



The International Supercritical CO<sub>2</sub> Energy Technologies Symposium  
Pittsburgh, PA U.S.A.  
March 2 - 5, 2026

*Paper #093*

March 4, 2026

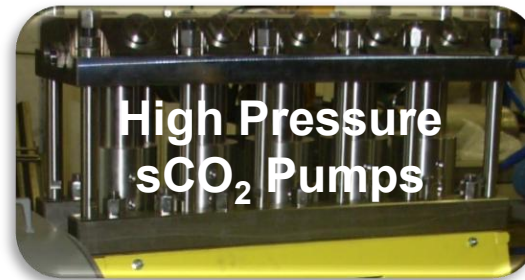
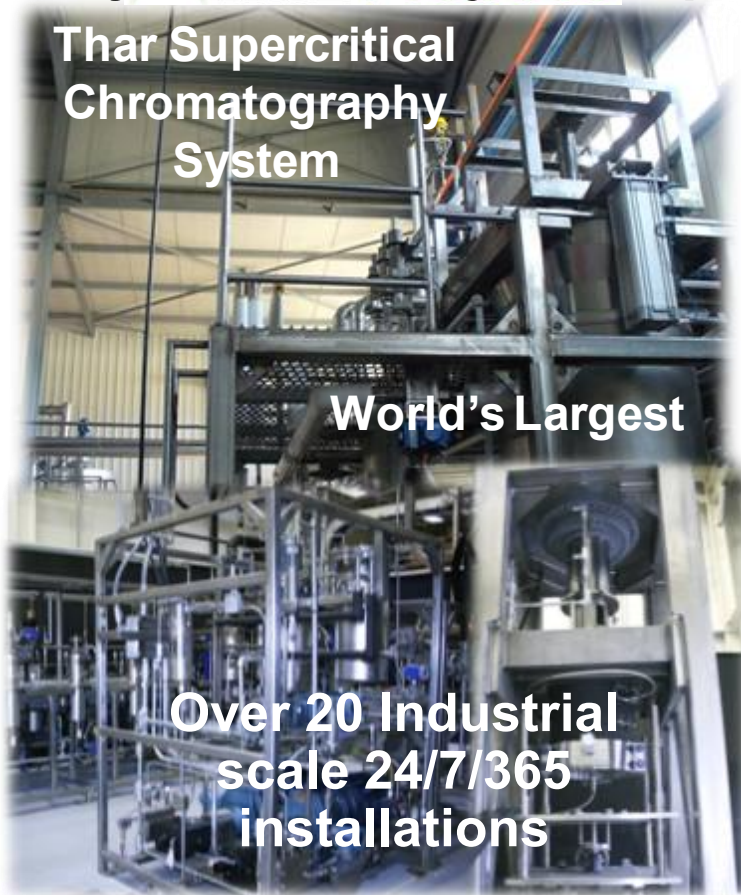
# Natural Refrigerant, Industrial High Temperature Heat Pump

Lalit Chordia, PhD, Vahid Vahdat, PhD, **Marc Portnoff**

**Thar**Energy

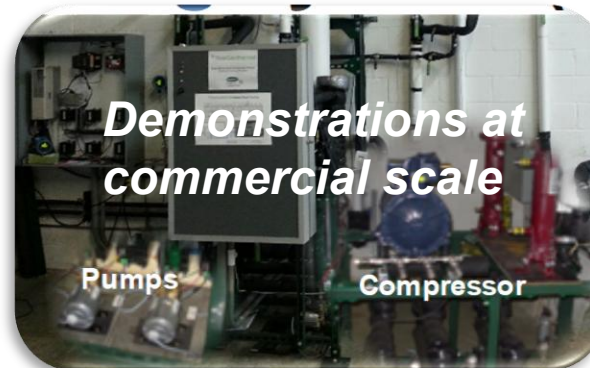
## Over 35 years of Innovation with “Green” Supercritical Fluid Technologies

### Design and commercialization of supercritical systems & major components



Over 5,000 scientific instruments installed

Direct Exchange, R744 (CO<sub>2</sub>)  
Geothermal Heating & Cooling

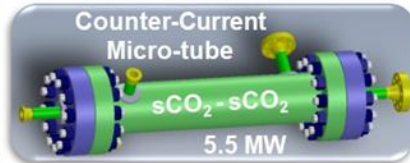


### Components & Cycle Development

*Turning concepts into hardware*

#### sCO<sub>2</sub> Brayton Power Cycle Development

**COMPACT** Heat Exchangers for sCO<sub>2</sub> Power Cycles



3D Printed, Inconel 718, sCO<sub>2</sub>-sCO<sub>2</sub> Recuperator

Design – Construct – Install  
**Primary Heater for Sunshot**  
One MWe sCO<sub>2</sub> Test Loop



1<sup>st</sup> HX made using Inconel 740H

Design – Construct – Operate  
**sCO<sub>2</sub> Heat Exchanger Test Loop**  
*Superior Thermal Performance Confirmed*



Gas Cooler Air-sCO<sub>2</sub>



2014



Design – Construct – Operate Largest GMP sCO<sub>2</sub> Extraction System in USA

2015



Expands into Liquid Chromatography

2016

Oxy Combustion Test Facility  
Design – Construct – Operate  
Demonstrate auto-combustion

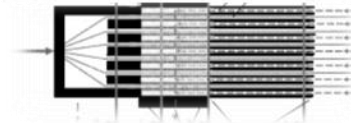


2017

UNITED STATES PATENT AND TRADEMARK OFFICE



Patent - Notice of Allowance  
Counter Current Heat Exchanger/Reactor



Thar Pharmaceuticals sold to



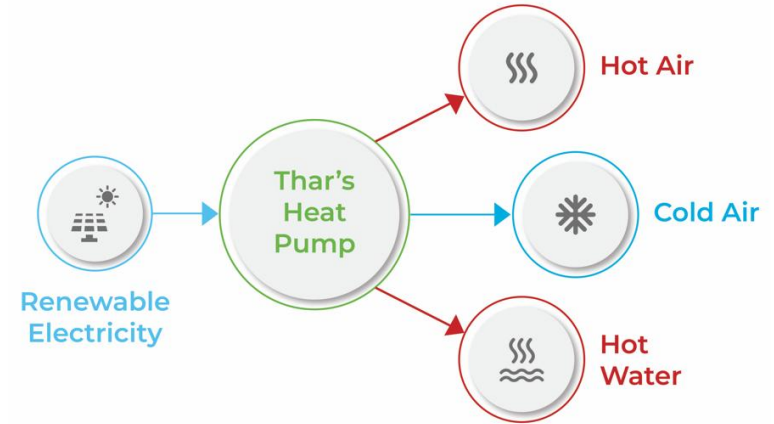
## System & Product Development

### Geothermal/Waste Heat Recovery

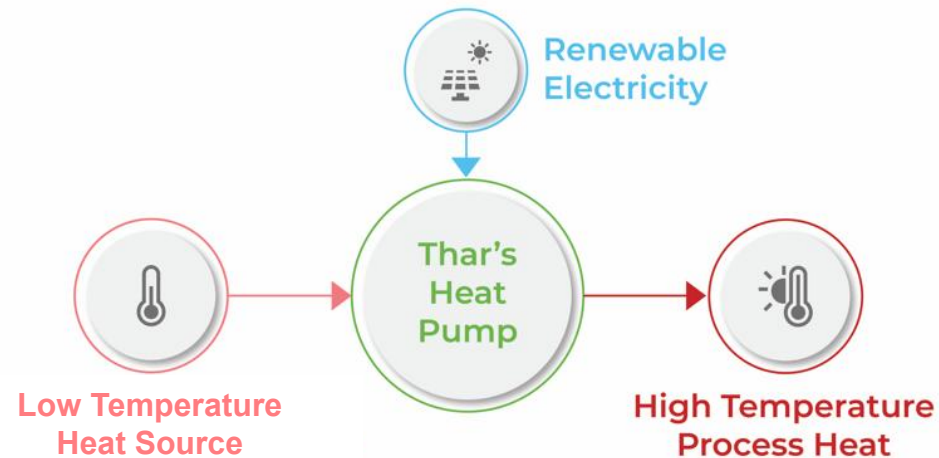
Cost Effective - Efficient - Modular



### Simultaneous Heating & Cooling

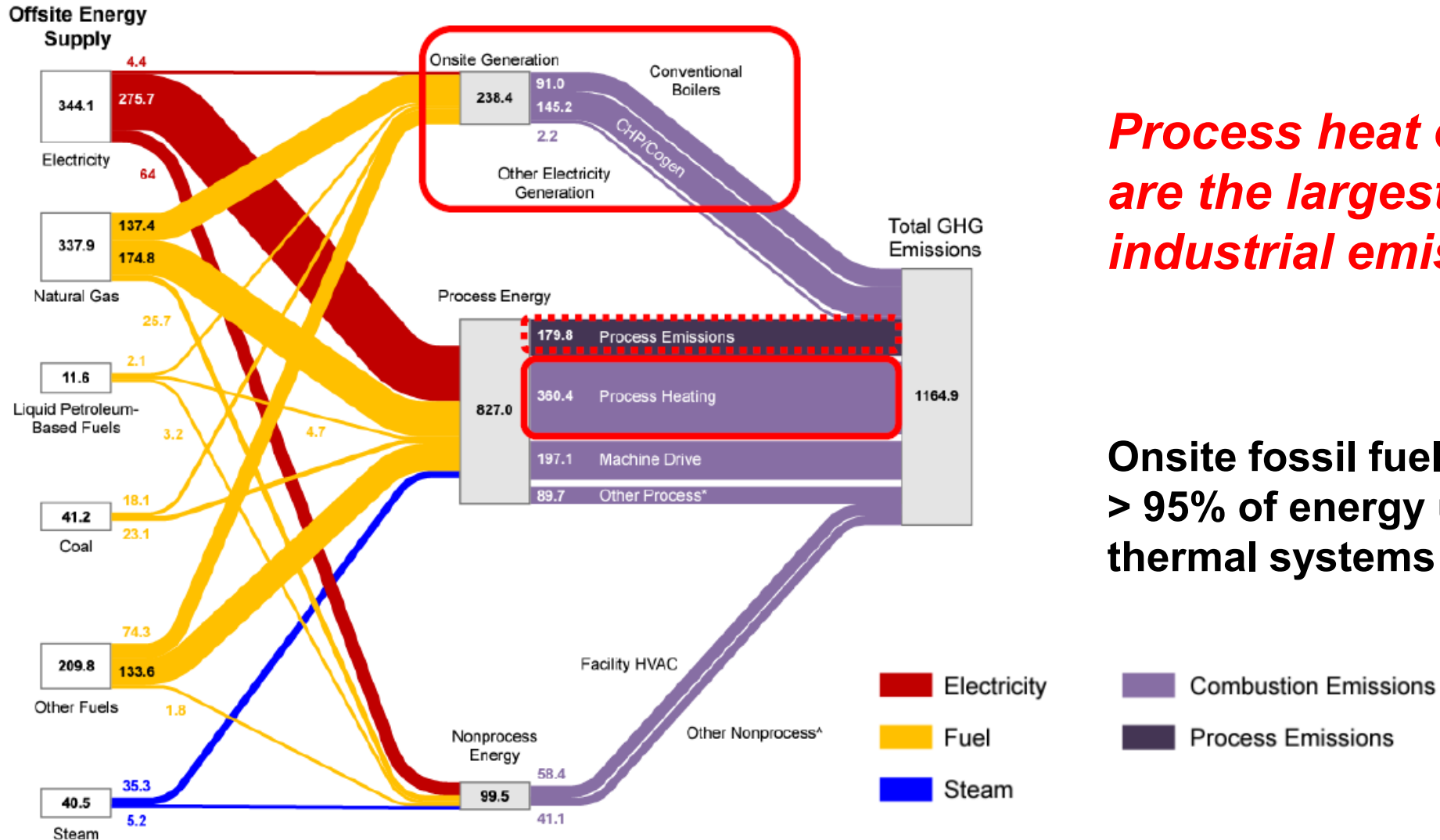


### High Temperature Heat Pump



# Process Heat Manufacturing Emissions

## U.S. Manufacturing GHG Emissions (MMT CO<sub>2</sub>e), 2018

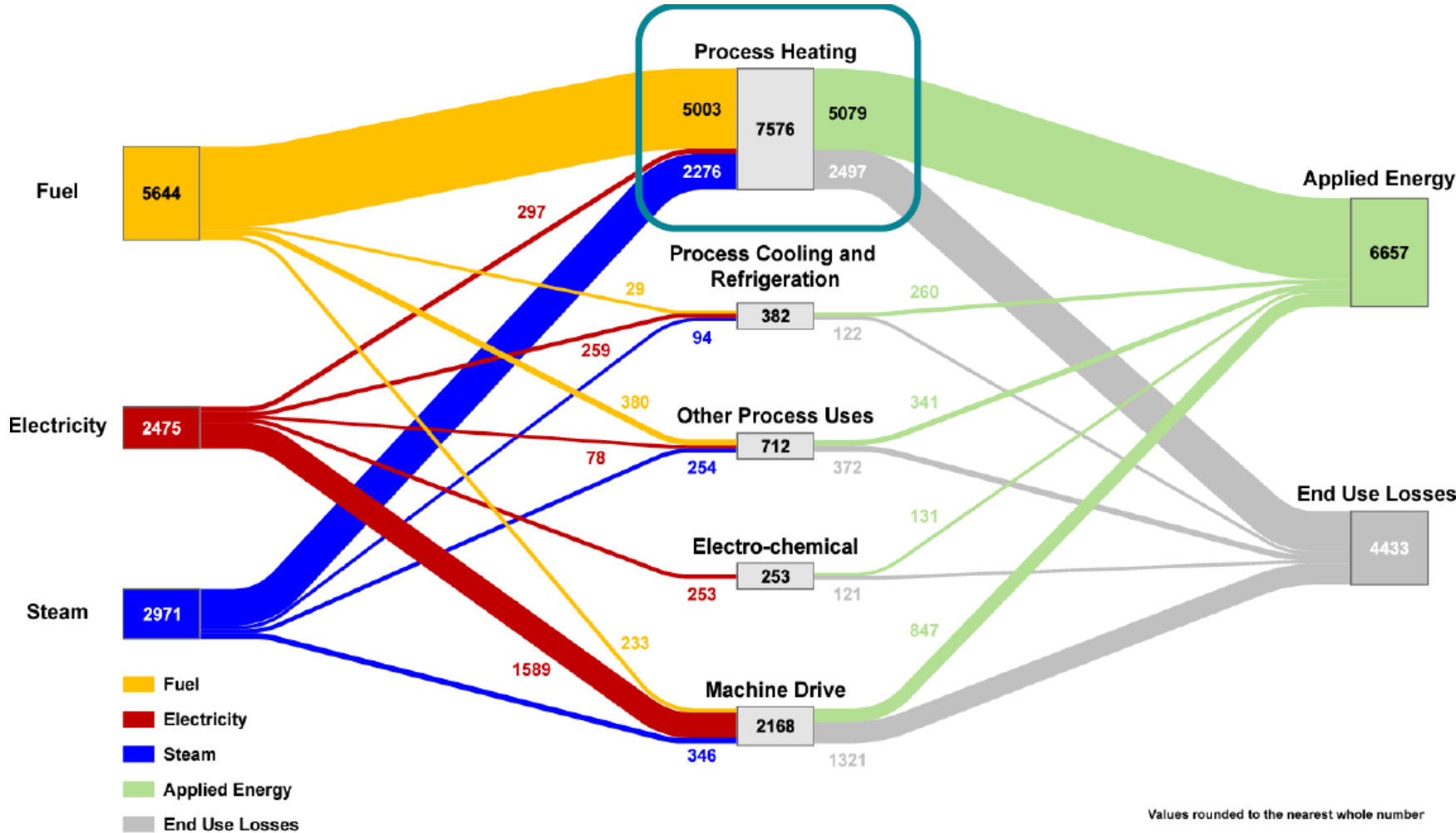


*Process heat emissions are the largest source of industrial emissions*

**Onsite fossil fuel combustion > 95% of energy used to power thermal systems**

## Process Heating is the Largest Single Source of Energy Loss in Manufacturing

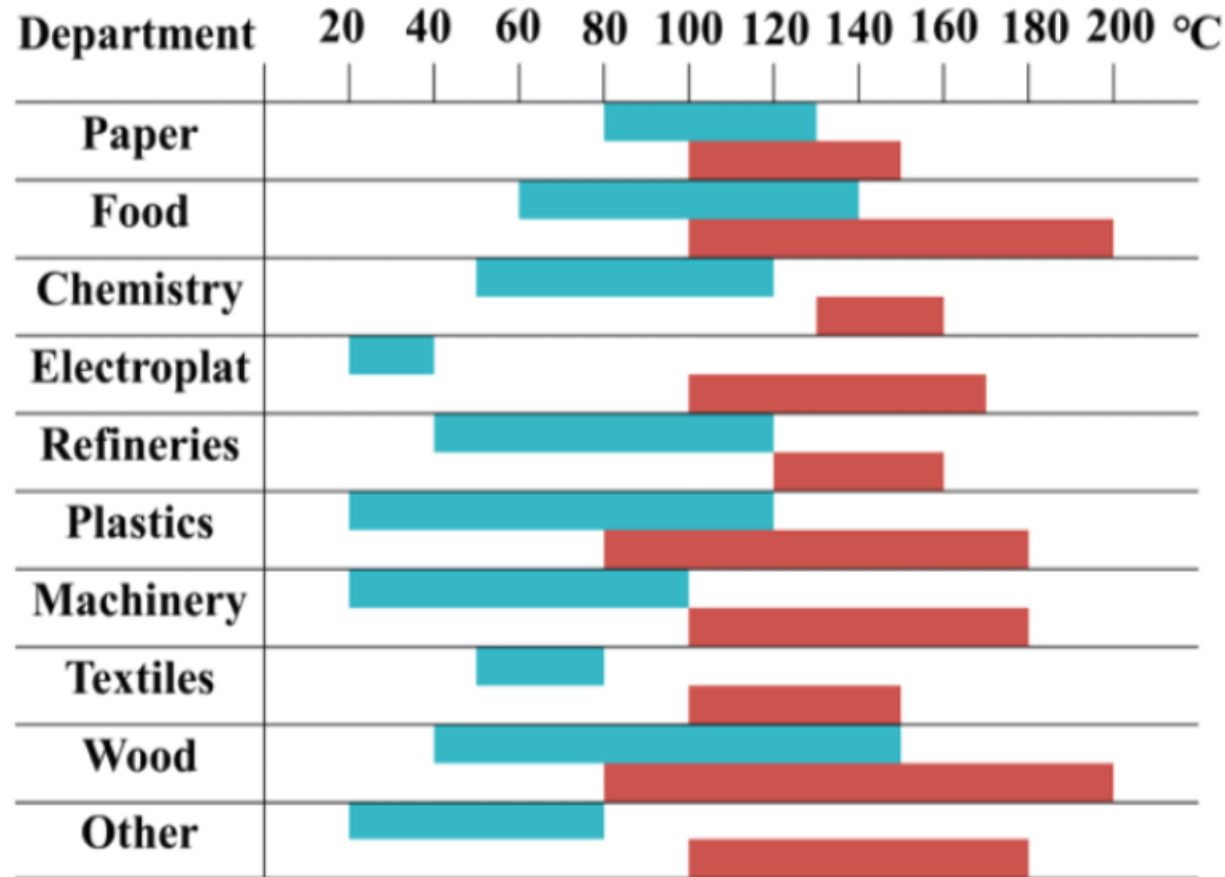
### U.S. Manufacturing Process Energy (TBtu), 2018



*~1/3 of process heat is lost*

- Industrial sector currently accounts for **~1/3** of our nation's energy-related CO<sub>2</sub> emissions.
- This creates **~52%** of the country's industrial direct greenhouse gas emissions.

## Industrial Process Heat & Waste Heat Temperatures Plot



**Waste Heat**

**Process Heat**

***Waste heat & 100-170°C steam co-exist***

Xudong Ma, Yanjun Du \*, Biao Lei, Yuting Wu, Energy, exergy, economic, and environmental analysis of a high-temperature heat pump steam system, International Journal of Refrigeration 160 (2024) 423–436

## High Temperature Heat Pump

*Process heat to the chemical, refining and food industries*

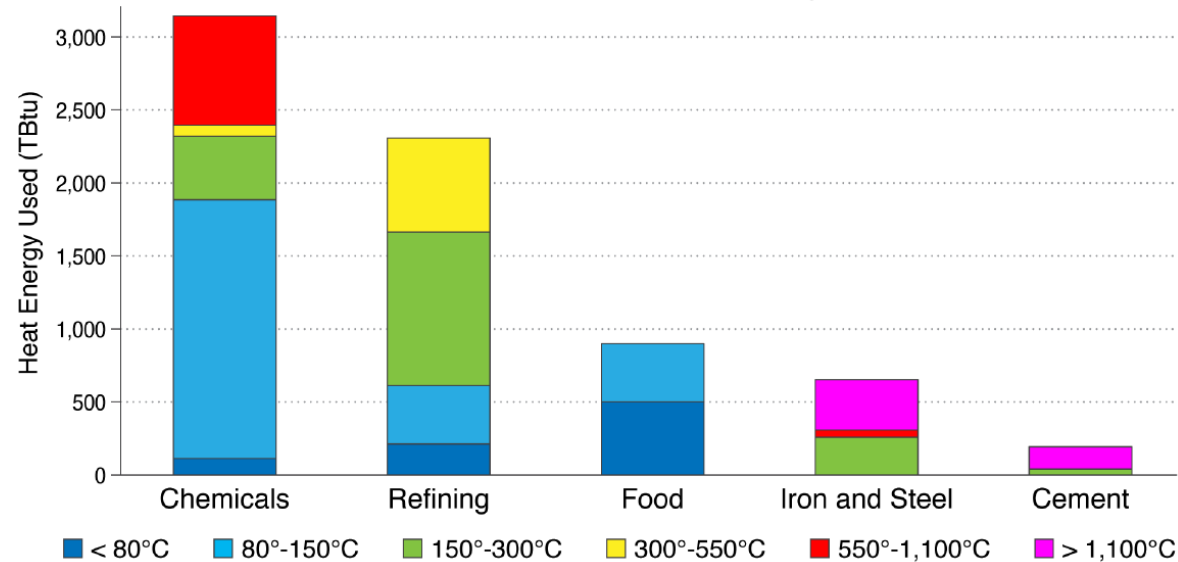


**Refining**



**Chemicals**

### Process temperature - Industry Distribution



**Food**

**130°C** accounts for ~42% of industrial thermal emissions  
**200°C** accounts for ~60% of industrial thermal emissions

## Clean Heat for Tall Buildings!



NYSERDA:

**Heating Tall Buildings** is the greatest single source of New York City GHG emissions.

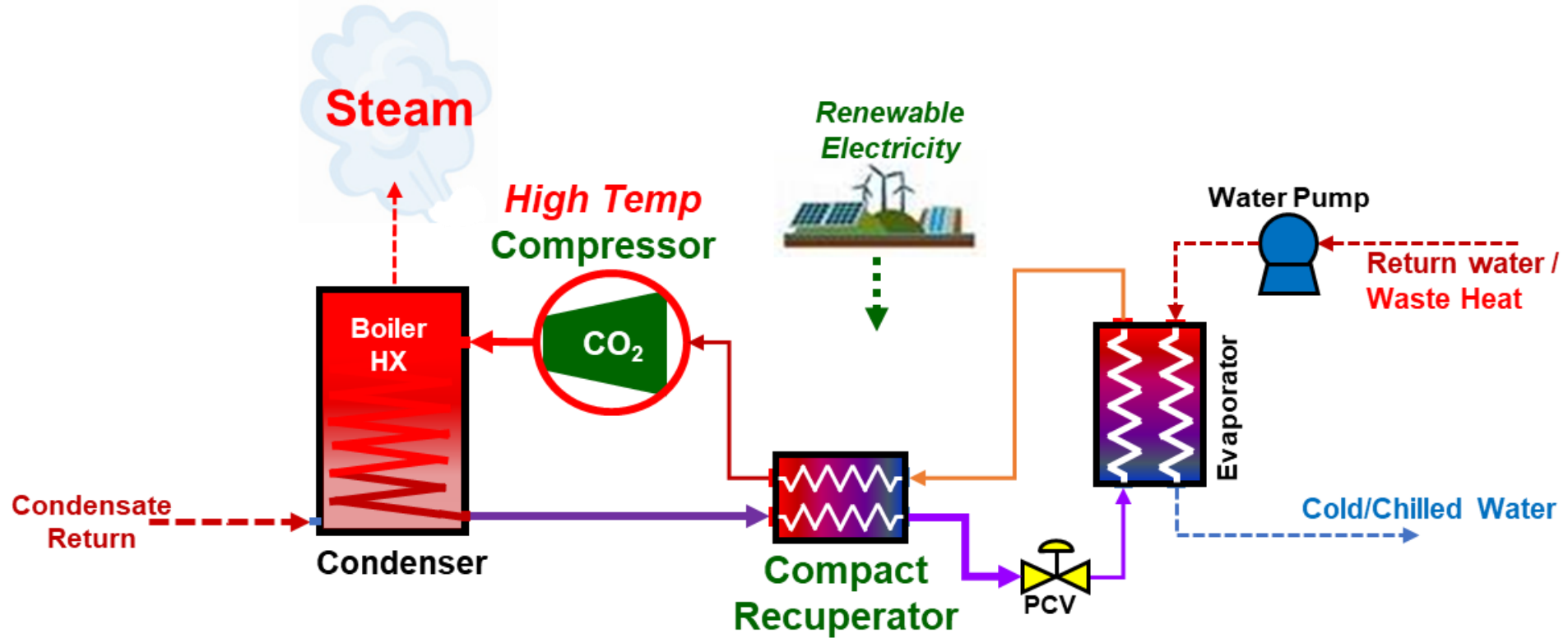
**>1 billion ft<sup>2</sup> of space**



**New Product Focus: Natural Refrigerant, Steam Heat Pump**

- Decarbonized **Steam Heat & Hot Water**
- Simultaneous **Heating** and **Cooling**
- Improved economics/efficiency
- **Lower Carbon Footprint**
- Drop-in replacement for gas-fired boilers

# One Stage Recuperated sCO<sub>2</sub> Steam Heat Pump Process Flow Diagram



## Steam Cycle Temperatures

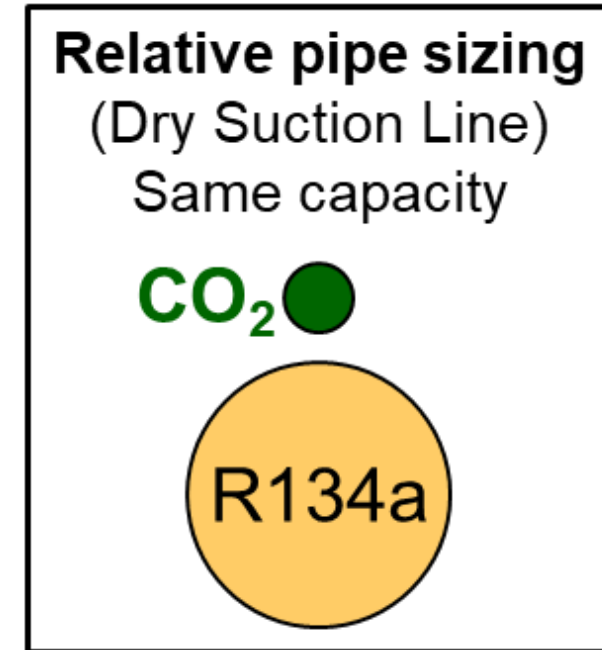
- Low T - 104°C
- Medium T - 160°C
- High T - 200°C

*Majority of existing application are Low and Medium Temperatures*

## Natural Refrigerant Carbon Dioxide (CO<sub>2</sub>, R744)

### ADVANTAGES:

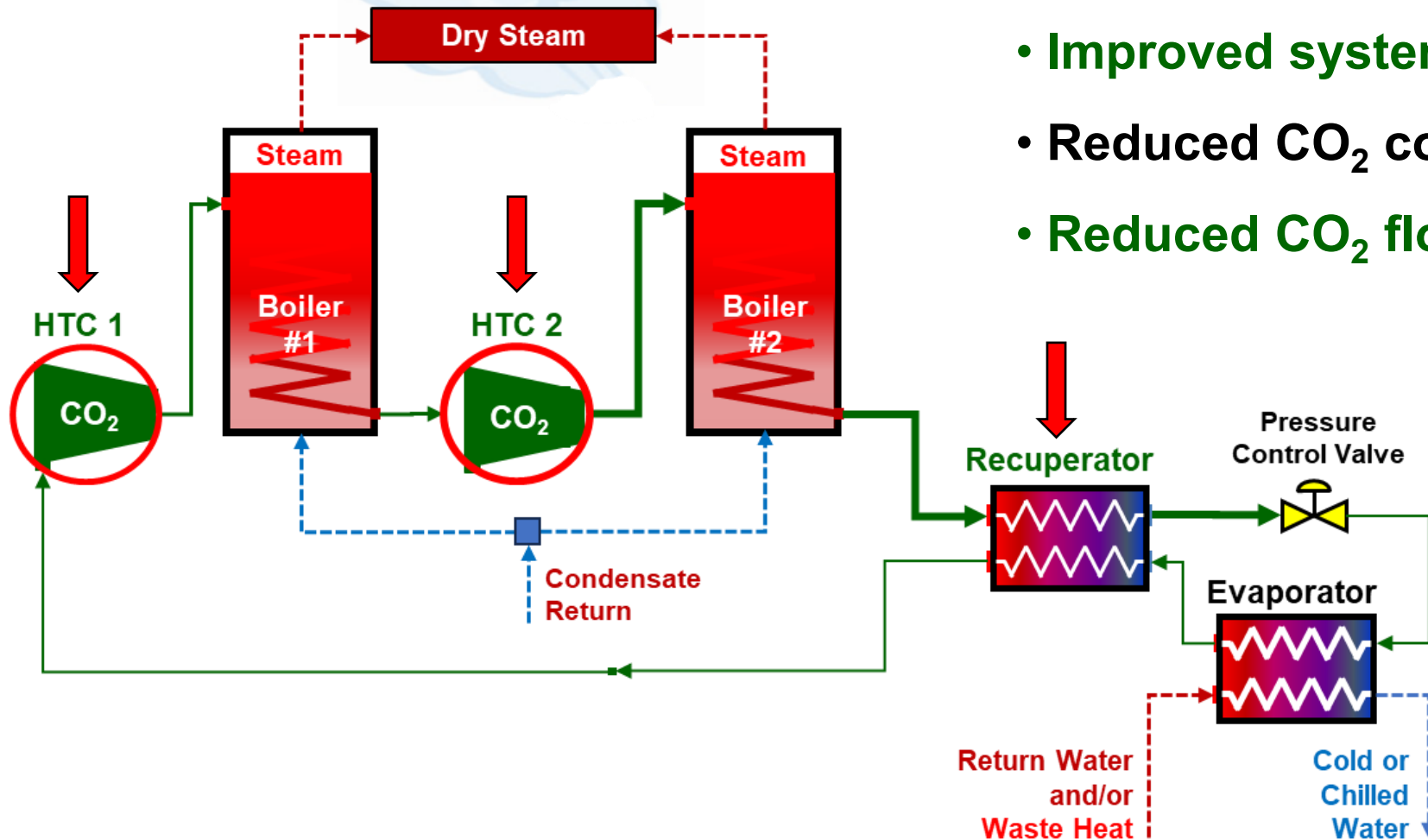
- Meets/exceeds A1 requirements
- Safe: Nontoxic, Nonflammable & Noncorrosive
- Significantly less expensive
- Substantially lower maintenance costs
- Does not affect the ozone layer
- Least impact on global warming
- Large carbon footprint reductions
- Unaffected by future legislation & taxation



- **Smaller components & refrigerant lines**
  - Higher cooling capacity
  - More efficient heat transfer

## Demo sCO<sub>2</sub> Steam Heat Pump System

### Two Stage Recuperated Cycle



### Recuperator Cycle Benefits:

- Improved system COP by ~40%
- Reduced CO<sub>2</sub> compressor pressure by ~45%
- Reduced CO<sub>2</sub> flow by greater than 50%

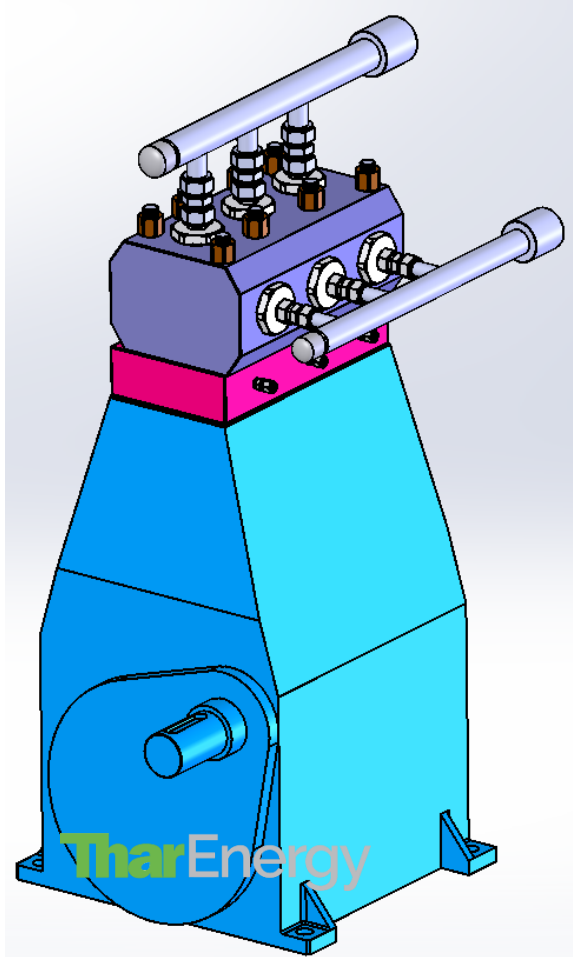
**High Temperature sCO<sub>2</sub> Compressor**

**Pres: 40 - 140 bar**

**Temp: 170°C +**

**Model**

**As tested**



**High  
Temp.  
Custom  
Seals**



## Steam Heat Pump Recuperator Stack-sheet Heat Exchanger (SSHX)

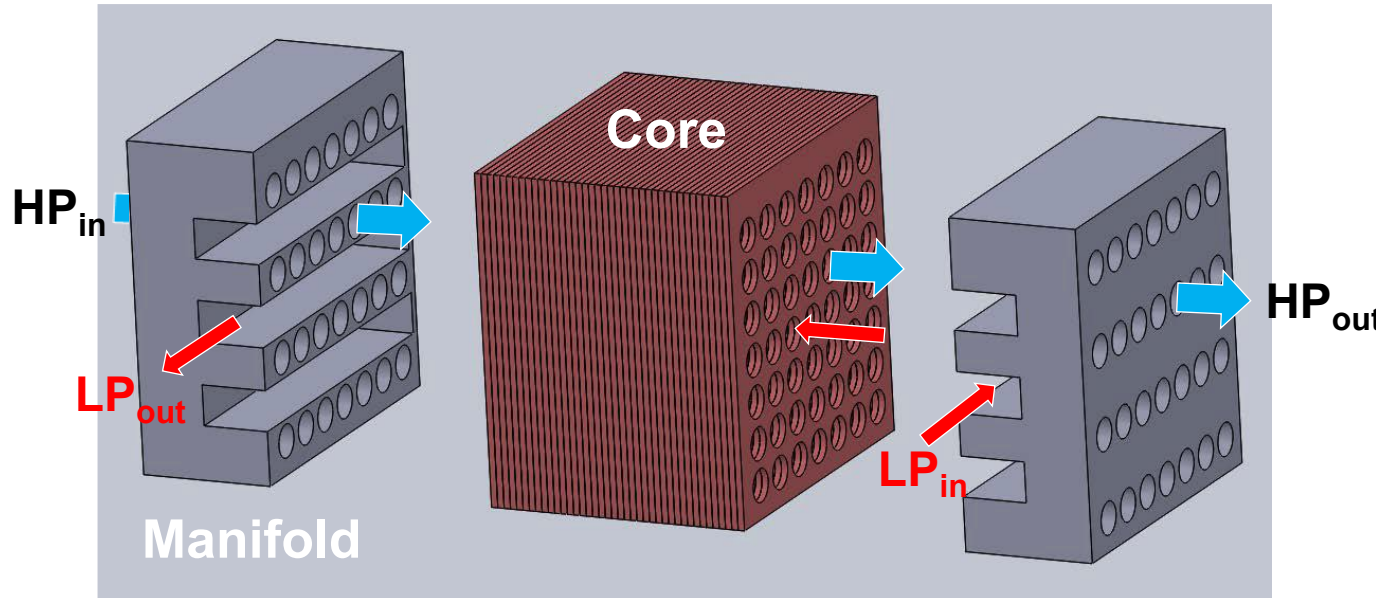
- ❖ **High thermal and hydraulic performance (counter-current)**
- ❖ **Improved structural integrity and thermal compliance**
- ❖ **Compact and light weight**
- ❖ **Optimized material usage**



**Design T/P: 300°C/300 bar**

**Effectiveness: ~95%**

## Stacked-sheet Recuperator Concept (SSHX)

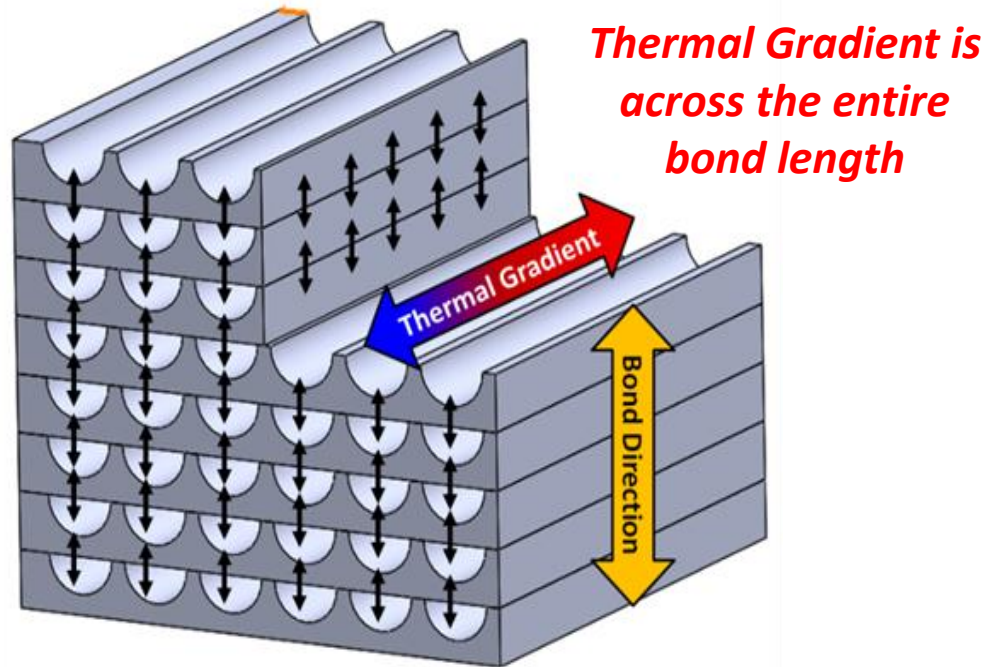


- Patterns cut, punched or etched into individual sheets
- Sheets are aligned, stacked, and joined (brazed, diffusion bonded)
- Manifolds/headers are added to separate flow streams and ensure uniform flow distribution

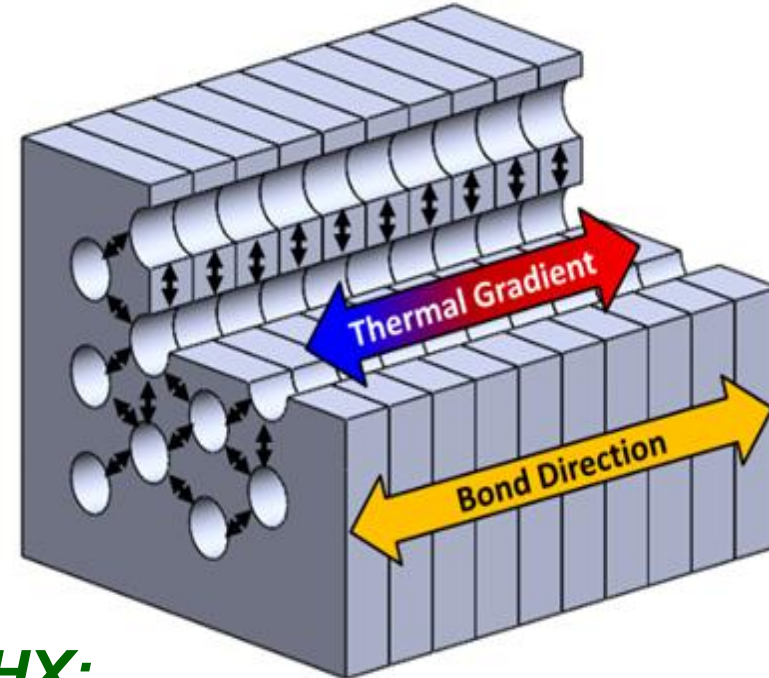
*The concept offers the opportunity for cost effective design enhancements*

**Accommodates advances in Subtractive and/or Additive Manufacturing**

# Mechanical & Thermal Stress Analysis - Printed-Circuit HX vs. SSHX



**Printed-Circuit HX:**  
*The bond between sheets is: perpendicular to the mechanical stresses & parallel to the thermal stresses*

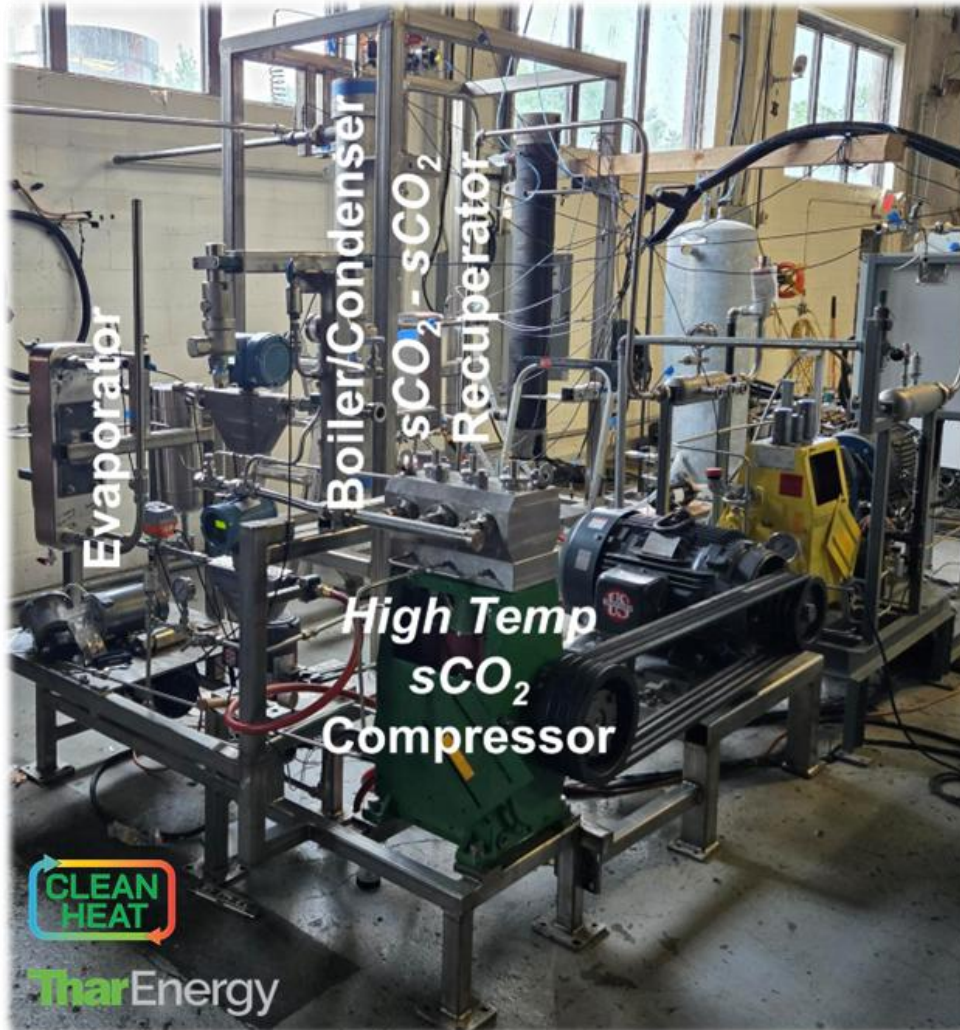


**SSHX:**  
*The bond between sheets is: parallel to the mechanical stresses & perpendicular to the thermal stresses*

*Improves structural integrity and thermal compliance*

## Demo sCO<sub>2</sub> Steam Heat Pump System

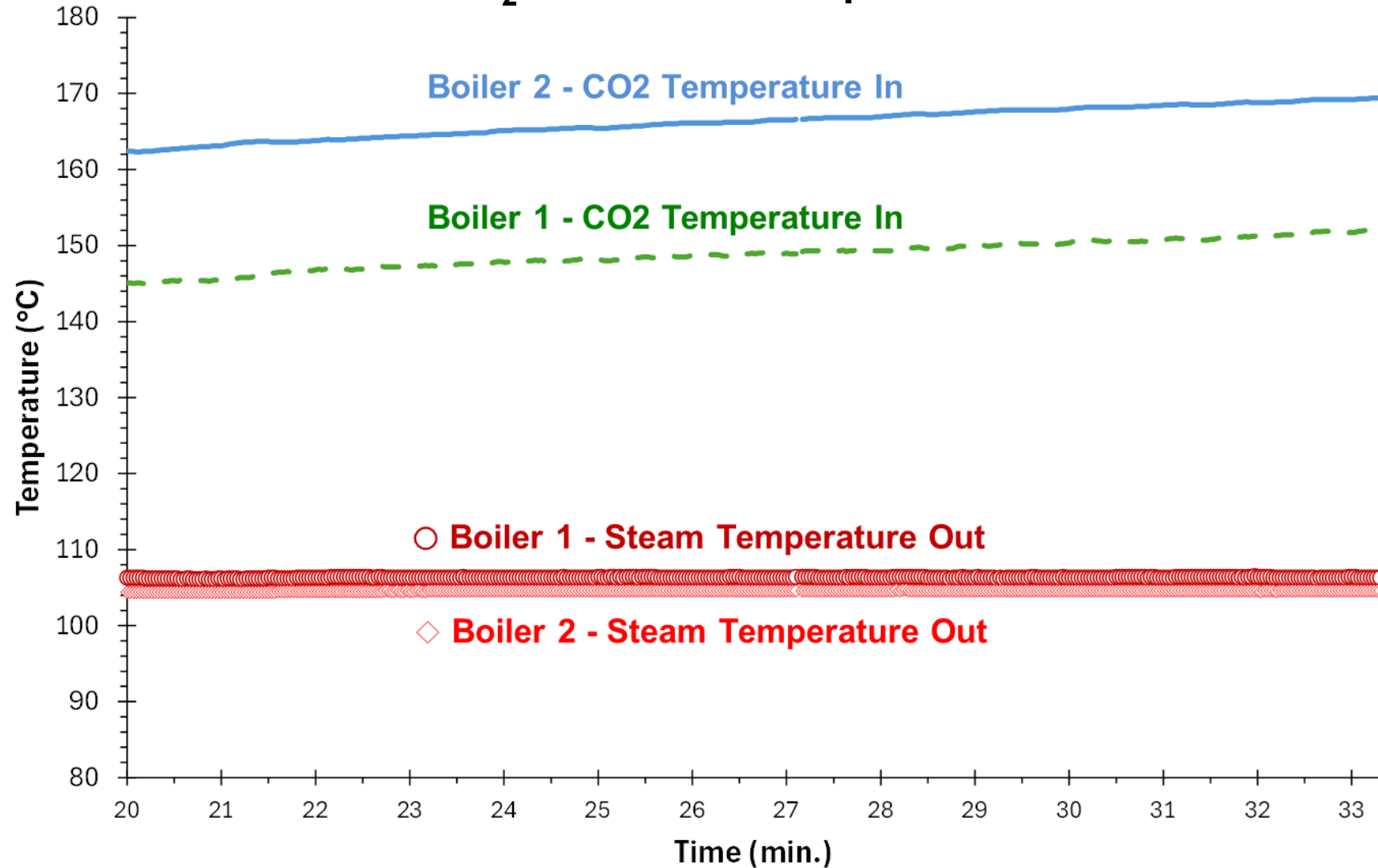
Two stage recuperated heat pump system



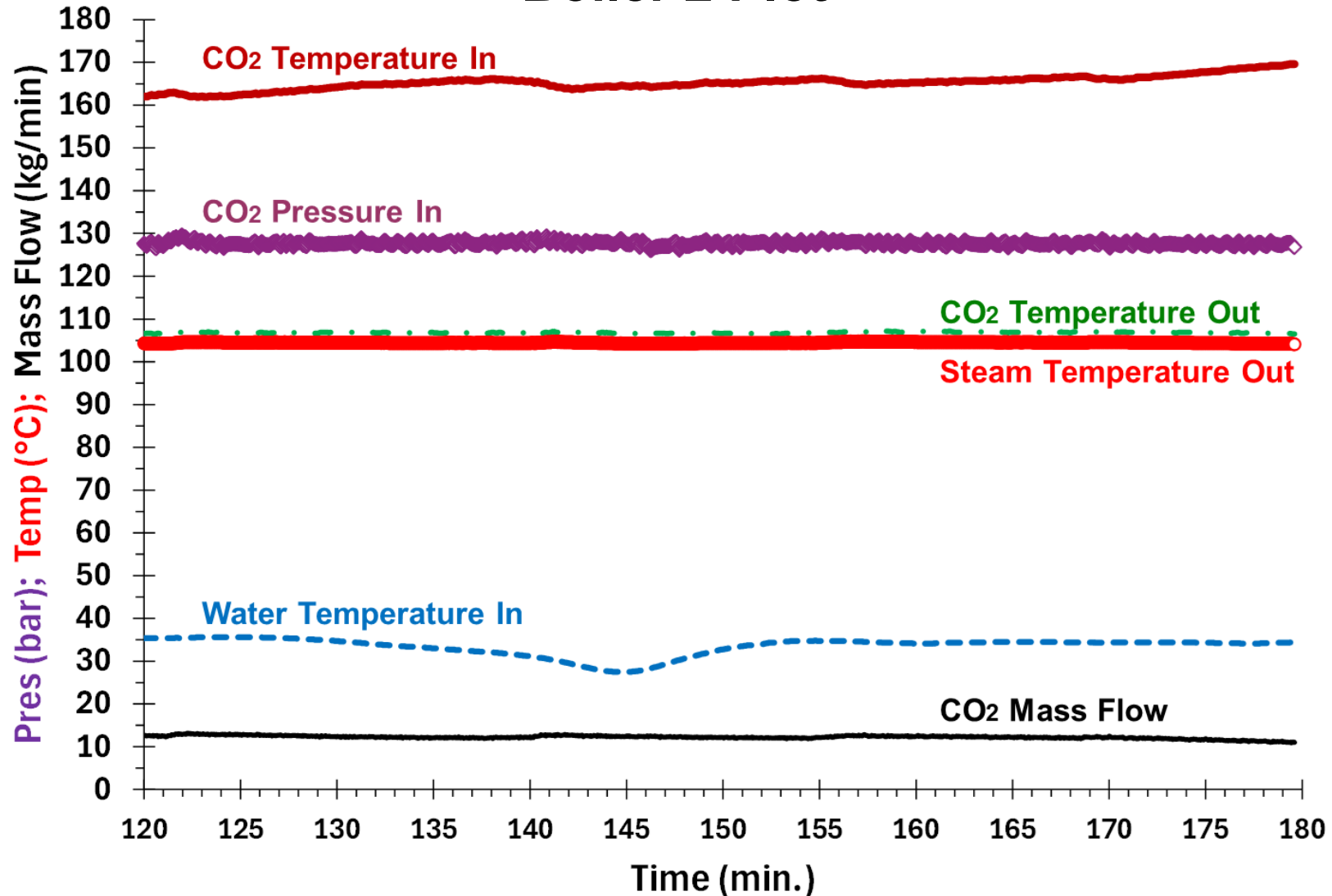
***Produced Low T/P Steam***  
**104°C (219°F) / 1.3 bar (19 psi)**



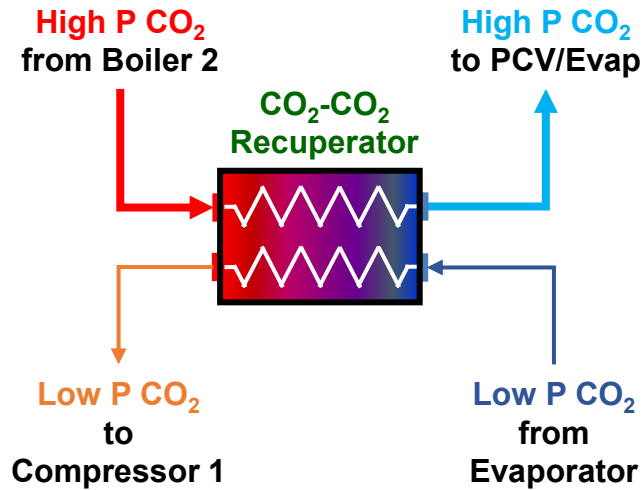
## Demo sCO<sub>2</sub> Steam Heat Pump System Boiler CO<sub>2</sub> and Steam Temperature Plot



## Demo sCO<sub>2</sub> Steam Heat Pump System Boiler 2 Plot

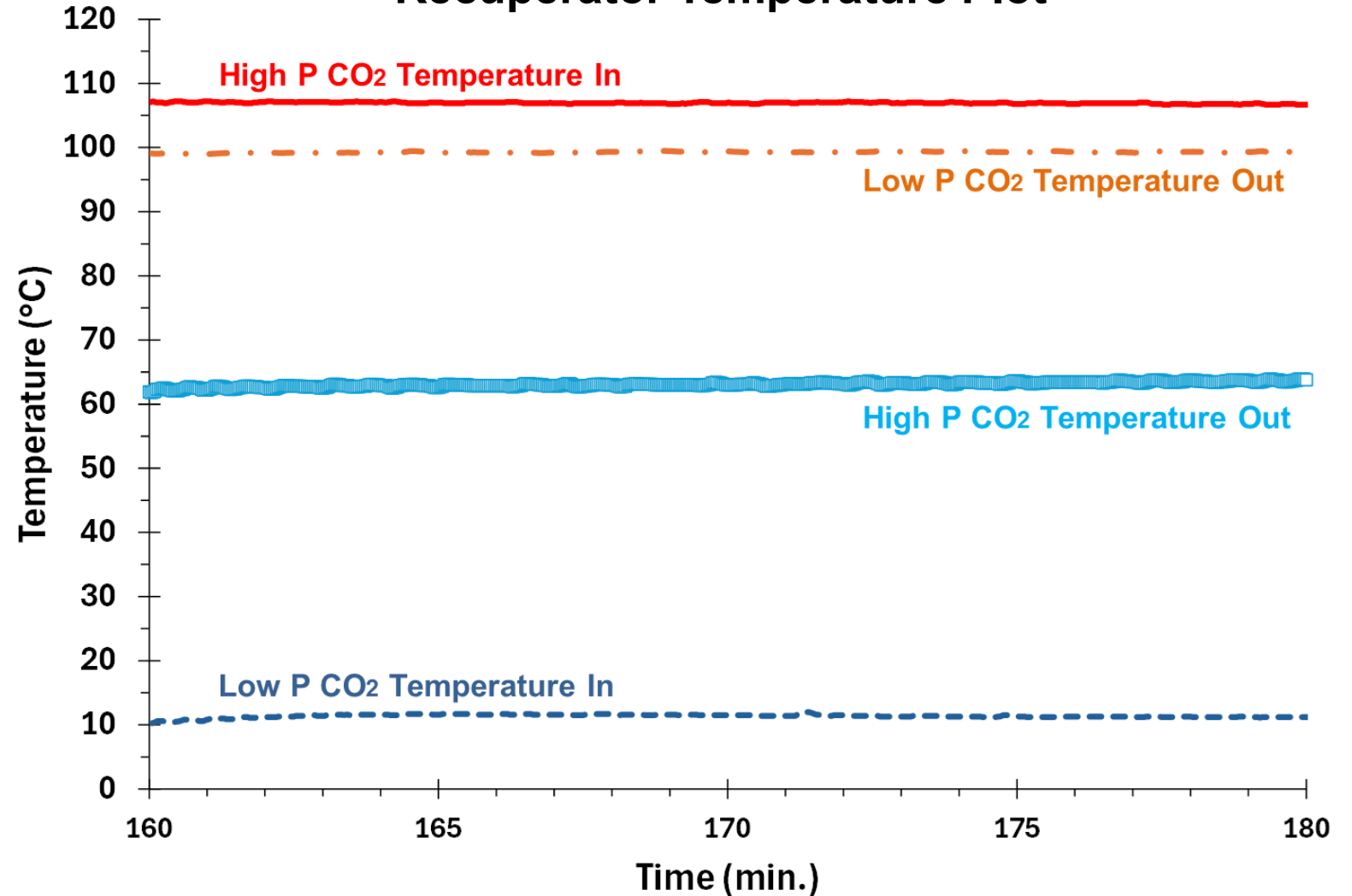


# Demo sCO<sub>2</sub> Steam Heat Pump System



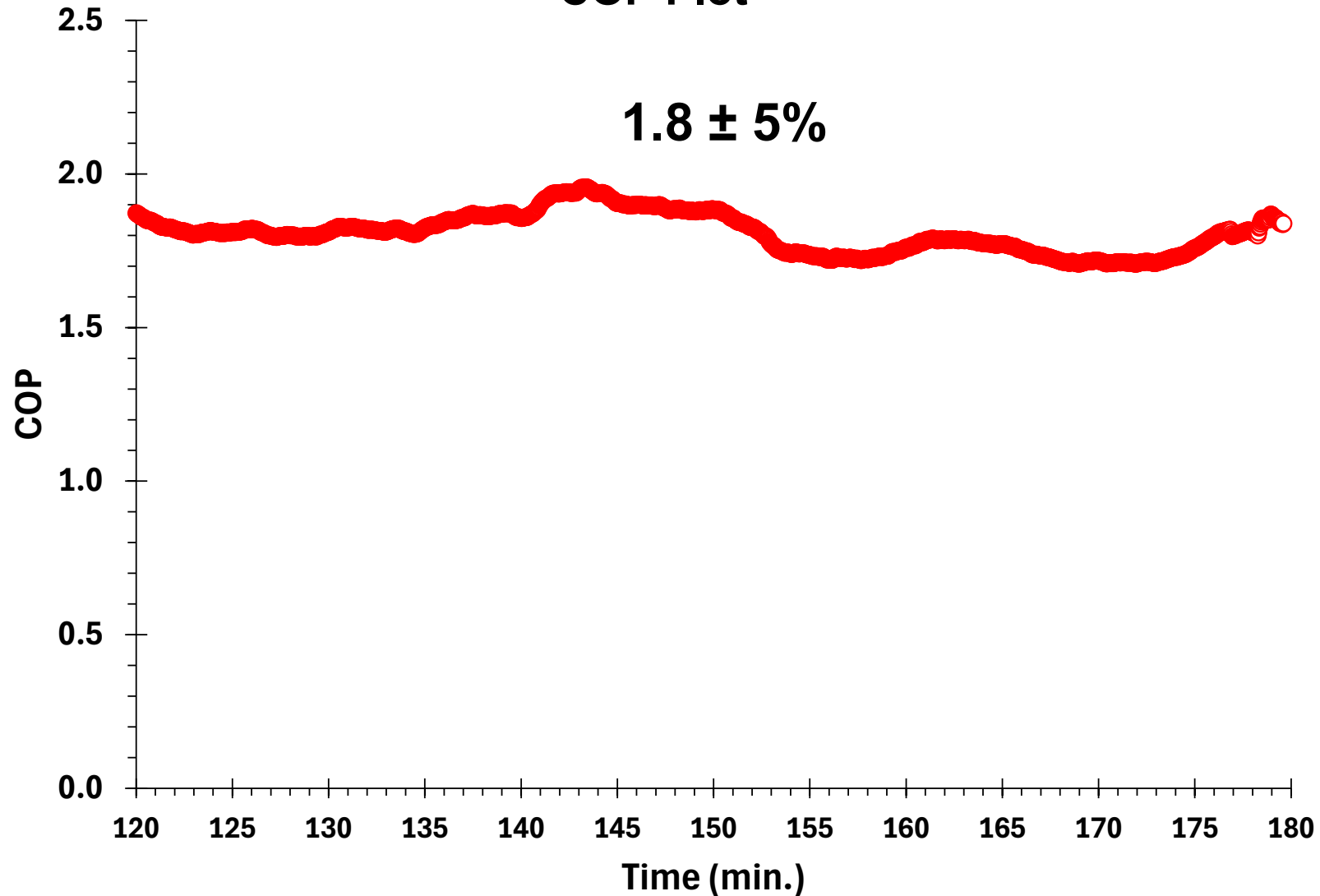
**~90% Effective**

## Recuperator Temperature Plot



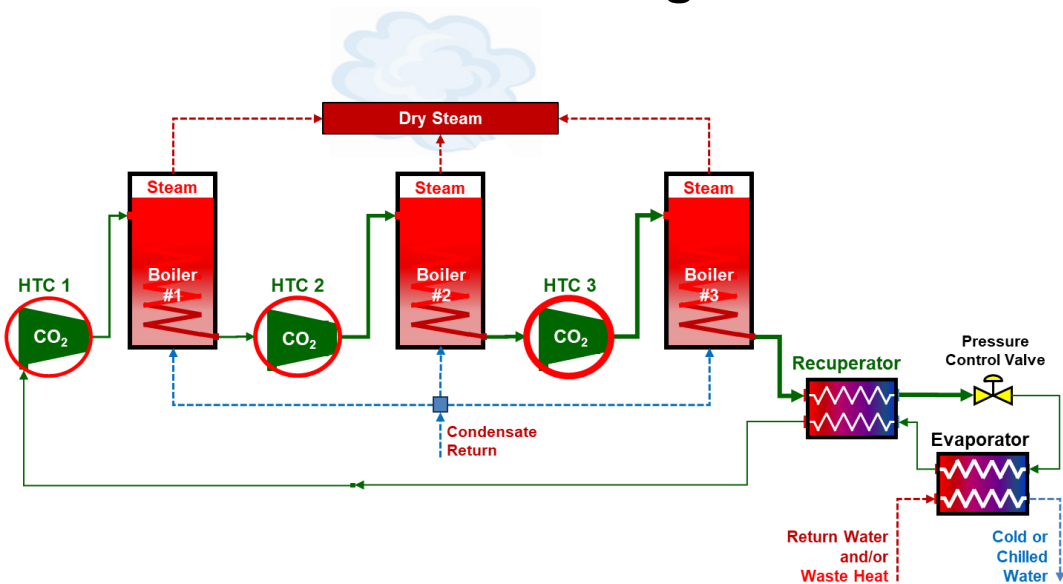
## Demo sCO<sub>2</sub> Steam Heat Pump System

### COP Plot



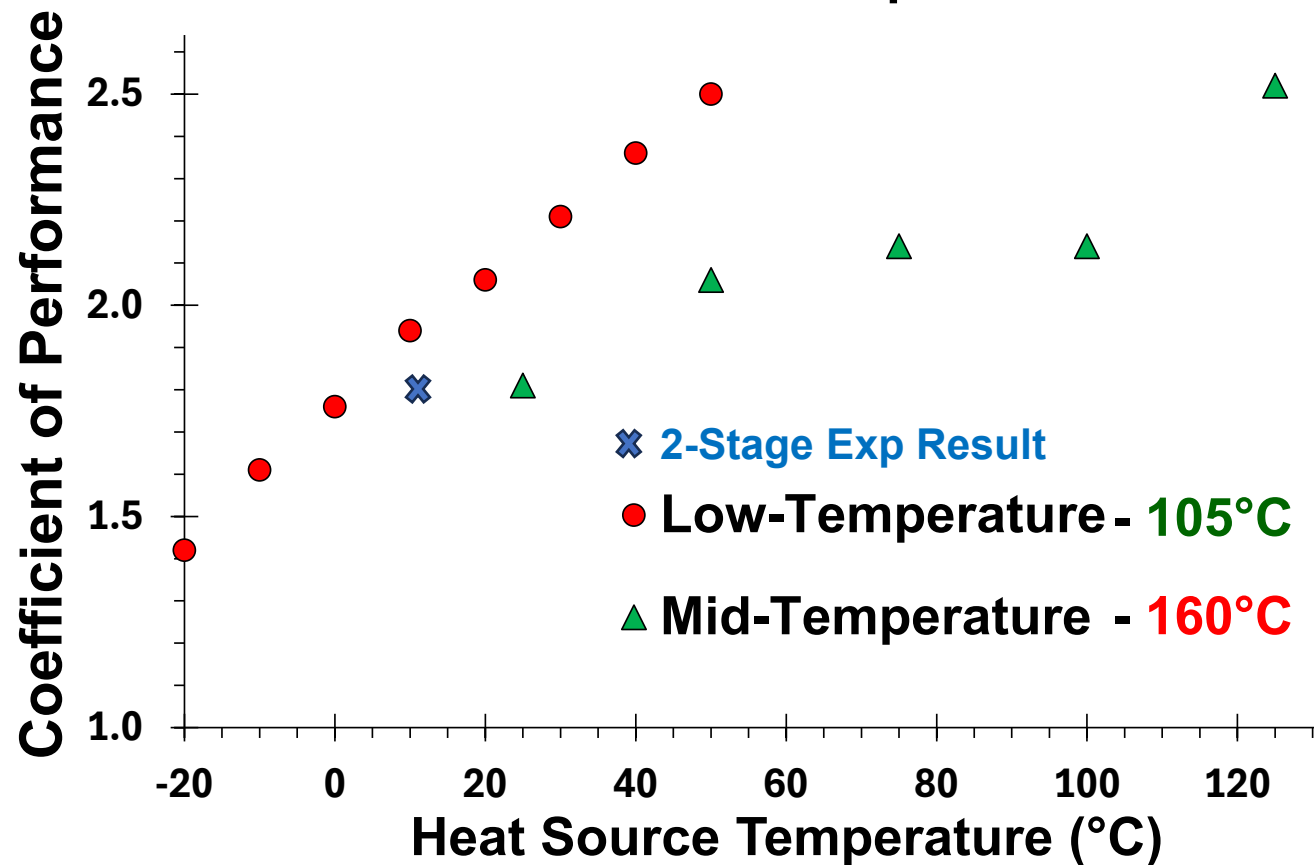
## Three Stage Recuperated sCO<sub>2</sub> Steam Heat Pump

Process Flow Diagram



*Need to balance improved COP with Capital Equipment costs*

COP vs Heat Source Temperature Plot



## Summary

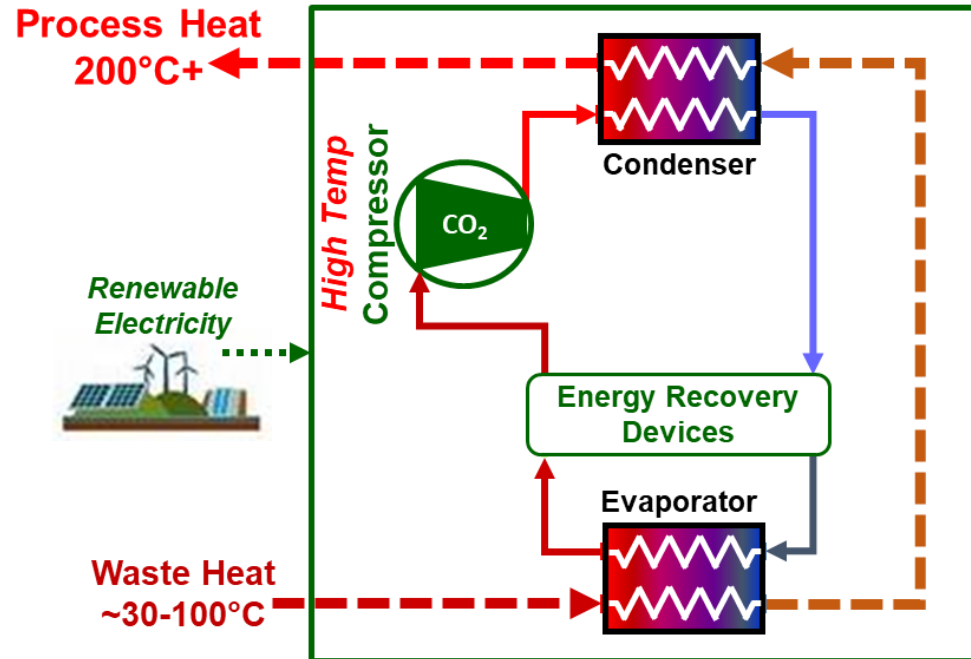
- **CO<sub>2</sub> has excellent refrigerant properties**
- **Validated novel iHTHP Steam cycle (104°C - 200°C)**
  - **High Carnot Efficiency** (65% of Carnot COP (50°C heat source and 200°C heat sink))
- **Demonstrated:**
  - **sCO<sub>2</sub> Recuperated Steam Heat Pump System**
    - Improved system COP by ~40%
  - **170°C High Temp sCO<sub>2</sub> Compressor**
  - **Novel Compact sCO<sub>2</sub> - sCO<sub>2</sub> Recuperator**

Thank you to U.S. DOE - Office of Critical Minerals & Energy Innovation -  
Industrial Technologies Office & The Clean Fight - Empire Technology Prize

*Thank you for your kind attention!*

**Questions?**

## Natural Refrigerant, CO<sub>2</sub>, High Temperature Heat Pump



*Designed to reduce the cost and environmental impact of process heat.*

### Options:

- Hot Air
- Hot Water
- Steam
- w/wo Chilled Water

Contact Information: Marc Portnoff, Principal Engineer  
Thar Energy, LLC / Clean Heat Technologies  
150 Gamma Drive, Pittsburgh, PA 15213  
[mportnoff@tharenergy.com](mailto:mportnoff@tharenergy.com)