dioxide(sCO2)

- "Super-critical" is a fluid state above the critical temperature and pressure (e.g. 31℃, 73.8bar for CO_2), the fluid in this state behaves like gas but with the density like that of a liquid.
- Result is high-power density machine (small footprint) that allows use of high-efficiency closed loop Brayton cycles
- As one of the heat recovery bottoming cycles, the closed loop Brayton cycle does not require any water, so removing water related BOP.

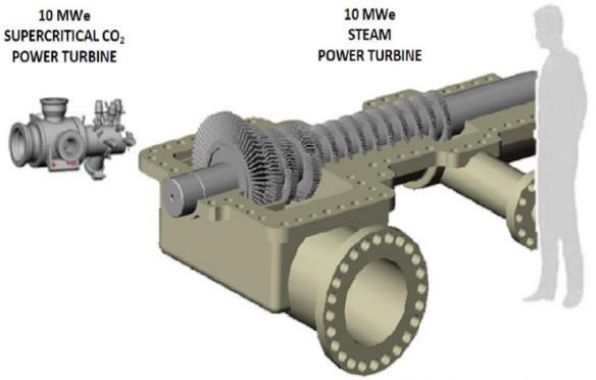


<CO2 Power Cycles>

(— Supercritical Brayton vs. - - Rankine)



<Efficiency Comparison : sCO2 vs. Rankine Cycle>[1)]



<Size Comparison : sCO2 vs. Steam Turbine>[2)]

1) Source: NETL, White, C. 2016. "Analysis of Between Cycles Utilizing Supercritical Carbon Dioxide"
2) Source: Power-Gen India 2012, "sCO2 Power Cycle : Why sCO2 can displace Steam"

HPS has successfully developed Integrally Geared sCO2 Power System through US DOE program

US DOE[1] 10MWe sCO2 CSP[2] Commercialization Development Program (APOLLO[3])

Program Target

Power 10MWe, Cycle Efficiency 50% (@Turbine Inlet Temperature 705℃)

Program Structure

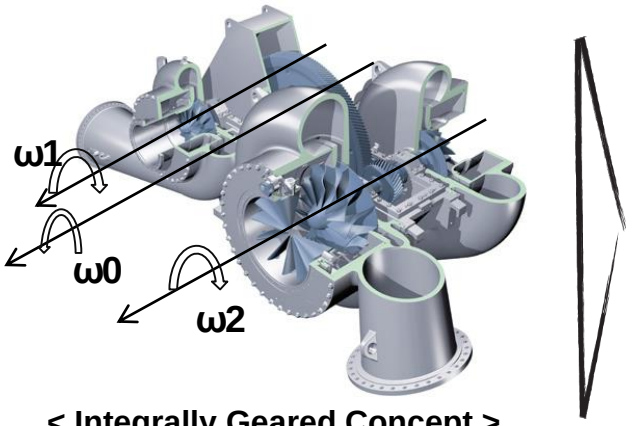
U.S. DEPARTMENT OF ENERGY — Main Contract — Southwest Research Institute — Co-development Contract — Hanwha Power Systems — Design / Manufacturing / MRT[8]

- U.S. DEPARTMENT OF ENERGY: • Funding, Management
- Southwest Research Institute: • Cycle Design, Shop Test
- Hanwha Power Systems: • sCO2 Engine Development

HPS Development Progress

November, 2015	Dec, 2016	Jul, 2019	Dec, 2021
HPS won DOE project with IG[4] Type sCO2 Engine	Concept/Preliminary design	Detailed Design/ Manufacturing/MRT	sCO2 Shop Test - Performance / Endurance

sCO2 Shop Test has verified both performance and mechanical/structural stability of sCO2 Turbomachinery.



< Integrally Geared Concept >

IG Type Features

- Decoupled RPM → Higher Component Efficiency
- Easy Inter-cooling, Re-heating → Better Cycle Efficiency
- IGV[5], VGN[6] → Flexible Operation
- Compact, Lower Cost

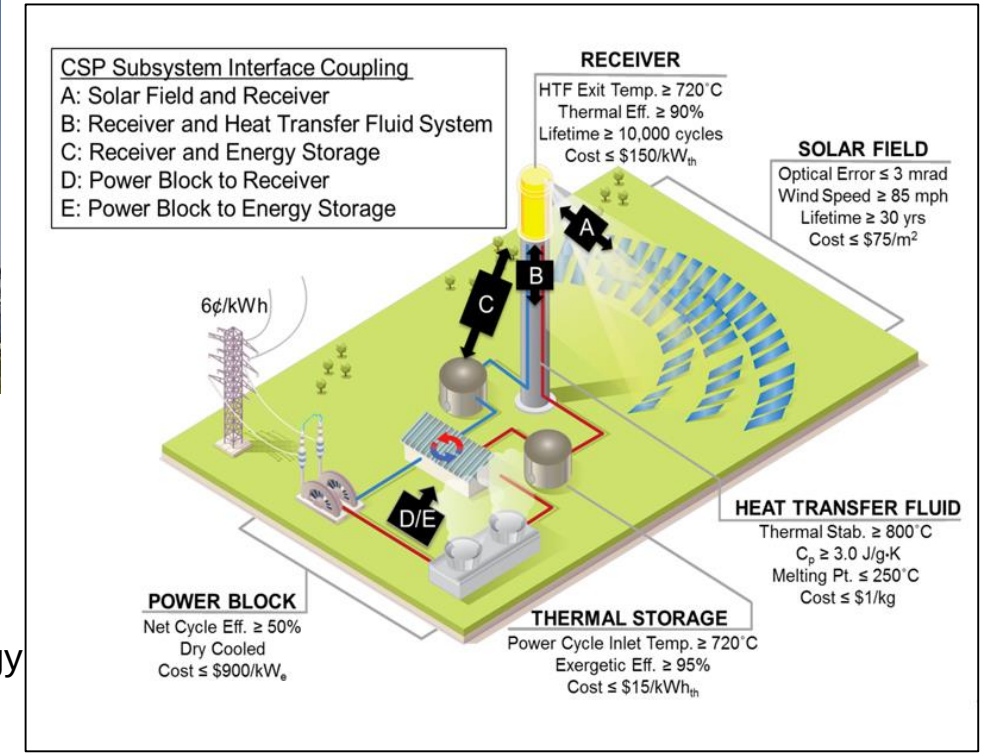
Application

- Max 30MW-class Capability
- WHR[7] : 5~30MW (Gas Turbine Waste Heat to Power)
- CSP : 5~30MW Single, 100MW (= ~30MW x 3 Multi-units)
- Nuclear : MNR (Micro Nuclear Reactor) 5~30MW

1) DOE : Department of Energy, 2) CSP : Concentrating Solar Power, 3) APOLLO : Advanced Projects Offering Low LCOE Opportunities
4) IG : Integrally Geared 5) IGV: Inlet Guide Vane, 6) VGN: Variable Geometry Nozzle, 7) WHR : Waste Heat Recovery, 8) Mechanical Run Test

2. sCO2 Power System Development Overview

DOE Apollo



- **US DOE had several rounds of funding for CSP-focused topics**
  - Initial large round (Sunshot) focused on investigating key technologies
  - Second round (Apollo) focused on technology demonstrations
  - Hanwha and GE were the two recipients whose work focused on turbomachinery
  - GE equipment targeted large power cycles (axial turbomachinery) 100-300MWe
  - Hanwha targeted smaller power cycles (radial turbomachinery) 5-25MWe

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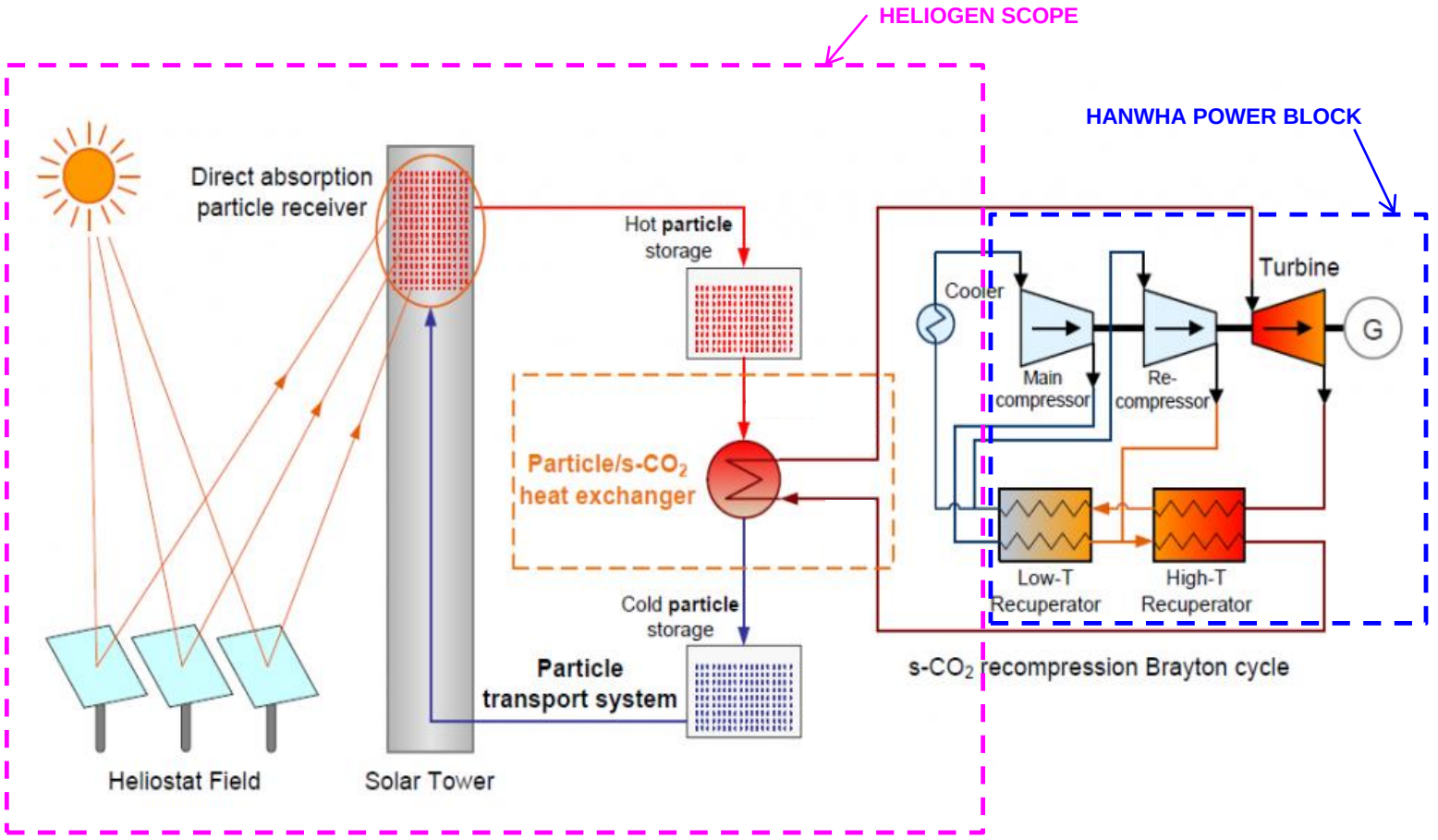
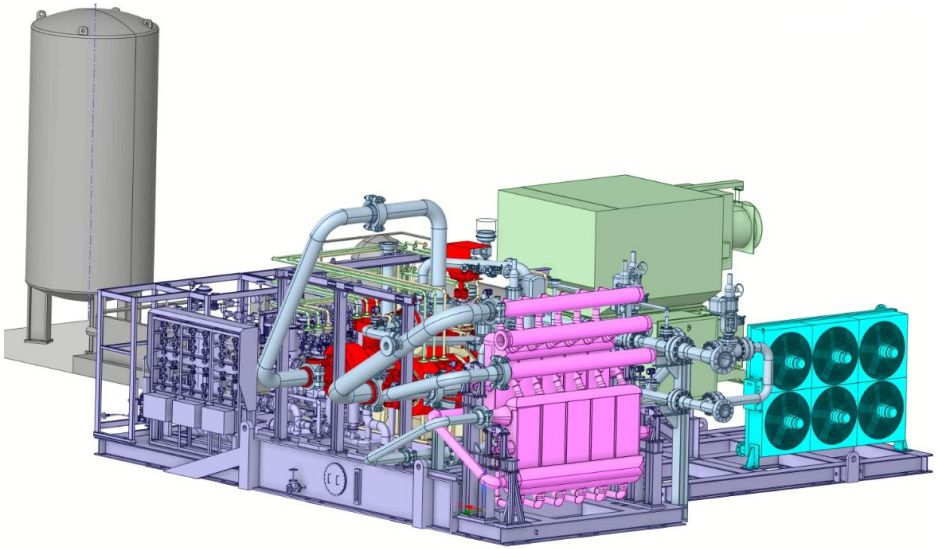
General CSP (Concentrated Solar Power) System Description

- After Receiving solar heat source through “Particle/S-CO2 Heat exchanger”, HPS power block generates electricity.
- sCO2 cycle is a recompression Brayton cycle that has a Main Compressor, Re-Compressor, Turbine (Expander), LT/HT Recuperators and Cooler.



2. sCO2 Power System Development Overview

- Full-scale commercial demonstration to be completed in 2025
- Concentrating solar power
- Power generation with no carbon emissions
- Incorporates thermal energy storage
- Recompression Brayton cycle selected to maximize efficiency
- Turbine inlet temperatures up to 625C
- CO2 inventory management system included to enhance off-design performance



SCO2 Waste Heat Recovery (WHR) for Industrial Applications

- sCO2 power systems are cost competitive value proposition and are viable alternatives for many industrial applications where there is a large volume of unused exhaust gas from manufacturing processes
- sCO2 WHR benefits
  - Clean baseload power
  - Higher efficiency and lower auxiliary loading than competitive technologies
  - Small Footprint
  - Modular design for easy installation
  - No Water Required
  - Low O&M costs
  - Supports client ESG branding and goals
  - Provides generation and ESG portfolio diversity
  - Zero GHG emissions
  - Offsets CO_2, NO_x and SO_x emissions
  - Can supply energy for on-site usage
  - Can qualify for green incentives and RECs under state renewable RPS requirements
  - Provides DG support, grid reliability and resiliency for resources

3. Applying sCO2 WHR in Industrial Markets

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Viable Industrial Market Applications

- Natural Gas Pipeline Compressor Stations
  - Clean heat stream
  - High temperatures
  - Simple integration
  - Small footprint for inside-the-fence installation
  - Opportunity to offset on-site energy usage
  - No water usage for remote locations
  - Provides carbon offsets for plant operations
  - Large market potential for development

Viable Industrial Market Applications

- Gas Processing and Chemical Plants
  - Clean heat stream
  - High temperatures
  - Simple integration
  - Black start capability
  - Islanding mode
  - Small footprint for inside-the-fence installation
  - Opportunity to offset on-site energy usage
  - Large market potential for development
- Steel and Iron Mills
  - Huge carbon offset potential
  - Large volumes of unused heat

3. Applying sCO2 WHR in Industrial Markets

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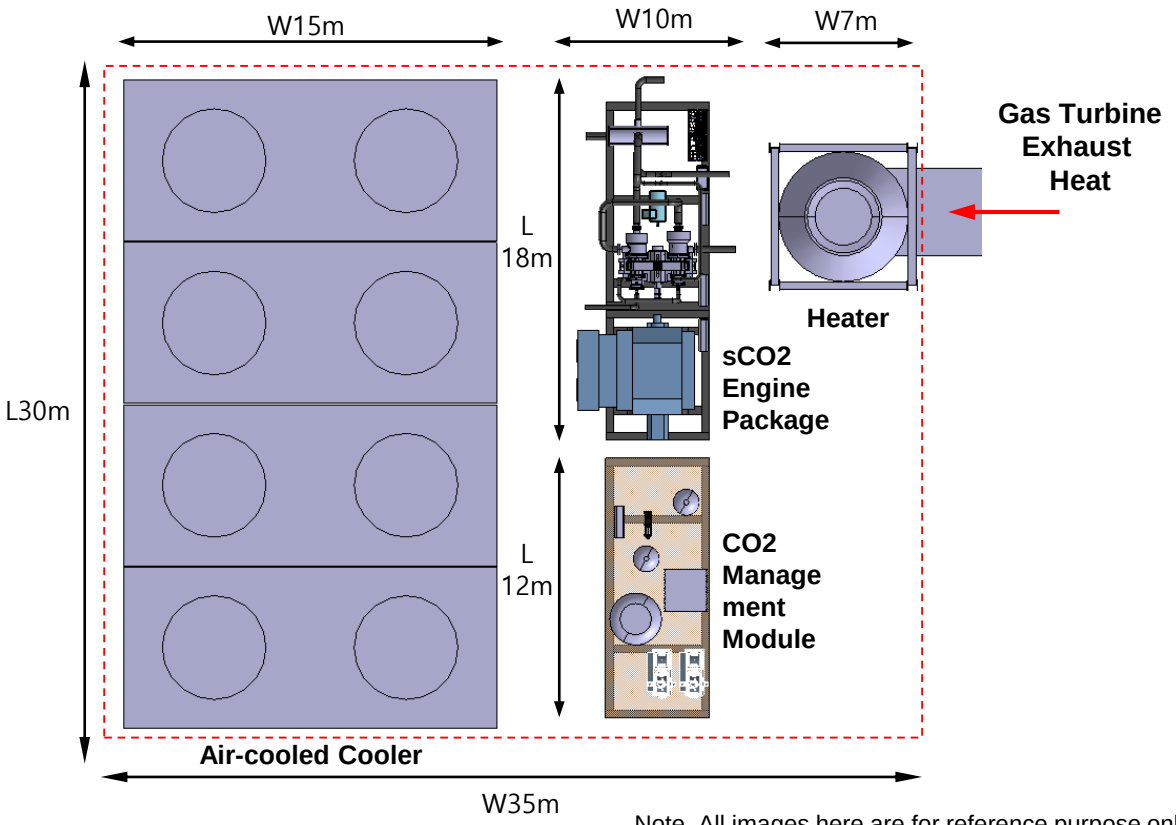
Viable Industrial Market Applications

- Cement Plants
- LNG Plants and Terminals
- Green Hydrogen Generation and Transmission Industries
- Ammonia Transportation and Production
- Glass and Ceramic Manufacturing
- Pulp and Paper Mills
- Refineries
- Biomass/biofuel
- Concentrated Solar Projects
    - High temperatures
    - Emerging technology with large potential

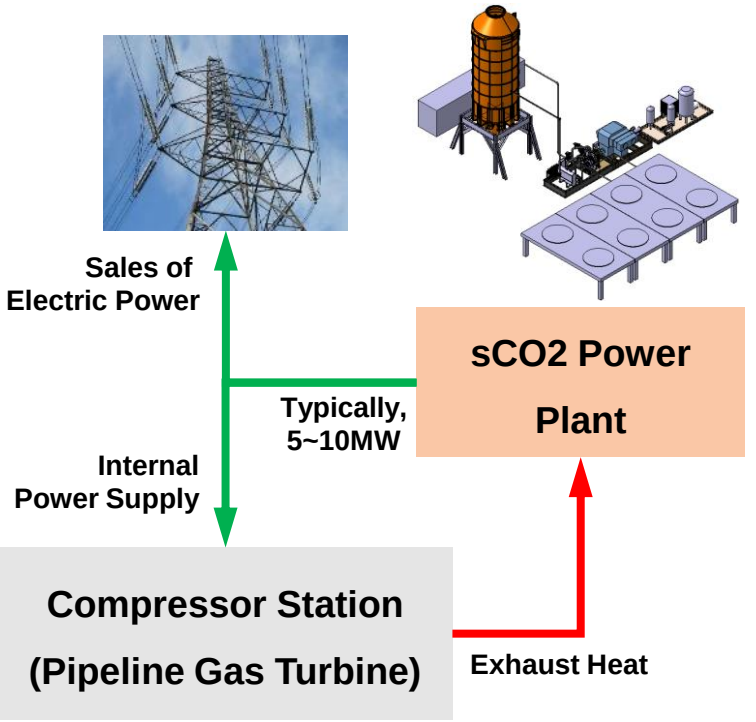
Internal Power Supply and Electric Power Sales

- Currently, most of exhaust heat from industrial applications is wasted to the atmosphere, although ORC[1] had been applied for WHR in some locations.
- Competitive features of the sCO2 power system will make it most profitable by supplying internal utilities power and sales of remaining electricity to grid, plus ITC[2] and carbon tax, if applicable.

Hanwha sCO2 Power Plant Typical Layout for Pipeline Station



Pipeline Business Model

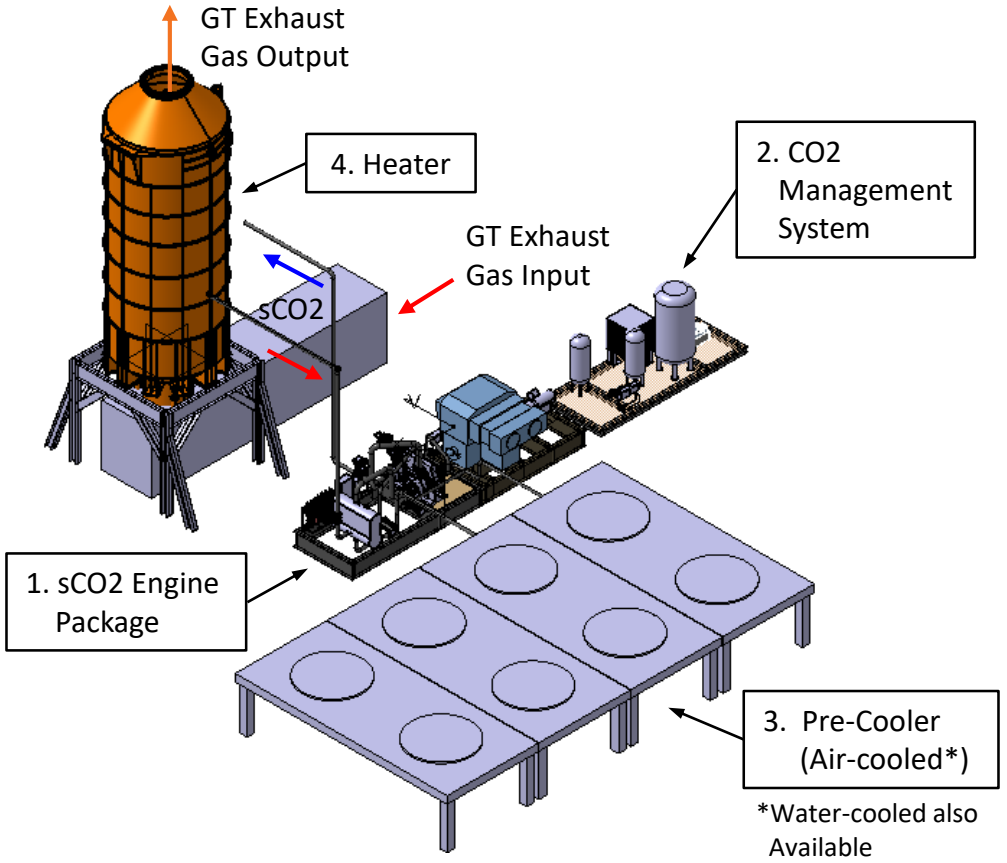


1) ORC : Organic Rankine Cycle
2) ITC : Investment Tax Credit

Note. All images here are for reference purpose only.
The footprint dimensions are subject to change by site conditions and further design optimization.

Hanwha sCO2 Power System Construction

- Modular power system is very simple and compact, enhancing easy deployment & maintenance.
- System unmanned operation is possible and the remote M&D[1)] could be also provided, optionally.



No.	Module	Function Description
1	sCO2 Engine Package	Covert thermal energy to mechanical, and finally electrical energy by sCO2 turbomachinery, heat exchanger (recuperator) and generator
2	CO2 Manage-ment System	(1) CO2 initial charge (fill-up) in sCO2 Closed -Loop (2) CO2 Leakage Refill into sCO2 Closed-Loop (3) CO2 Supply and Retrieve for sCO2 Closed-Loop as per power system operation mode such as partial load demand
3	Pre-Cooler	After expansion and recuperation of sCO2, it cools down sCO2 in front of compressor inlet.
4	Heater	Heat sCO2 by recovering heat from GT exhaust gas

1) M&D : Monitoring & Diagnostics

< 5MWe-class Hanwha sCO2 Power System General Layout & Scope of Supply >

Environmentally Sound Solution

- Clean and efficient alternative: a reliable solution for environmentally sound, affordable electricity

- CO2 Offsets, ESG Branding for Pipeline Companies, Portfolio Diversity, Resiliency, Water-free
- Base-load operation with a flat curve for capacity as opposed to intermittent renewables resources

Environmental Value Propositions

Item	Hanwha sCO2 Power System
Emission Offset[1)]	▪ Standard 6MW sCO2 unit will save approximately[1)]: 1) 44,700 tons of CO2 per year 2) 55,800 kg of NOx per year 3) 201,000 kg of SO2 per year
Environmental Credits Potentials	▪ Creates tradable renewable energy credits & emission reduction/offset credits → CO2, NOx, SOx ▪ Waste Heat Recovery is qualified as “Green Power” in many states in US → Qualified in some states’ RPS (Renewable Portfolio Standard)
Emission Free	▪ Electricity generation with no additional fuel and no additional emissions ▪ Decarbonization option for clients’ portfolios ▪ Zero GHG emissions
ESG Value	▪ Waste to power in the compressor stations creates the value of ESG management

1) Offsetting energy generated by typical coal-fired power plants and assuming the plant’s capacity factor at 85% (7,446hr/yr)

Discussion - Q&A

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