STEP SCO2 10 MW Demonstration Plant Update

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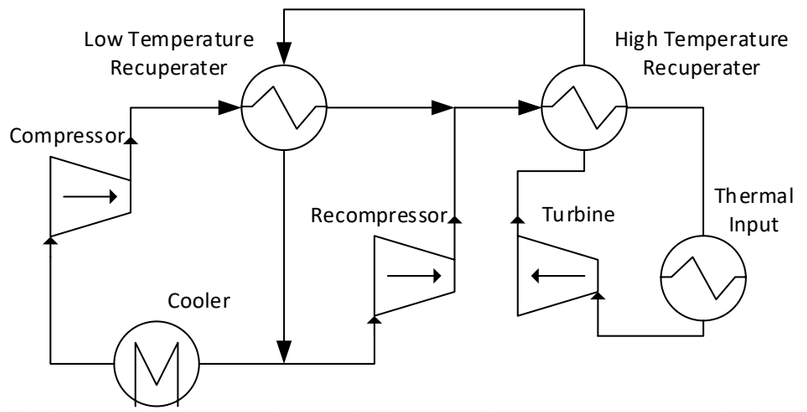
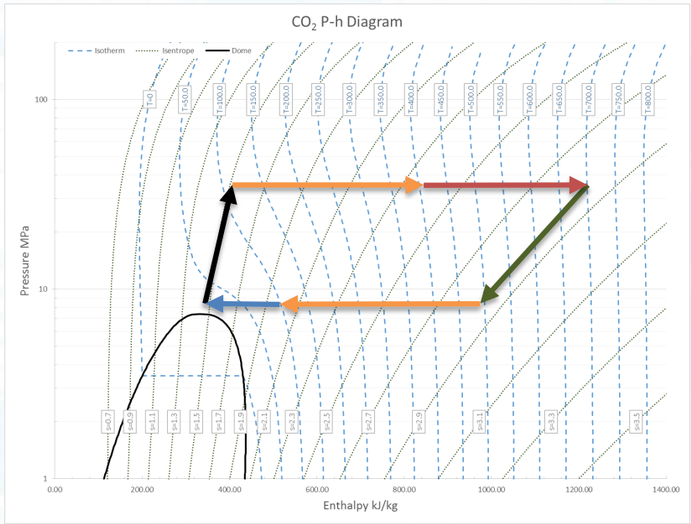
Supercritical Carbon Dioxide (sCO_2) Cycles

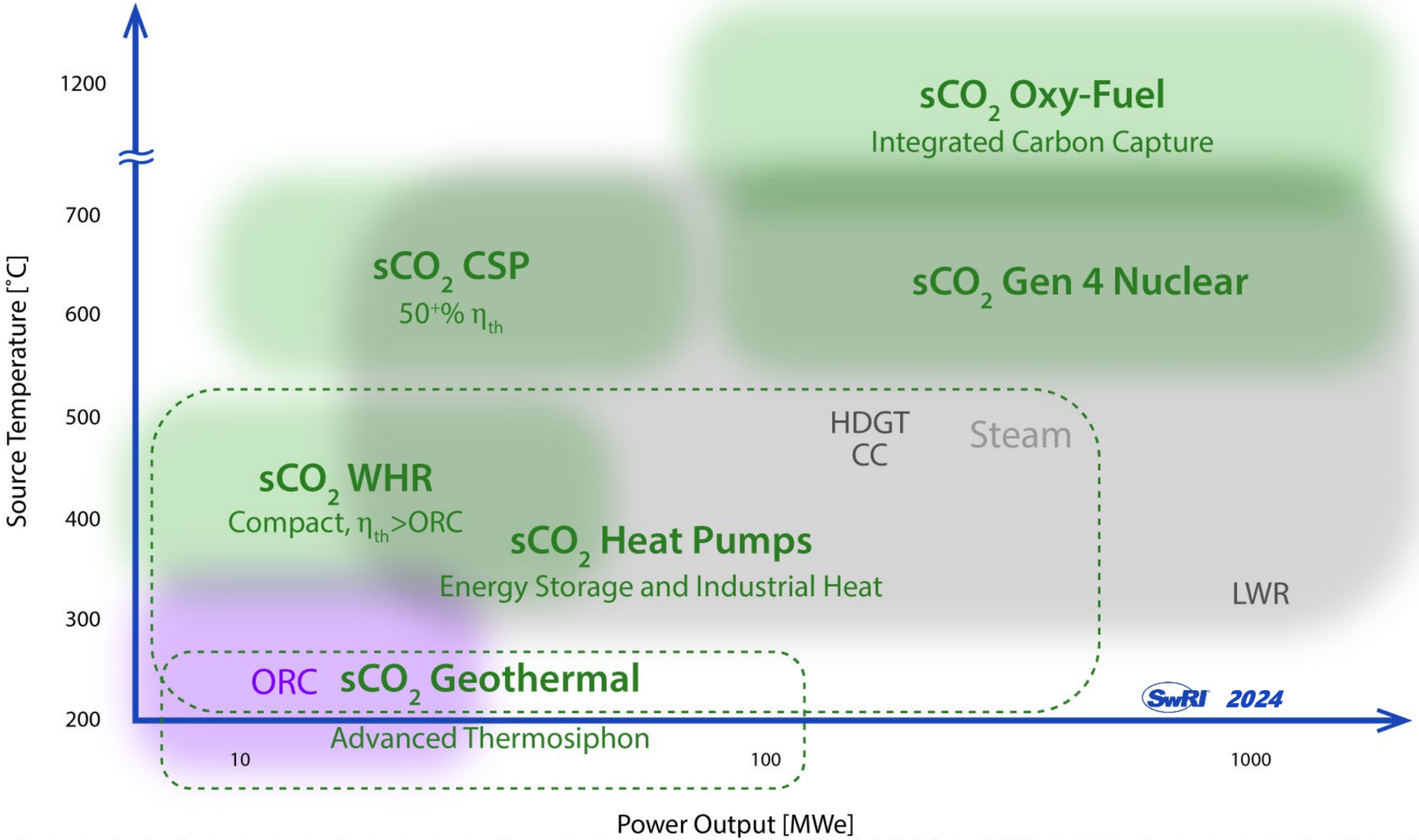
- Investigated since early 1900s, revisited since 1999, enabled by new technologies
- Favorable fluid properties:
  - Inert
  - Non-toxic at low concentrations
  - Unfreezable above 5.11 atm
  - Thermally stable at temperatures up to1700 °C
  - High density → turbine power density ~10x steam turbines
  - High thermal conductivity, low viscosity → compact heat exchangers
- No "boiler" → eliminates staffing requirements
- Potential for lower $/kW due to higher efficiencies, power densities,
- STEP 10 MWe Demonstration achieved Simple Cycle operation
- Commercial systems announced
- 70 MW heat pump in operation since Dec 2024 by MAN



Recompression Brayton Cycle achieving >50% thermal efficiency over ~700 °C turbine Inlet

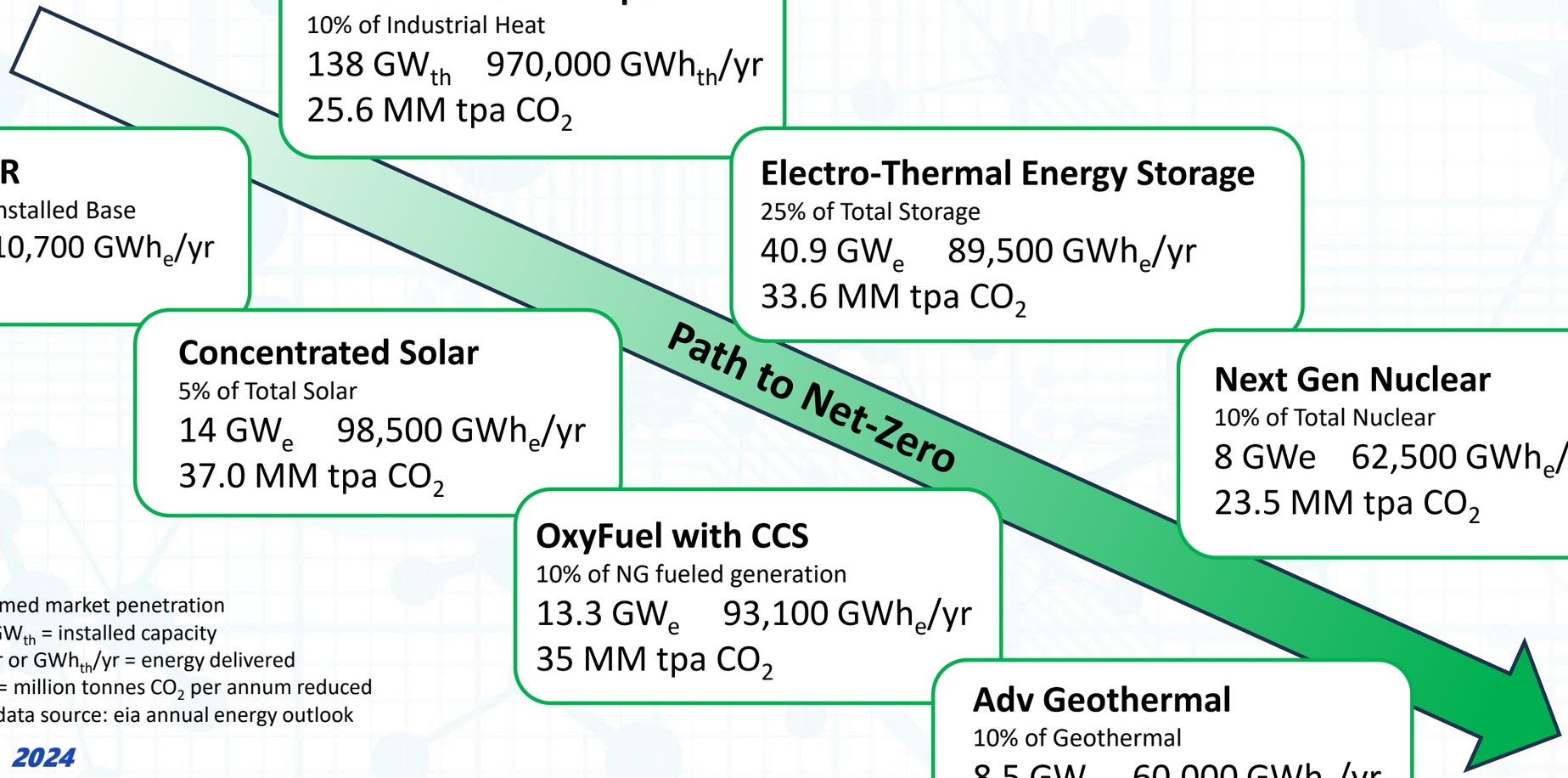


sCO_2 Power System Application Space



CO_2 Cycles – Versatile Tool for the Energy Transition

Potential Impact by 2050



Industrial Heat Pumps
10% of Industrial Heat
138 GW_{th} 970,000 GWh_{th}/yr
25.6 MM tpa CO_2

Small WHR
25% of SCGT Installed Base
9.3 GW_e 10,700 GWh_e/yr
4 MM tpa

Electro-Thermal Energy Storage
25% of Total Storage
40.9 GW_e 89,500 GWh_e/yr
33.6 MM tpa CO_2

Concentrated Solar
5% of Total Solar
14 GW_e 98,500 GWh_e/yr
37.0 MM tpa CO_2

Next Gen Nuclear
10% of Total Nuclear
8 GWe 62,500 GWh_e/yr
23.5 MM tpa CO_2

OxyFuel with CCS
10% of NG fueled generation
13.3 GW_e 93,100 GWh_e/yr
35 MM tpa CO_2

Adv Geothermal
10% of Geothermal
8.5 GW_e 60,000 GWh_e/yr
22.5 MM tpa CO_2

Total Potential
181.2 MM tpa CO_2
~12% of Current Electric Power Emissions

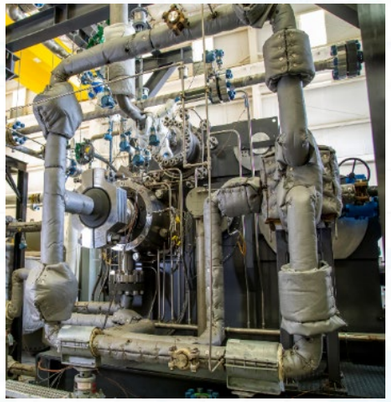
% = Assumed market penetration
GW_e or GW_{th} = installed capacity
GWh_e /yr or GWh_{th}/yr = energy delivered
MM tpa = million tonnes CO_2 per annum reduced
Primary data source: eia annual energy outlook

SwRI 2024

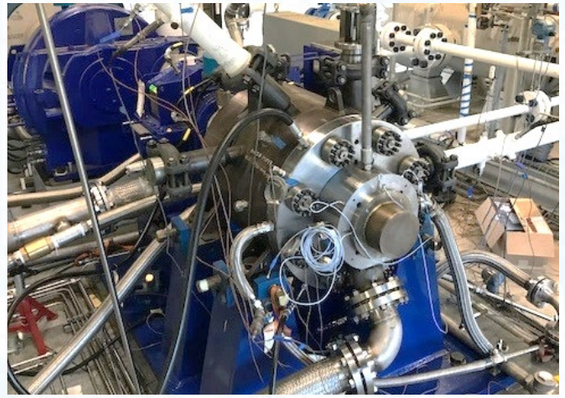
Past Development Work for sCO_2 Cycles, Components, Systems

Design, Fabrication, Testing of 10 MWe-Scale Machinery

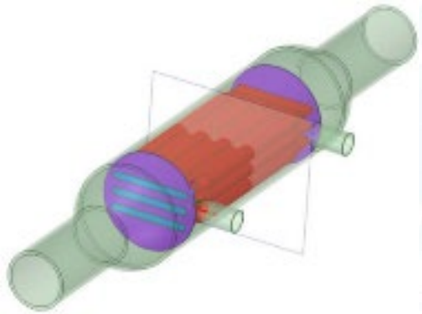
SunShot 10 MWe-scale Axial Turbine w/GE
Test at 715 °C, 27000 rpm, 1/10th flow

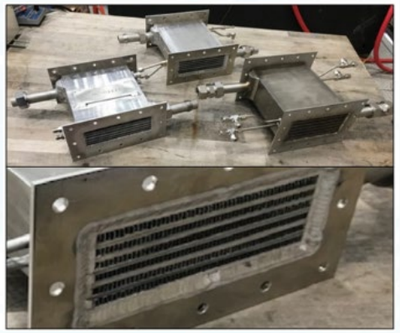


Hanwha Integrally-Geared 10 MWe-scale Radial Turbine/Compressor: Test at 720 °C, full-flow compressor 1/10 flow turbine



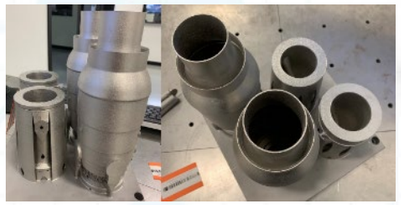
GE APOLLO 10 MWe Centrifugal Compressor w/ GE: Full-Scale Test at 27000 rpm

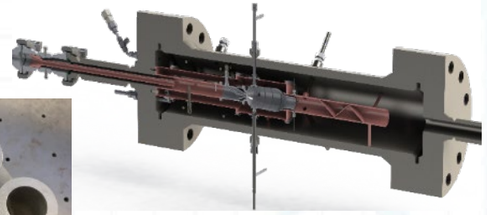




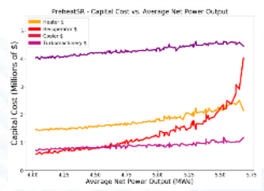
Heat Exchanger Development and Testing:

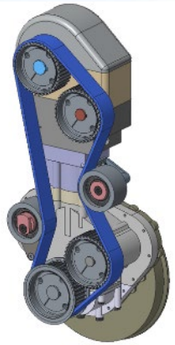
Primary Heaters, Recuperators, Wet/Dry Coolers

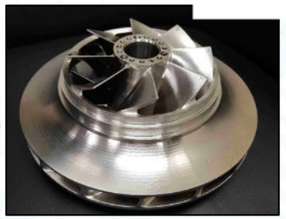


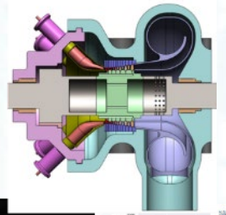


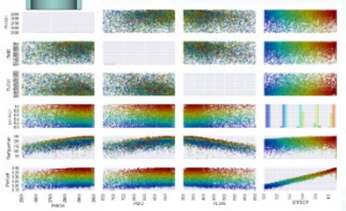
Oxy-Combustor Development and Testing











…and Seals, Economics, System Optimization, Advanced Cycles, Aero Testing, Machine Design

Supercritical Transformational Electric Power (STEP) Demo Project

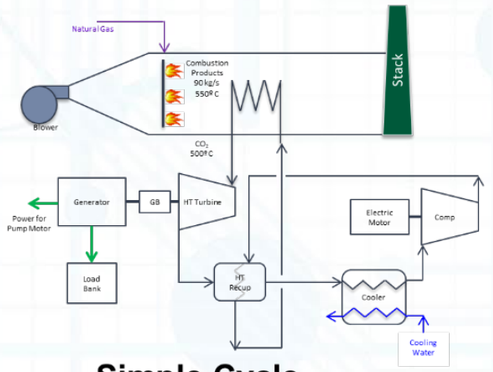
- $169.7M project to design, construct, commission, and operate a 10 MWe sCO_2 demonstration power plant
- **Objectives:**
  - Advance sCO_2 power from TRL3 to TRL7
  - Demonstrate pathway to net plant efficiency > 50%
  - Demonstrate control and operability at 500°C and ≥700°C turbine inlet temperatures with 10 MWe power generation
- **Project Partners:**
- **Industry Co-Funders:**

www.STEPdemo.us

STEP Project Objectives and SwRI Roles

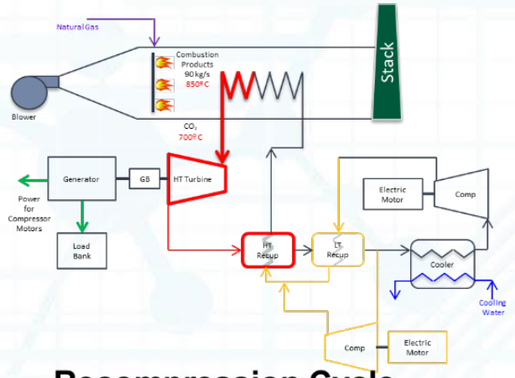
Verify System Performance & Operability:

- Quantify component and system performance
- Demonstrate operation across control parameters
- Measure transient response through start-up, load change, and shutdown



Simple Cycle

- Shortest time to initial data
- Controls & safety
- Component performance
- Steady & transient cycle data



Recompression Cycle

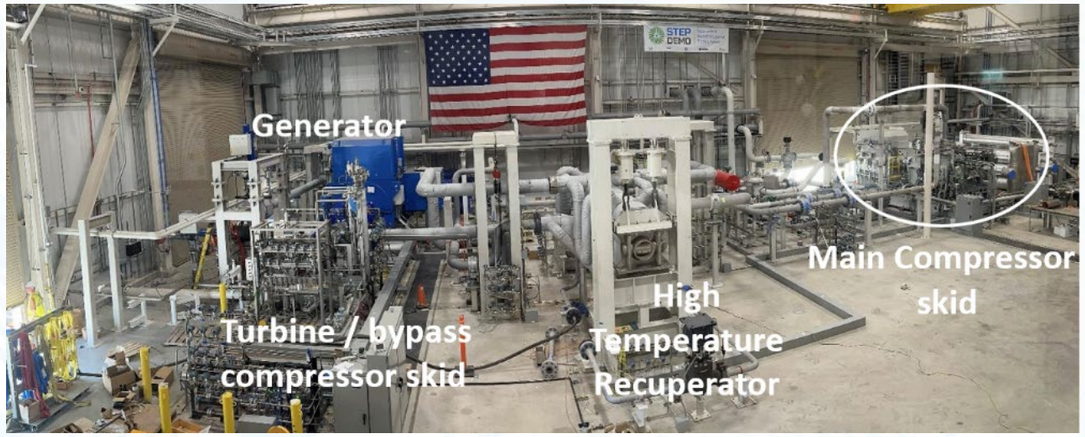
- Inventory management
- Starting transients
- Parallel compressor control
- SOA component efficiencies
- Cycle efficiency > 50%

Reconfigurable facility:

- Accommodate future testing

SwRI Roles:

- Host Site
- System integration and operation
- Data acquisition and controls
- Piping
- Turbine design and fabrication (with GE)
- Heater protection valve
- Process electrical



STEP Facility Layout & Specifications

STEP DEMO

Test Bay for Process Hardware
- 20k square feet on-5 acre lot
- 30 ton bridge crane
- CO2 inventory, lube oil, shop air

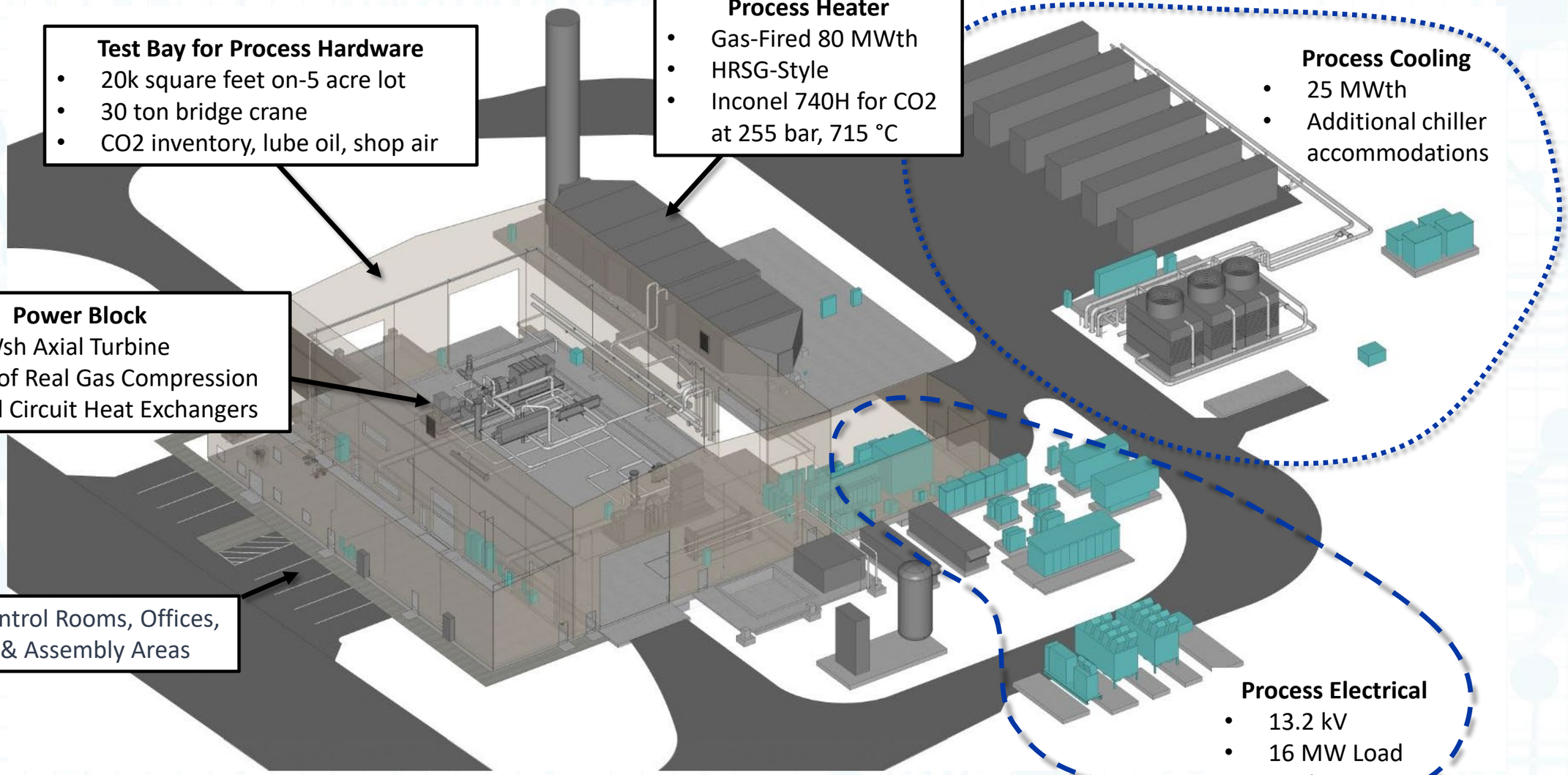
Process Heater
- Gas-Fired 80 MWth
- HRSG-Style
- Inconel 740H for CO2 at 255 bar, 715 °C

Process Cooling
- 25 MWth
- Additional chiller accommodations

Power Block
- 16 MWsh Axial Turbine
- 4 MW of Real Gas Compression
- Printed Circuit Heat Exchangers

Control Rooms, Offices, & Assembly Areas

Process Electrical
- 13.2 kV
- 16 MW Load Banks



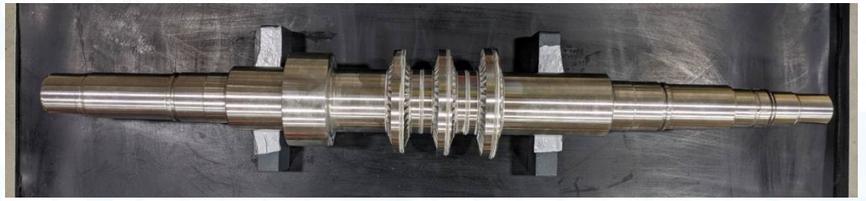
MECHANICAL ENGINEERING

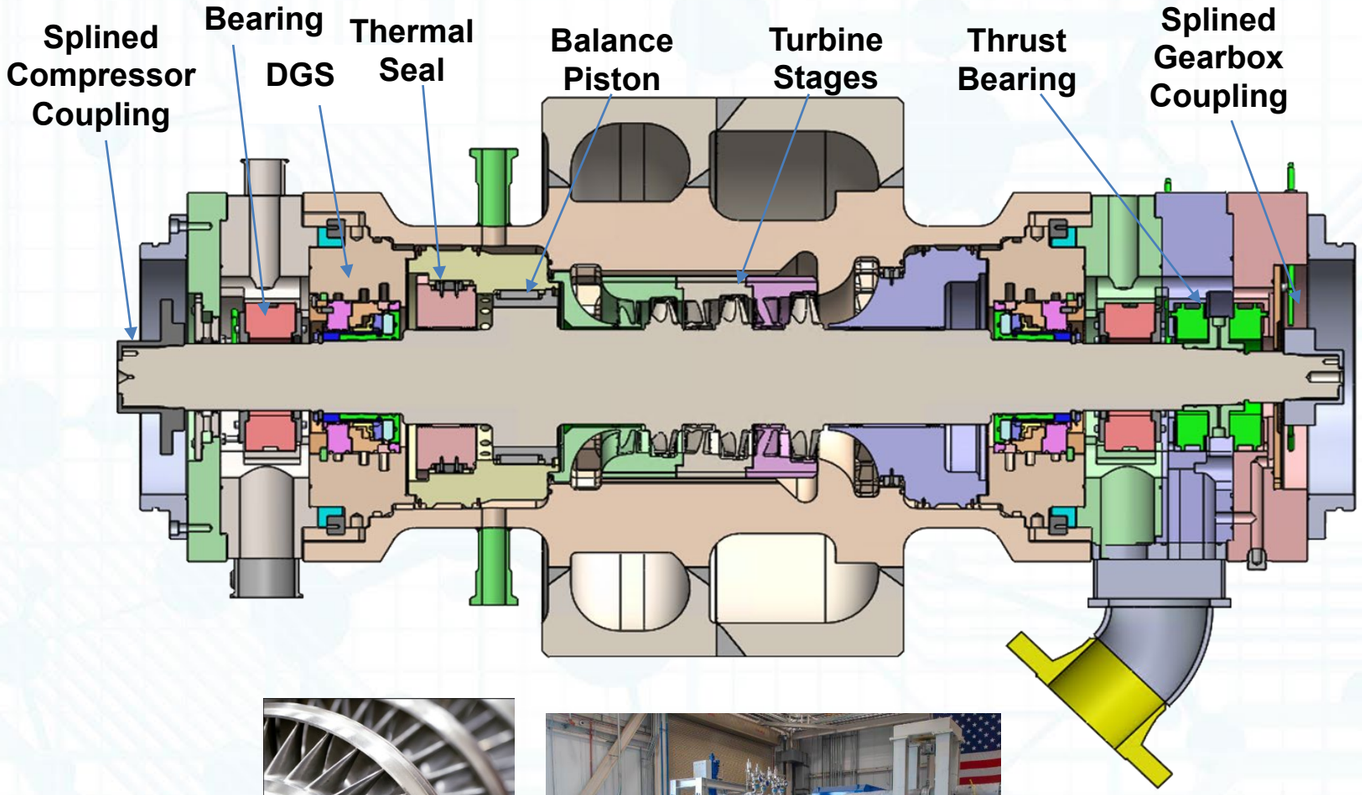
SwRI

swri.org

STEP Turbine Achievements

- ~1/10 the size of an equivalent steam turbine
- The world's highest power density industrial terrestrial turbine
- 16 MW (21,000 hp) produced by 86 kg (190 lb) rotor (186 kW/kg)
- Made from Nimonic 105 heat treated forging
- Airfoil shapes cut using a 5-axis electrode discharge machining (EDM) by Baker Hughes





STEP sCO_2 Technology Maturation Achievements

- Successfully demonstrated gas-fired indirect sCO_2 plant operation at 500 °C simple recuperated cycle "max" conditions generating ~4 MW net power while grid-synchronized
- All major components commercially procured except turbine jointly designed by GE Vernova and SwRI:
  - Compressors: Baker Hughes
  - Heat Exchangers: Parker Heatric, Optimus, Vacuum Process Engineering
  - Heater Protection Valve and 500 °C Turbine Trip Valve: SchuF, AVS/HORA
  - Plant Controller: GE Mark VI
- Demonstrated repeatability through multiple operations, also safely demonstrated fast and slow trips
- Plant design details available to JIP members
- Some risks remain:
  - High-temperature operation, esp. >600 °C
  - Long-duration testing

STEP Simple Cycle Test Program

- Test program of increasing speed, temperature, and power

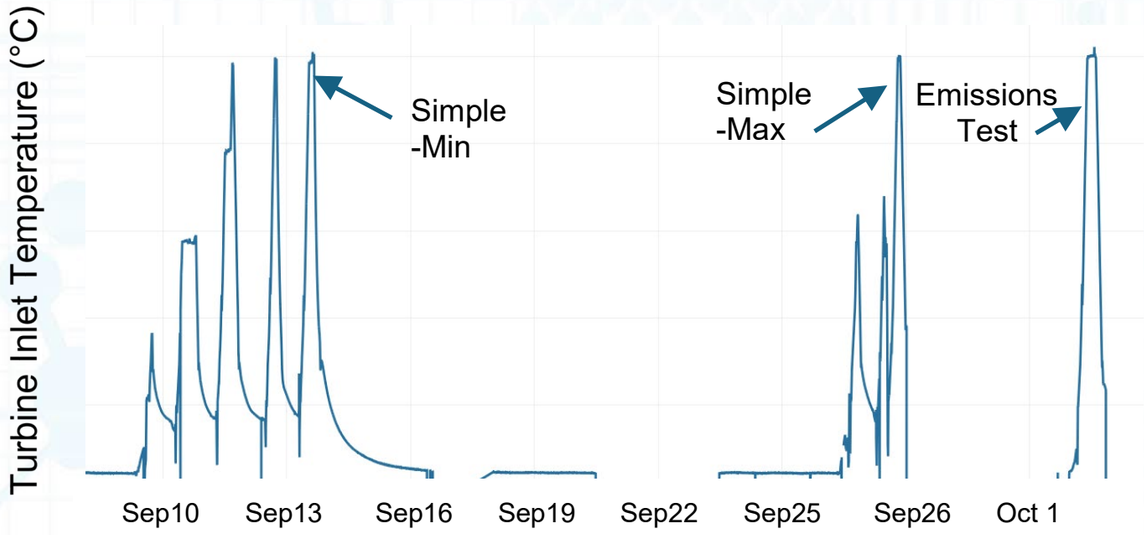
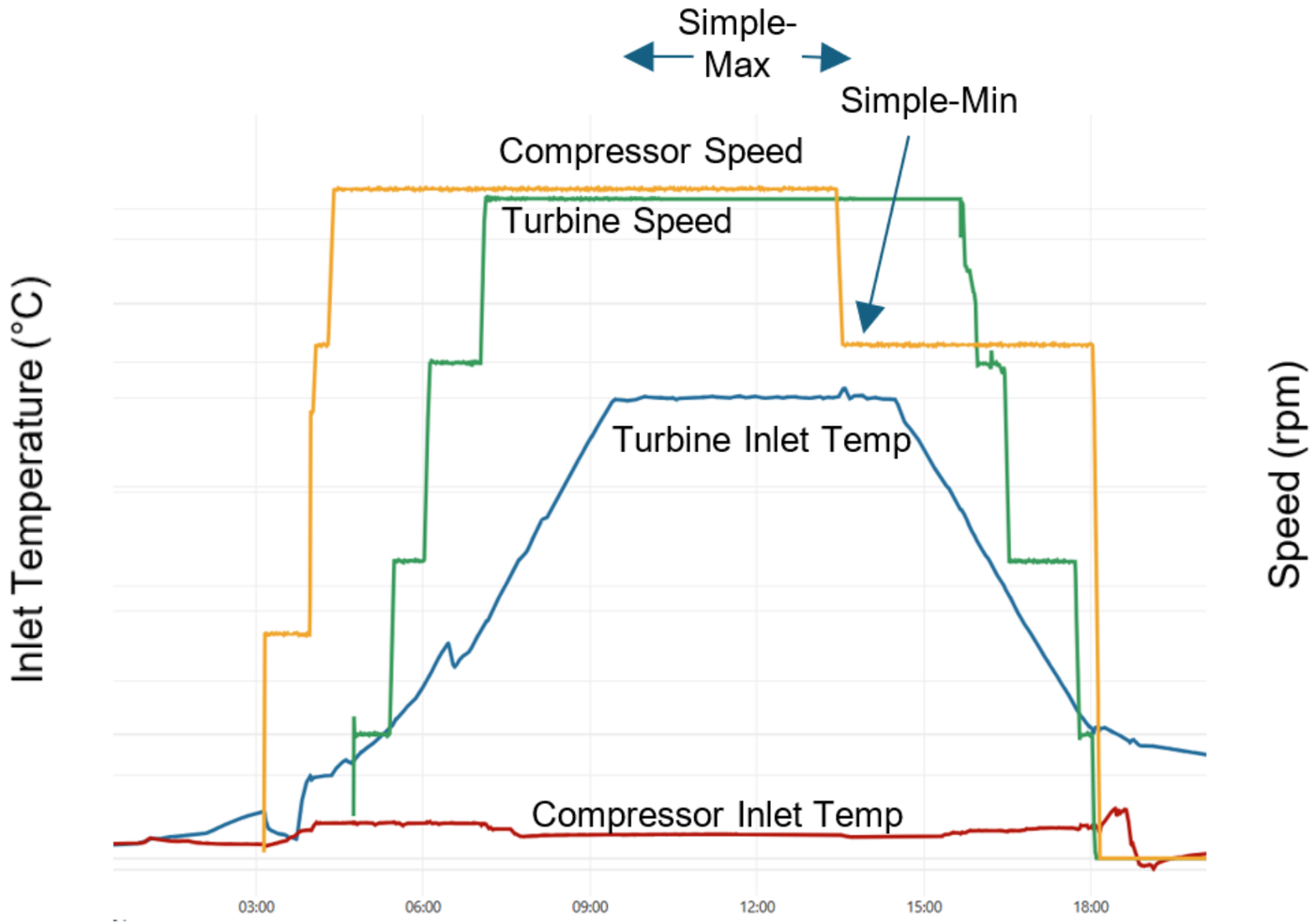


Figure 1. STEP Test Campaign Reaching 500 °C Turbine Inlet Temperature for Simple-Min, Simple-Max, and Emissions Test

Goal	Max Power	Trip
Verify turbine at full speed and high temperature with low load to check performance	100 kW on Load Banks	N/A
500°C TIT with Load Banks	150 kW on Load Banks	N/A
Ammonia injection in the heater for emissions reduction	290 kW on Load Banks	Turbine Gearbox vibrations
Achieve Simple Min	2.6 MW on Load Banks	Overvoltage resulting on a turbine overspeed
Grid synchronize	1.1 MW to Grid	No current measured on breaker bus
Achieve Simple Max	8.3 MW aero 7.4 MW generator 3.9 MW to Grid	N/A
Emission Testing at Simple Max, Repeat Simple Min	3.9 MW gross power to Grid	N/A

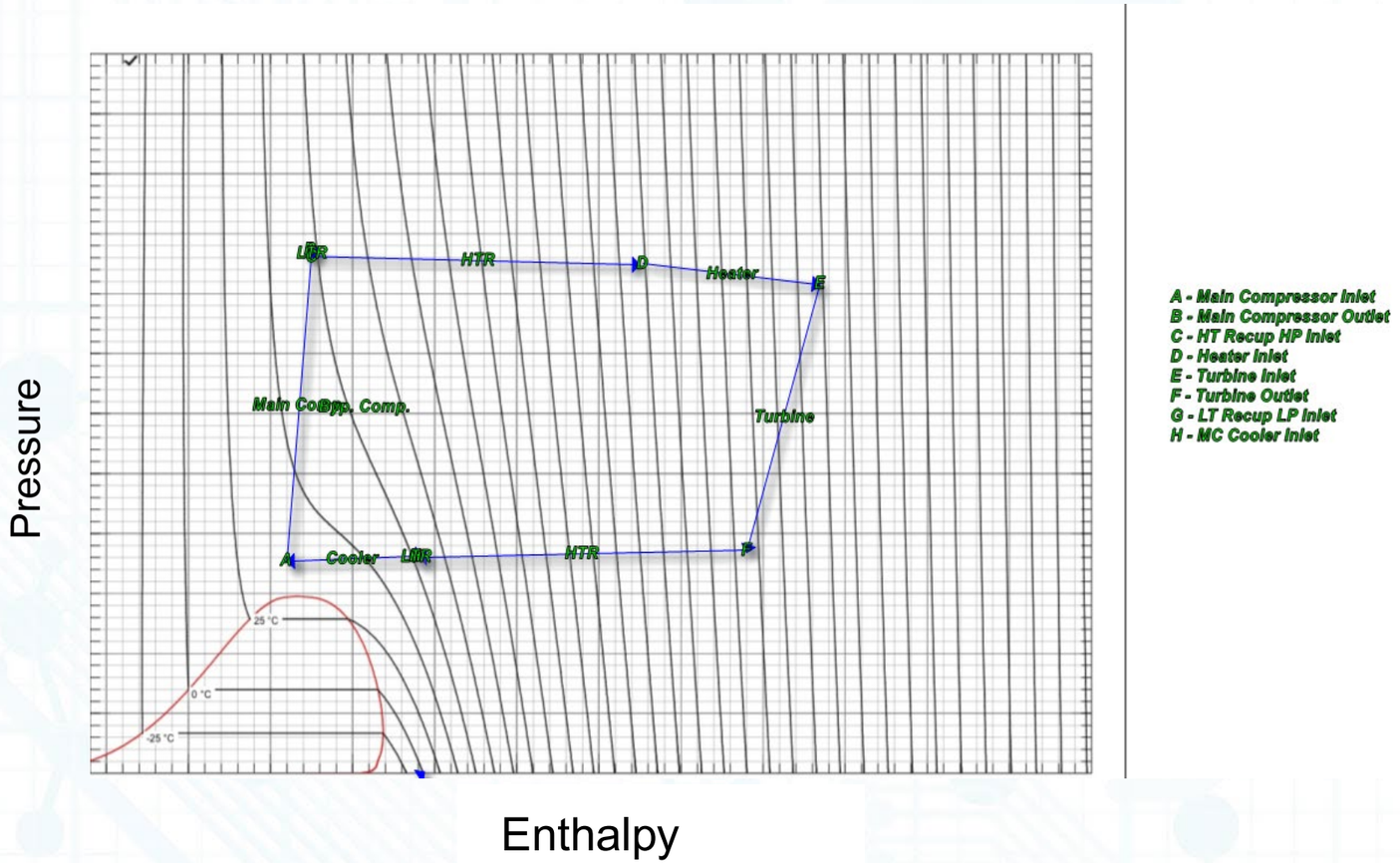
6-hour Emissions Test

- A 6-hour emissions test required to verify natural gas heater emissions test
- Both Simple Cycle maximum and minimum power conditions demonstrated



Simple Cycle Power Cycle

- Real-time pressure-enthalpy diagram measured and compared to predictions
- Turbine, compressor, and heat exchangers demonstrated good performance close to prediction



Conclusions

- sCO_2 systems have progressed through many component and now system development activities to increase technology readiness level
- Low- and medium-temperature systems are commercially available and have active commercial projects via companies like Hanwha, MAN Energy Systems, Echogen Power Systems, and others for waste heat recovery, heat pumps, and energy storage
- STEP 10 MWe demonstration has advanced simple recuperated sCO_2 cycles up to 500°C through full-scale pilot testing
- Opportunities exist in industrial decarbonization to utilize sCO2 power cycles and oxy-fuel combustion