High-Temperature CO_2 Heat Pumps for Industrial Decarbonization

Acknowledgments and disclaimers

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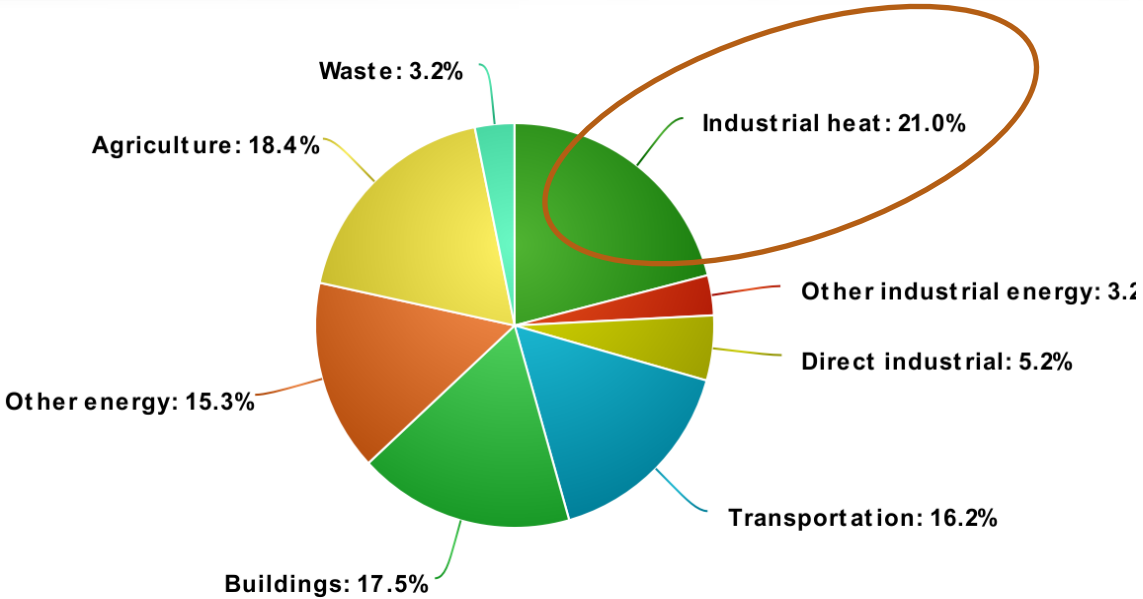
The opportunity and the problem: Decarbonizing Industry

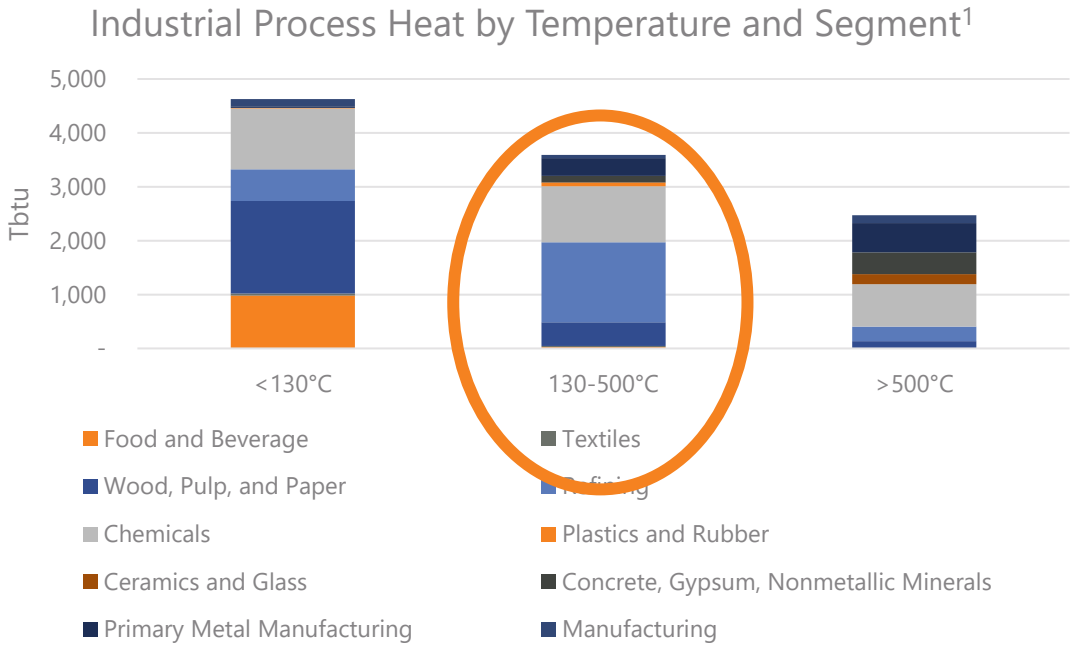


- **21% of global GHG emissions** from industrial process heat
- Electrification with renewable sources larger opportunity than eliminating all transportation emissions

Medium Temperature Process Heating Applications

Target markets include:

- Chemicals & refining
- Wood, pulp & paper
- Manufacturing
- District heating (steam and pressurized hot water)



1. McMillan, Colin (2019): Manufacturing Thermal Energy Use in 2014. National Renewable Energy Laboratory. 10.7799/1570008

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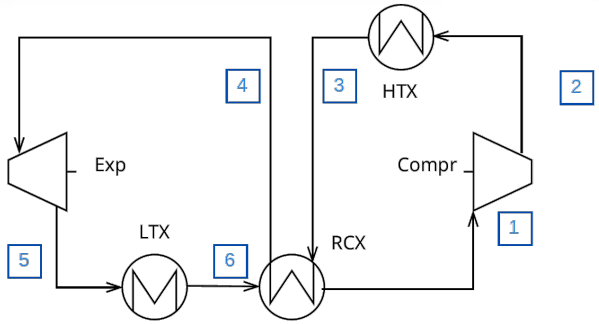
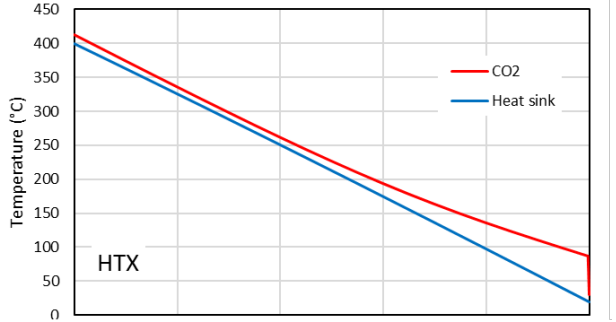
Refrigerant options

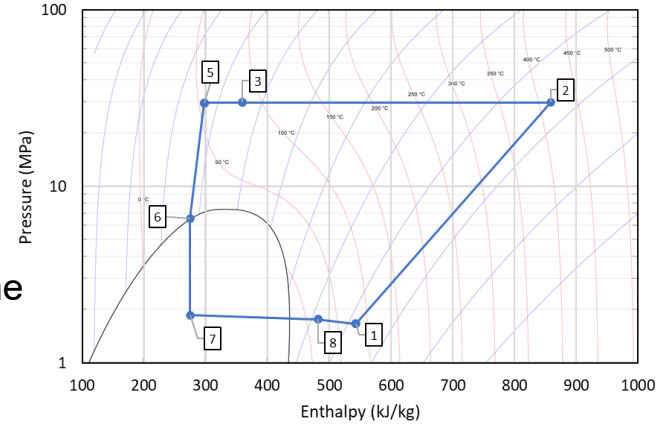
- HFC/HFO: R245fa, R1233ze(D) and similar
  - Limited high temperature capability (thermal decomposition above 150°C)
  - Being phased out due to GWP and/or ODP issues
- R717: Ammonia
  - High health risk: 300 ppm ILDH
- R600a/R601a: isobutane and isopentane
  - High fire risk: Flash point < -50°C
- R744: CO_2
  - Thermally stable
  - Zero ODP, GWP=1
  - Zero fire hazard
  - Low health risk: 40,000 ppm ILDH

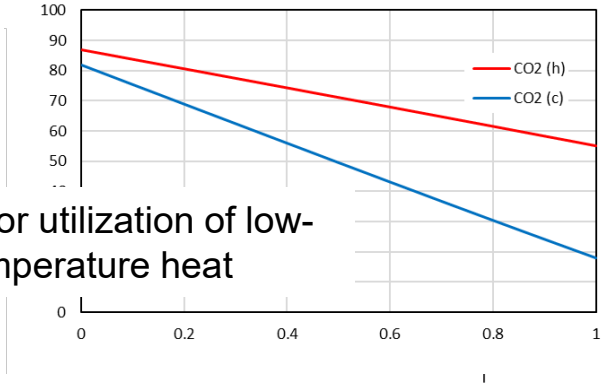
Baseline approach – Simple recuperated cycle





Requires very high compressor exit pressure & pressure ratic





Expansion into middle of dome

Poor utilization of low-temperature heat

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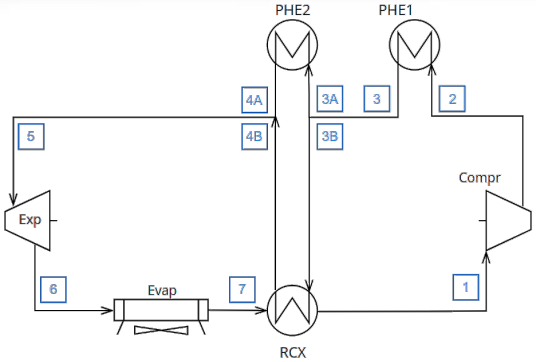
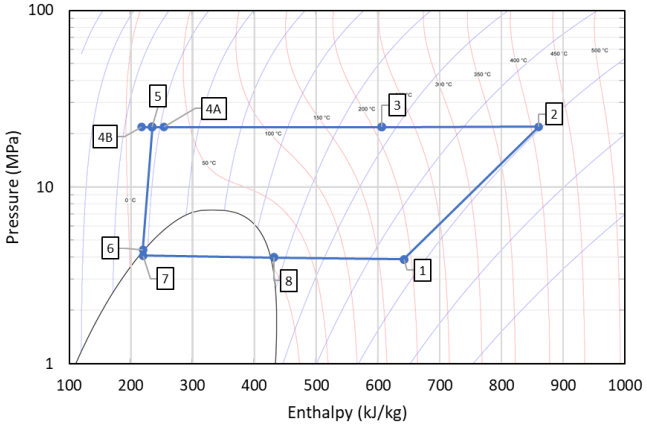
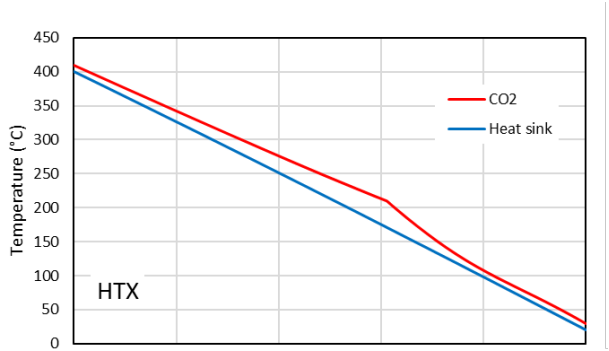
Leveraging what we learned from WHR cycles

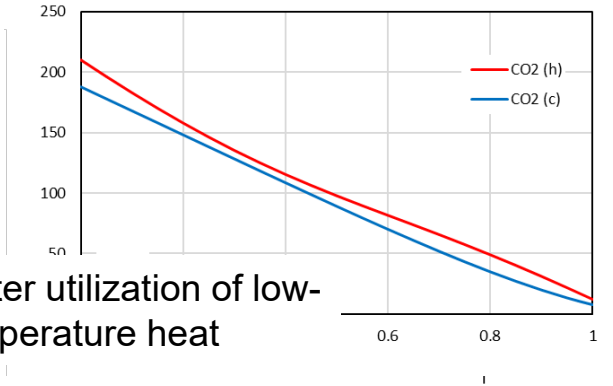
Much lower compressor exit pressure & pressure ratio

Expansion into liquid phase









Better utilization of low-temperature heat

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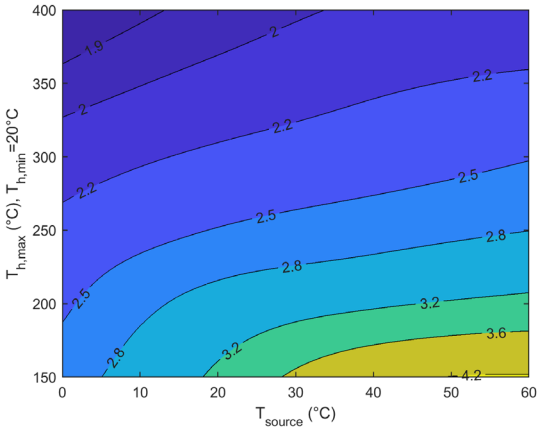
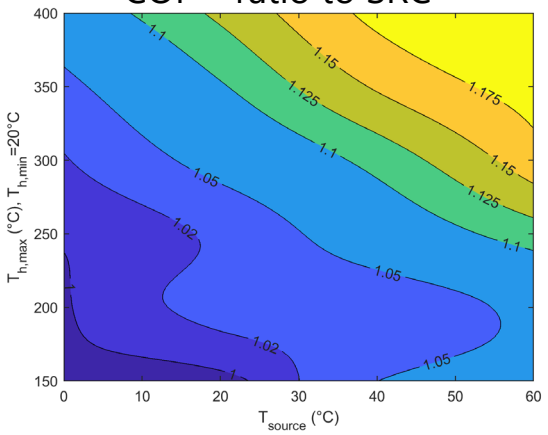
Performance summary

COP



COP – ratio to SRC



- Modeling notes:
  - Same compressor/expander efficiency for both cycles (80%), with 0% eff in 2-phase region
  - 30 MPa compressor discharge limit
  - Same total heat exchanger UA for both (~ equivalent cost)
  - Higher performance benefit available to new cycle if UA/cost allowed to increase

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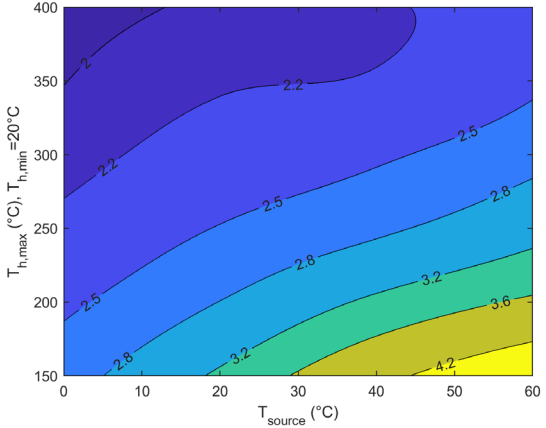

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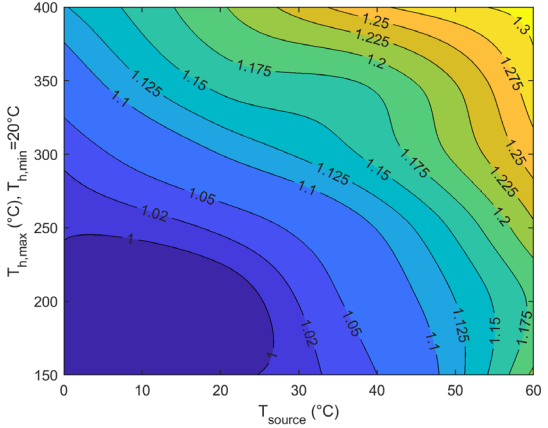

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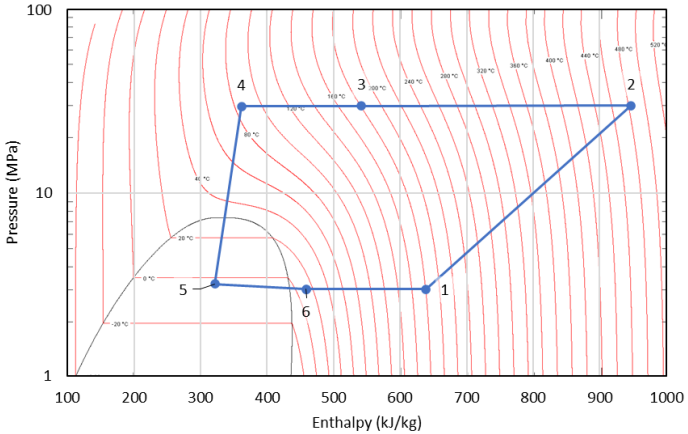
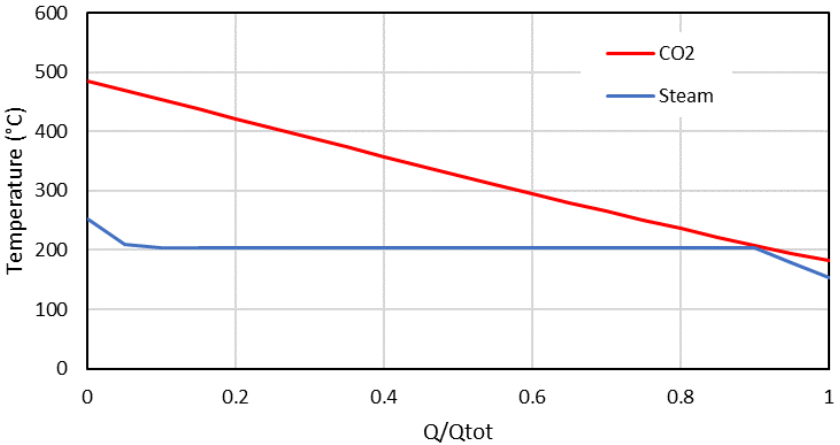
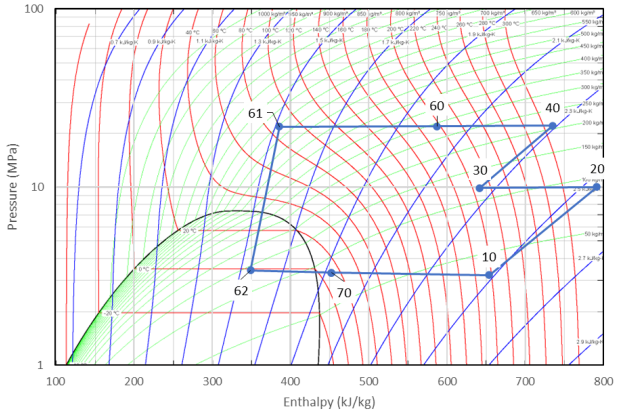
Transcritical CO_2 heat pumps traditionally viewed as limited to hot water-type applications

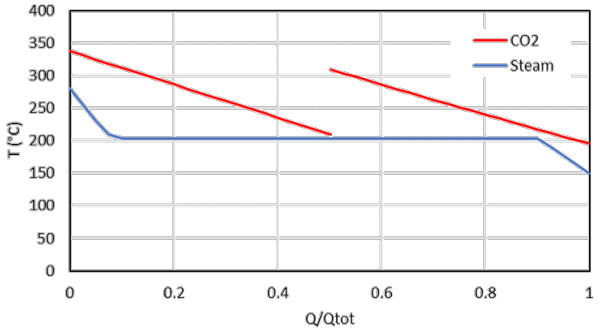


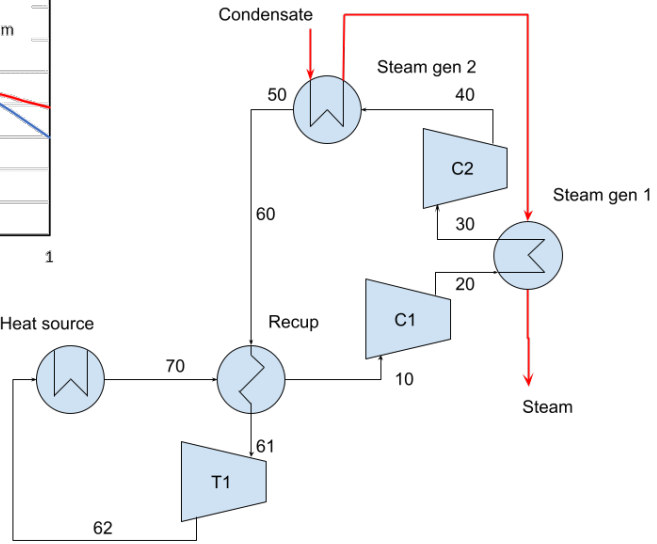


- Transcritical cycle – temperature glide on high-pressure heat exchanger (“gas cooler”) is mismatched to constant-pressure boiling process
- COP ~ 1.4
- Expansion into middle of the dome

Dealing with the pinch problem



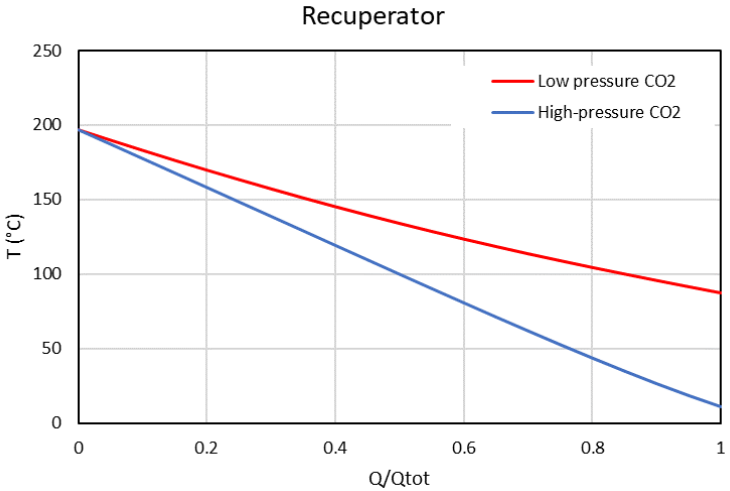




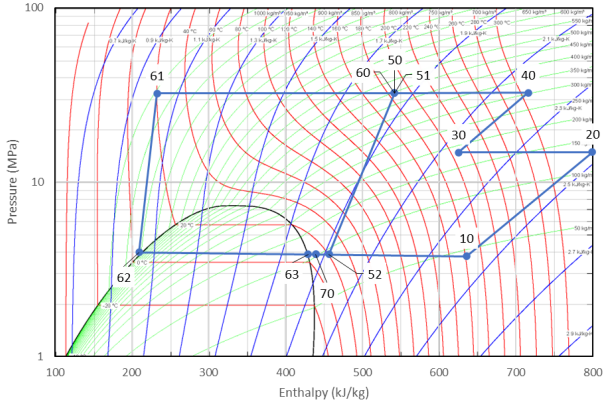
- Option 1 – Splitting compression into multiple stages
- Increase COP by ~ 0.02, reduces peak temperatures
- Still expands into middle of the dome

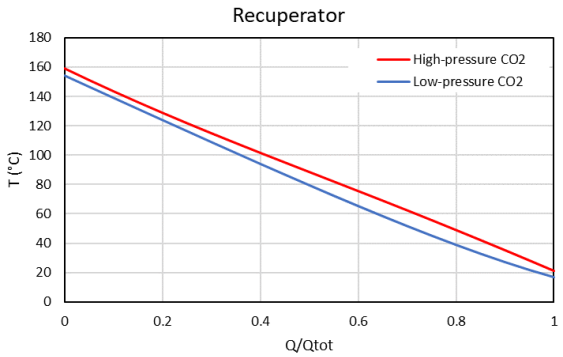
Why didn't that work better?

- Recuperator has its own pinch problem:
- Maximum exergetic efficiency when T(Q) slopes are equal

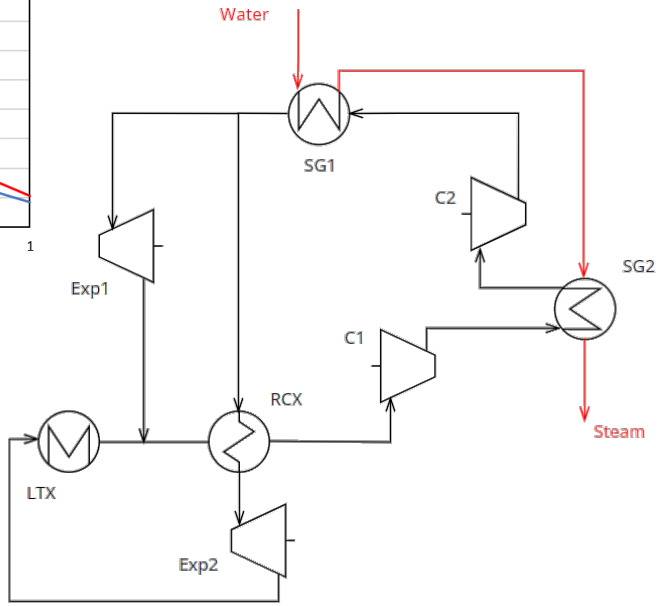


New cycle addresses t-CO_2 shortcomings, improves performance





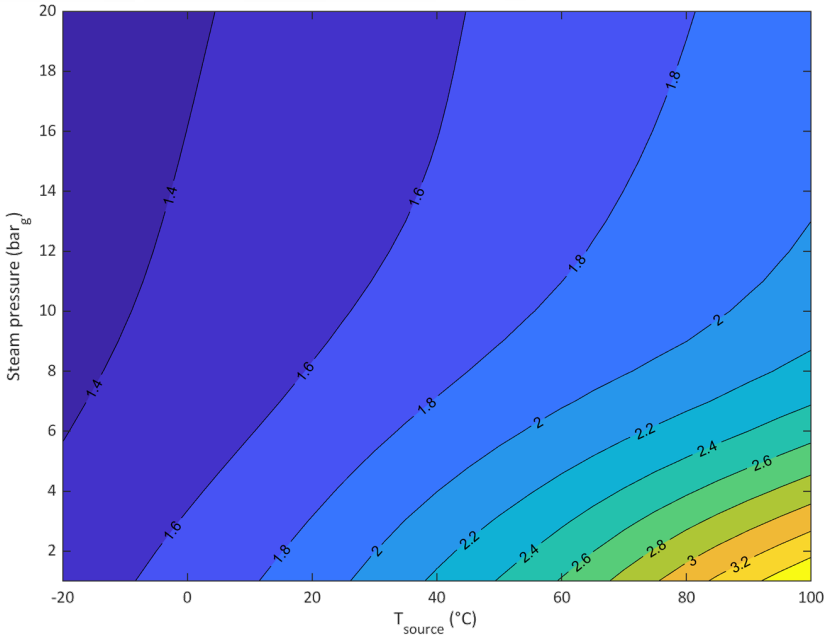
USPTO application 63/392,646



- Bypassing a portion of the flow around the HP side of the recuperator matches glide better
- Performance improves to COP ~ 1.6
- Expanders are now single-phase

“Green Steam”

- Conventional heat pumps can only generate low pressure steam (<2 barg); for medium pressure steam, conventional heat pumps require:
  - A secondary steam compressor **AND**
  - An abundant source of waste heat
- New system can generate medium pressure steam from ambient sources with COP values of 1.4 to >2, offering a simple and cost-effective replacement for traditional steam boilers



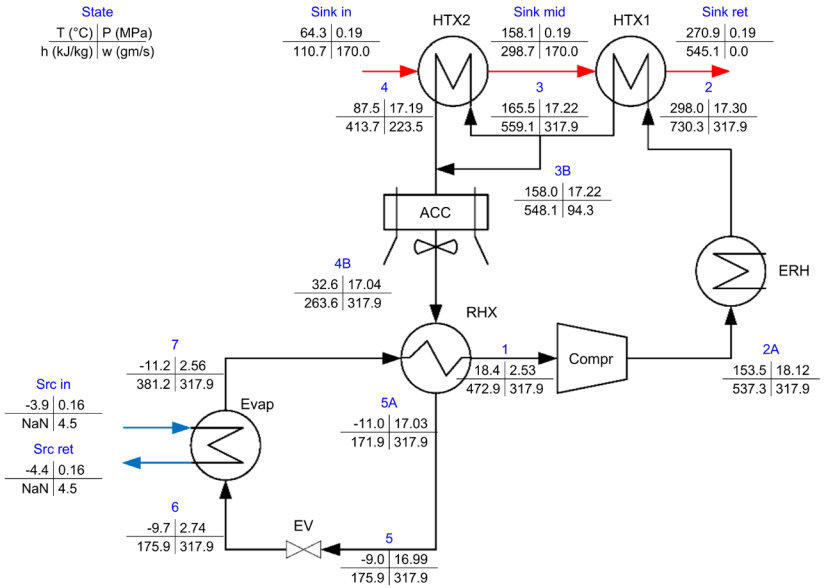
Laboratory-scale testing

- Low-speed recip compressor, ~ 20 kW
- PCHE recuperator
- Expansion valves (no turbines)

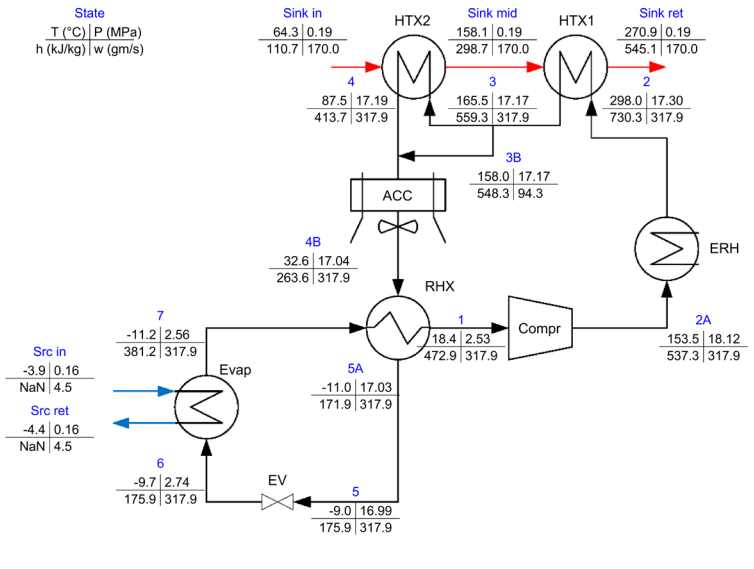
- 2 test configurations
  - Single-phase fluid (HTF) heating with 2-stage PCHEs
  - Steam generation with tube-in-tube HX

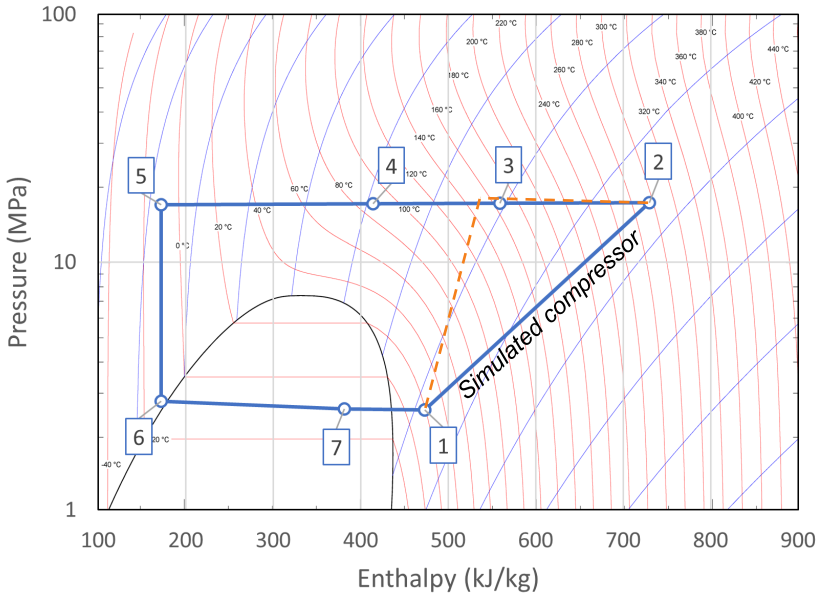
HTF testing

- Manufacturer piston seals limited temperature capability
  - Water-cooled cylinder, intercooled and limited inlet temperature
  - Intentionally dumped heat upstream of recuperator to limit compressor inlet temperature
  - Added heat externally to simulate intended compressor outlet conditions

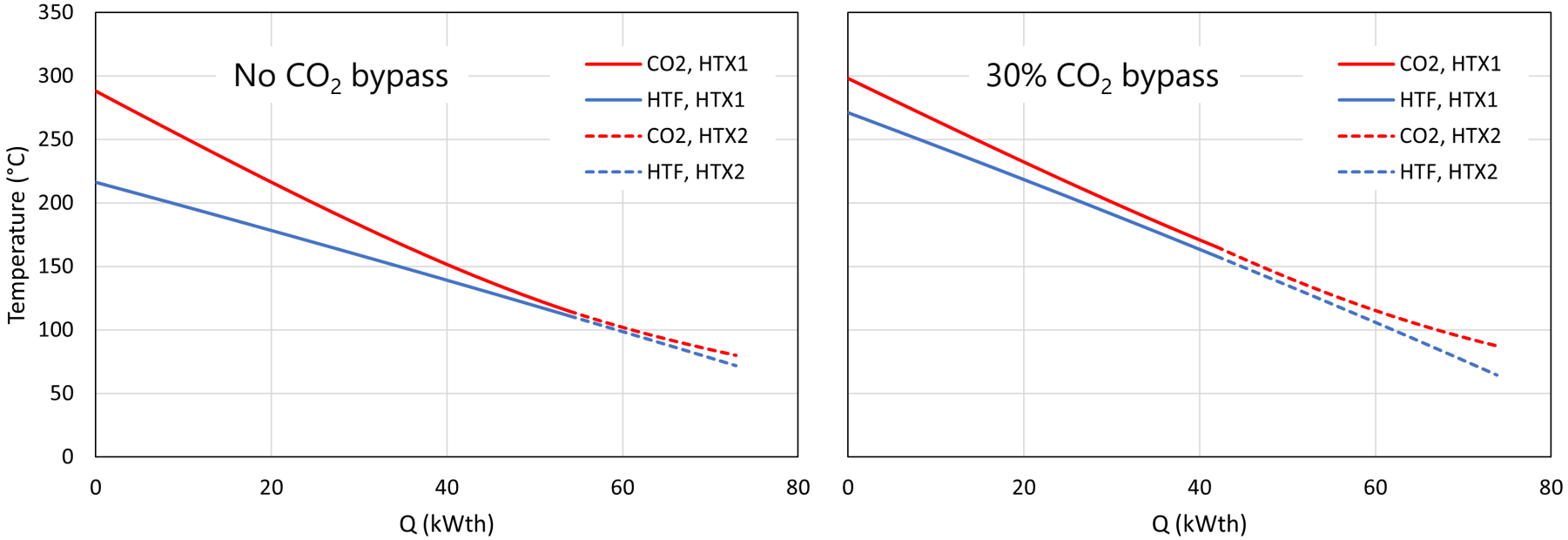


HTF testing





2-stage HTX – impact of midpoint CO_2 bypass



Key results – demonstrated significantly closer temperature approach of heat sink, heat extraction from -4°C source

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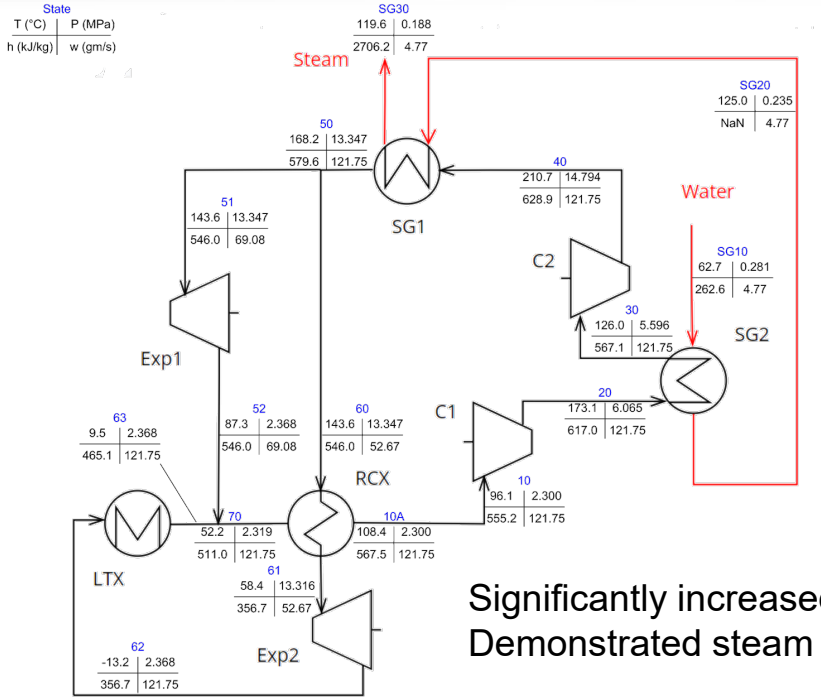
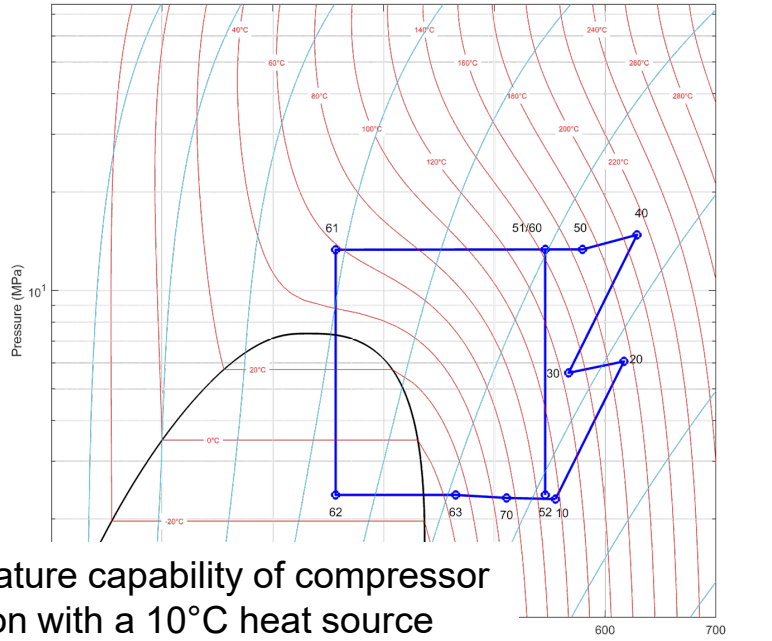
Steam generation testing

- Replaced OEM piston and rider rings with graphite-filled PTFE
- Disable cylinder wall cooling
- Replaced intercooler with steam generator heat exchanger (tube-in-tube)
- Added second stage heat exchanger at compressor exit

HPSG test results





Significantly increased temperature capability of compressor
Demonstrated steam generation with a 10°C heat source

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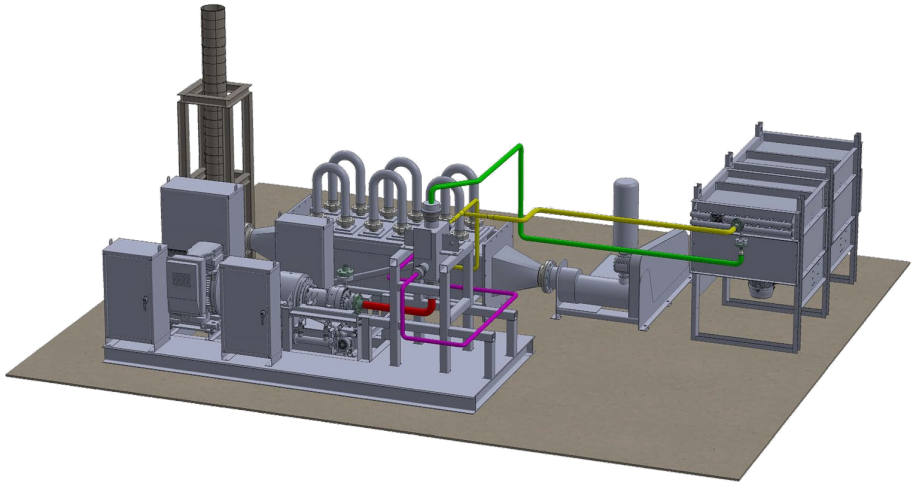
Development and commercialization timeline



- Continuing to refine laboratory-scale system
- 500 kW pilot and 10 MW demo systems in development stage,
  - DOE IEDO proposal for 500 kW air heater pilot selected for negotiation
  - ARPA-E SCALEUP proposal for 10 MW steam system in Seattle under evaluation
- Targeting commercial 5-10 MW systems by 2027

Industrial decarbonization solution

- Innovative cycle design with a thermally-stable, oil-free, natural refrigerant
- High COP = low operating costs compared with DEH
- System uses well-proven industrial compressors, heat exchangers and expanders
- System leverages Echogen's 15 years of sCO_2 system design and operation
- Commercial development under way, targeting 2027-2028 introduction