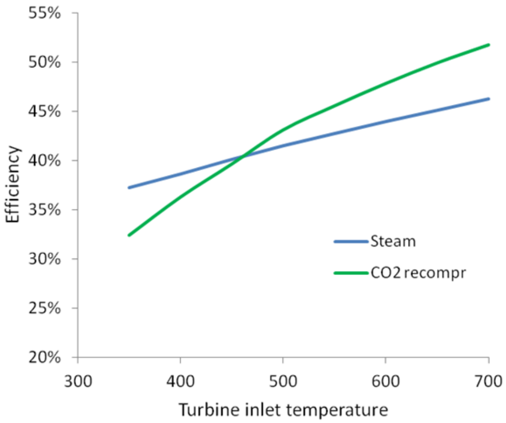
ECHOGEN
power systems

Supercritical CO_2-Based Power Cycles and Long-Duration Electrical Energy Storage

The promise of sCO_2 to displace steam



sCO_2 offers higher efficiency at lower cost than state-of-the-art steam

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SPECIAL REPORT

SUPERCRITICAL CO_2 THE NEXT BIG STEP?

MATCHING TURBINES & COMPRESSORS

CENTRIFUGAL COMPRESSOR PERFORMANCE

WASTE HEAT RECOVERY

COAL REVIVAL

Echogen Power Systems background

- Founded in 2007
- Original mission:
  To develop and commercialize a better exhaust and waste heat recovery power system using CO_2 as the working fluid
- First company to deliver a commercial sCO_2 power cycle
- New mission:
  Developing a CO_2-based long-duration electrical energy storage system


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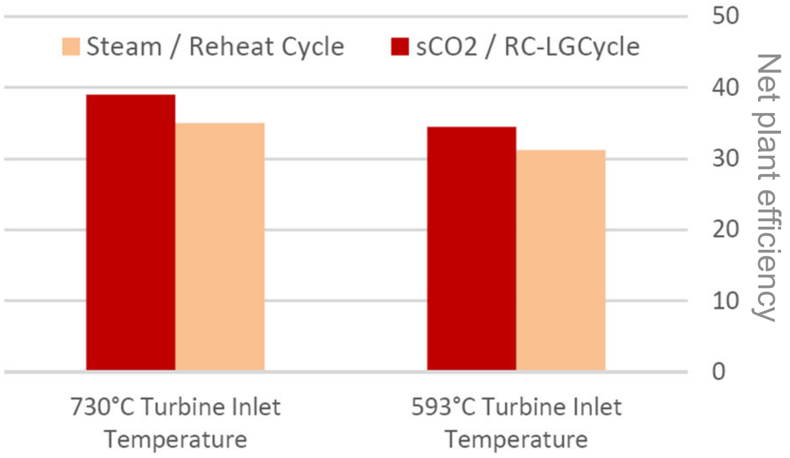
Recent and ongoing Echogen sCO_2 projects

- Coal-fired design studies and heat transfer testing
- Solar thermochemical energy storage development and test
- High-temperature heat exchanger testing
- CCGT & WHR commercialization
- Pumped Thermal Energy Storage development

DOE award: DE-FE0025959

Indirect-fired applications

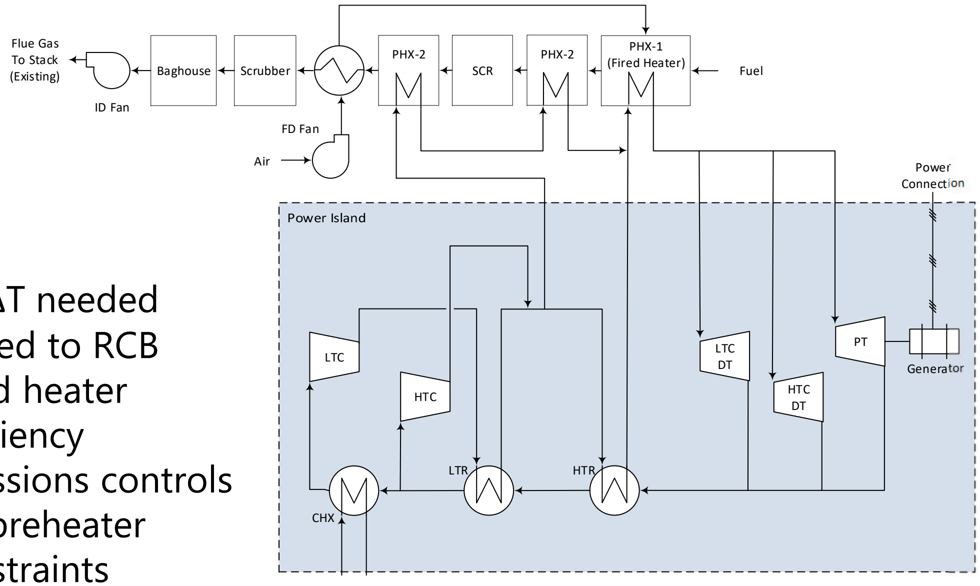
- Clear potential for significant gains in efficiency (3-4 points)
- No planned coal-fired units in US
- ~100 MW of new biomass-fired units in US under construction



Miller, J. D., Buckmaster, D. J., Hart, K., Held, T. J., Thimsen, D., Maxson, A., Phillips, J. N., and Hume, S., 2017, “Comparison of Supercritical CO2 Power Cycles to Steam Rankine Cycles in Coal-Fired Applications,” *Proceedings of ASME Turbo Expo 2017*, Paper GT2017-64933.

DOE award: DE-FE0031585

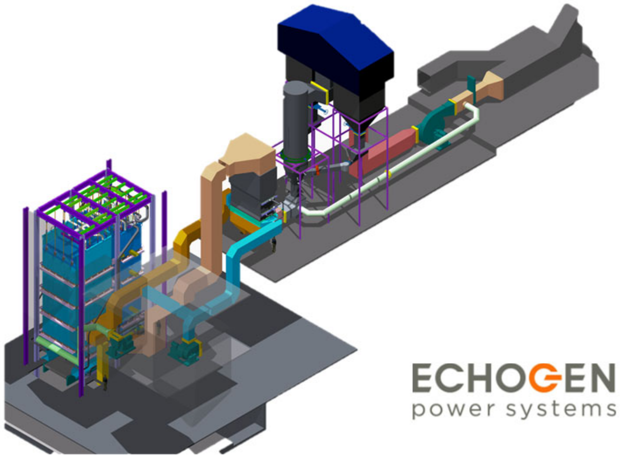
Integration with coal-fired power plant – LSP program



Larger ΔT needed compared to RCB

- Fired heater efficiency
- Emissions controls
- Air preheater constraints

Completed Phase II (FEED Study), did not propose Phase III (Construction and test)



DOE award: DE-FE0031928

Coal-fired primary heater design

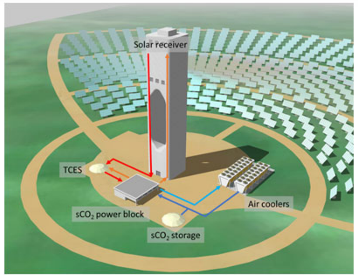
- Testing- and Model- Based Optimization of Coal-fired Primary Heater Design for Indirect Supercritical CO_2 Power Cycles
  - BYU (prime), San Rafael Energy Research Center, REI, Riley Power and Echogen
  - Key outcome is heat flux modeling and measurement under severe conditions with CO_2 as coolant/working fluid

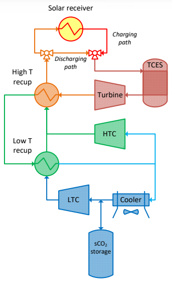
- Refurbishing and uprating original sCO_2 demo skid to provide high-temperature CO_2 for heater test

DOE award: DE-EE0008126

CSP programs – Thermochemical energy storage

Joint program with Southern Research





High-temperature reversible reaction:

$$MgO + CO_2 = MgCO_3 + 191 \text{ kJ/mol}$$

Pelletized sorbent in 25 MPa vessel, charge at 700°C

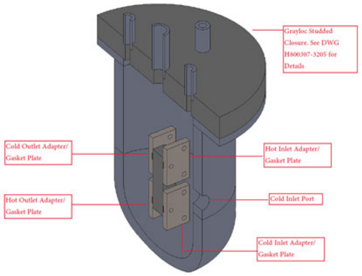
Sorbent development at SRI, lab system and transient modeling at Echogen

Unfortunately, sorbent bed fused during early high-temperature cycle

DOE award: DE-AR0001125

ARPA-E HITEMMP support

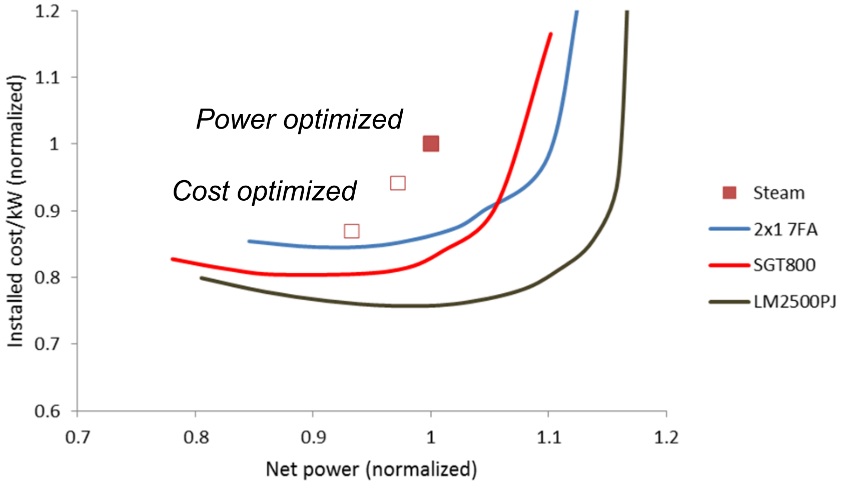
- Design, fabrication and commissioning of a portable heat exchanger test rig for Missouri S&T Univ.
  - 650°C, 25 MPa, 5 gm/s
- Reconfiguring lab system to run 800°C at 8 MPa, 300°C at 20 MPa, 0.25 kg/s for 50 kW recuperator testing
- Designing/fabricating heat exchanger interface components



CCGT and WHR development and commercialization

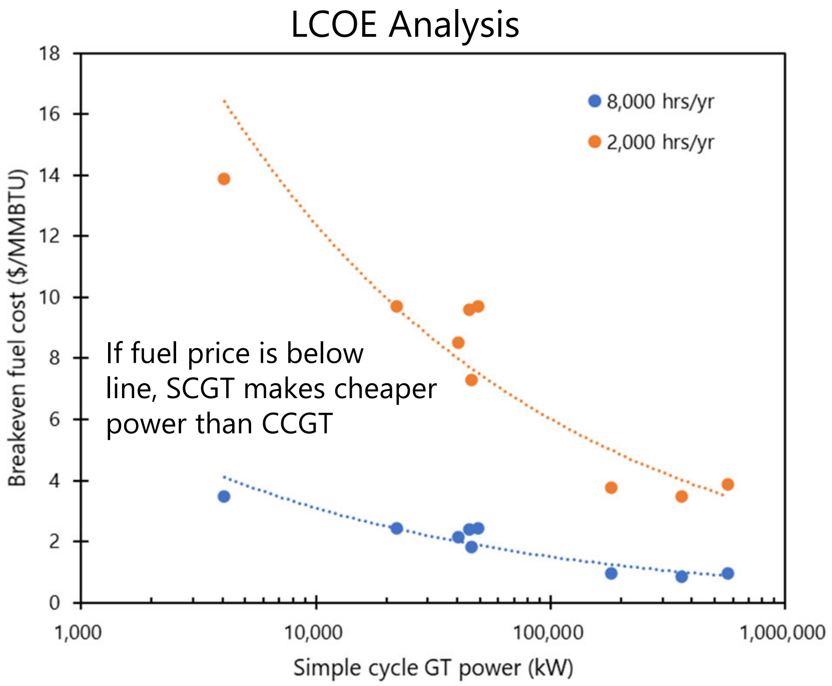
EPS100 during factory test

Held, T. J., 2015, "Supercritical CO_2 Cycles for Gas Turbine Combined Cycle Power Plants," Power Gen International, Las Vegas, NV.

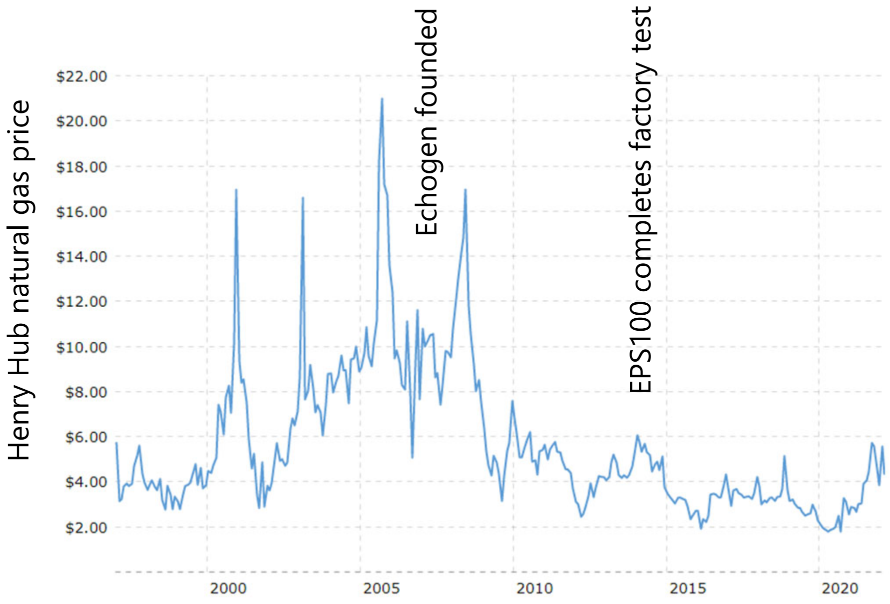


- 10-20% lower cost for same power
- 7-14% higher power for same cost

SCGT vs CCGT economics are challenging!



If fuel price is below line, SCGT makes cheaper power than CCGT

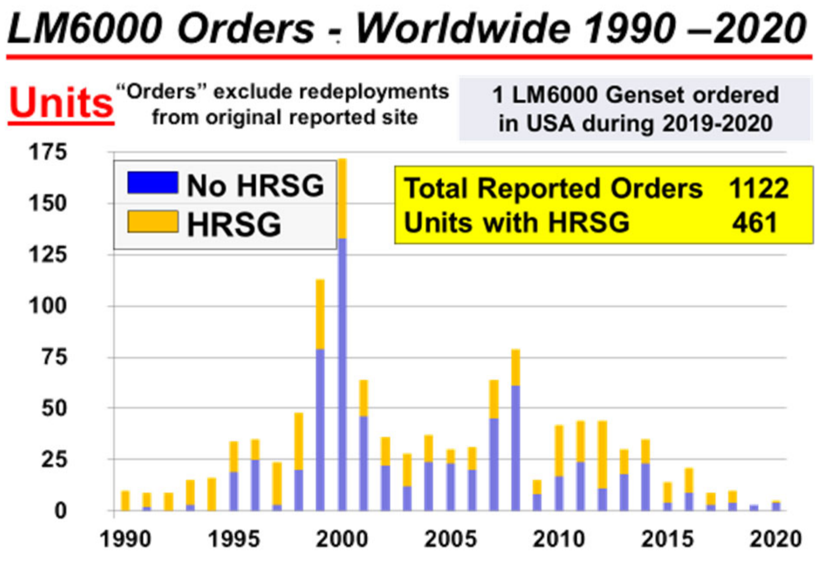


Echogen founded

EPS100 completes factory test

CCGT applications – a difficult market

- GT orders have fallen significantly
- NG costs have remained ~ $2-4 per MMBTU since 2010, reduces economic incentive to improve efficiency
    - Carbon economic penalties would serve to artificially increase fuel cost, but politically challenging in US
- Hydrogen-fired GTs offer a potential long-term opportunity
    - $1/kg (DOE target) is equivalent of ~ $8/MMBTU



Axford Turbine Consultants LLC Rev Apr 2021

Industrial waste heat recovery

- Broad spectrum of potential applications
- Tend to be in the 1-20 MWe range
- sCO_2 is an excellent technical fit
- Economics have always been challenging
  - New ITC helps (26% through 2022, 22% in 2023)
  - Carbon incentives could play critical role
  - Competing for “Green Dollars” with other renewable generation

Long-Duration Energy Storage with CO_2

Pumped Thermal Energy Storage: Electricity stored as heat & cold

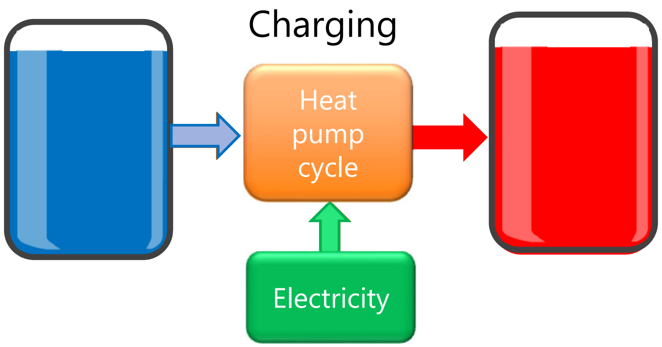
Thermodynamic cycles transform energy between electricity and heat

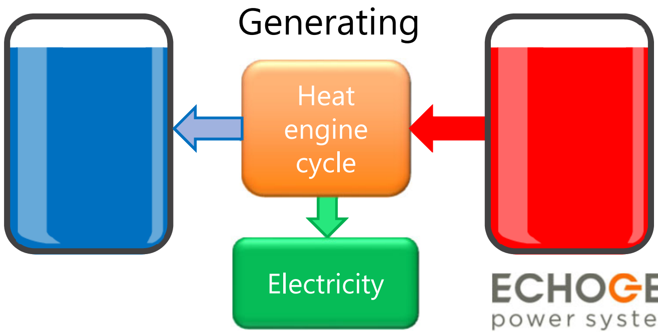
Charging cycle

- Heat pump cycle
- Uses electrical power to move heat from a cold reservoir to a hot reservoir
- Creates stored energy as both “heat” and “cold”

Generating cycle

- Heat engine cycle
- Uses heat stored in hot reservoir to generate electrical power
- “Cold” energy improves performance of heat engine





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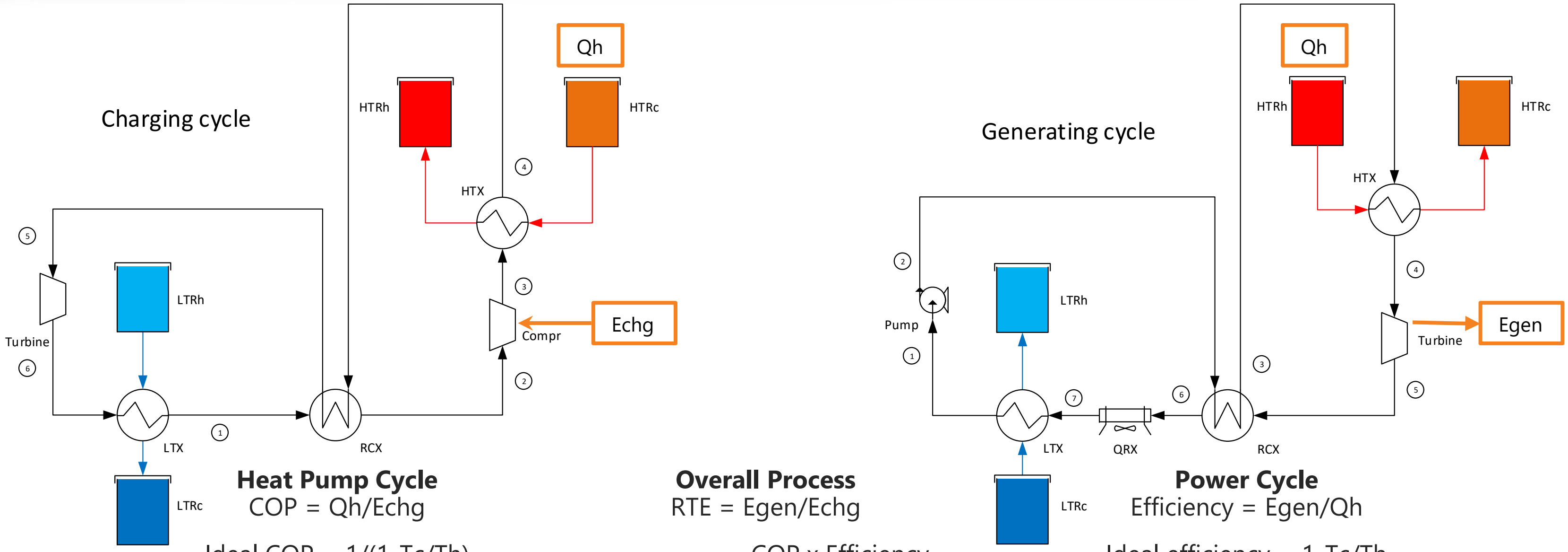
Pumped Thermal Energy Storage basics



Heat Pump Cycle
COP = Qh/Echg

Ideal COP = 1/(1-Tc/Th)

Overall Process
RTE = Egen/Echg

= COP x Efficiency

Power Cycle
Efficiency = Egen/Qh

Ideal efficiency = 1-Tc/Th

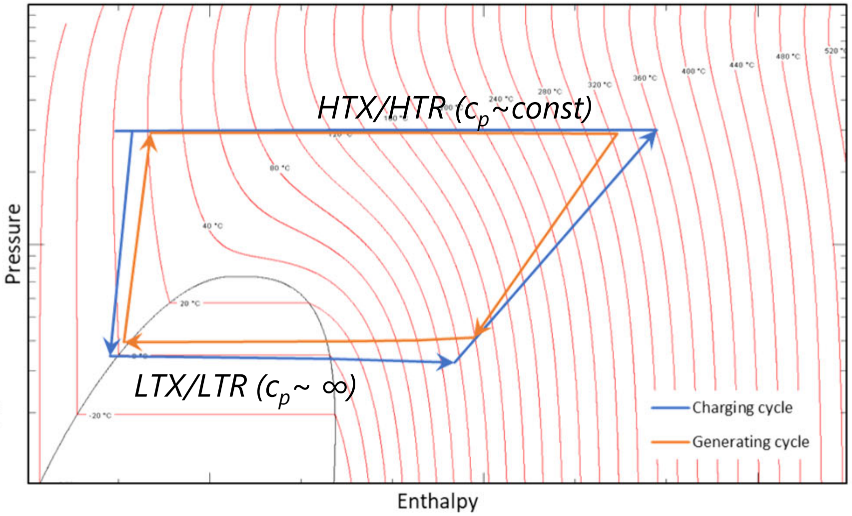
Ideal cycle RTE = COP_{Carnot} x η_{Carnot} = 100%

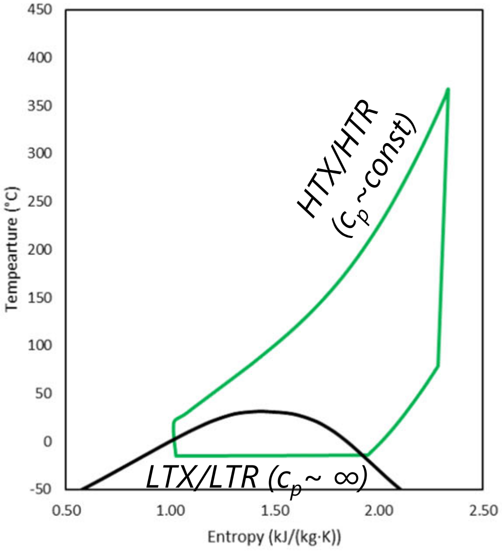
Non-ideal processes result in RTE ~60%, even at modest temperature ratio

Thermodynamic properties and operating state drive reservoir selection

HTX heat transfer is supercritical - sensible enthalpy transfer interaction with HTR

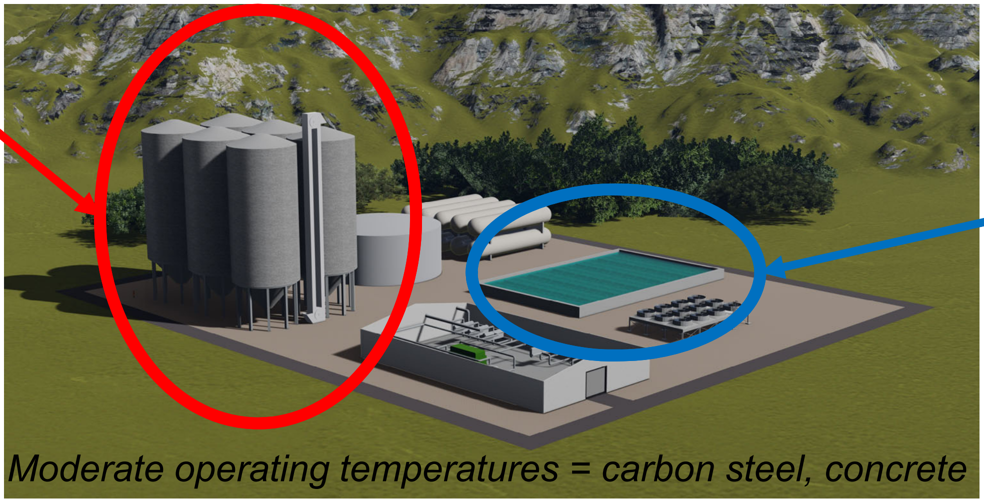
LTX is subcritical – condensation and evaporation - ~ constant temperature interaction with LTR





Ice/water equilibrium and sand reservoir materials = low cost, low impact

Material selection key to cost, sustainability, strategic goals



Hot reservoir = conventional sand

Cold reservoir = water/ice mixture

Moderate operating temperatures = carbon steel, concrete

Echogen CO_2-based PTES system design uses materials that are: safe, low cost, environmentally sustainable, recyclable, domestically-available

DOE award: DE-AR0000996

ARPA-E DAYS Program – PTES Proof of Concept

~200 kWth system, including both charging and generating cycles

Low-Temperature Reservoir (LTR)

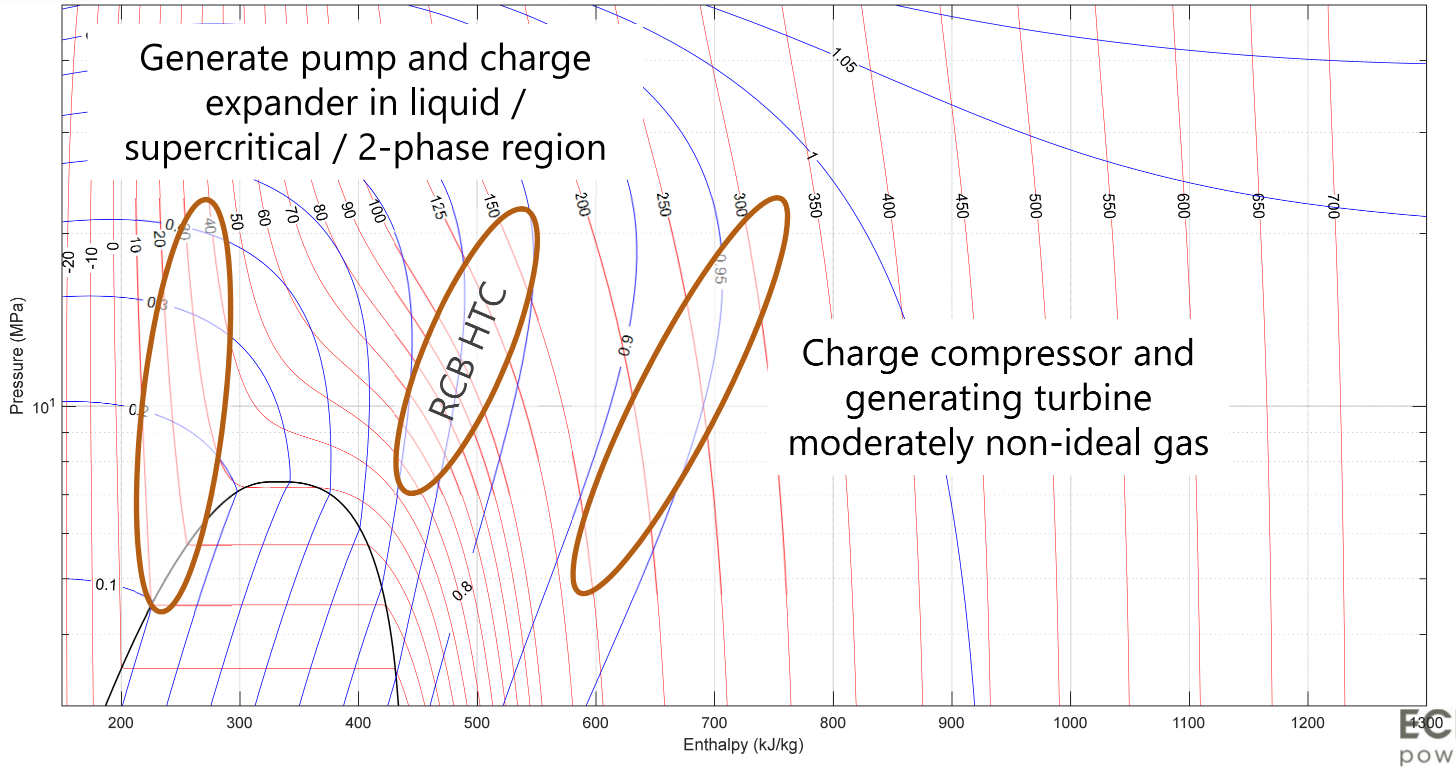
CO$_2$ heat pump & power cycle

High-Temperature Reservoir (HTR)

Build 1
- Completed testing October 2020

Build 2
- Sand HTR system under construction
- Complete testing Sept 2022

PTES turbomachinery design challenges



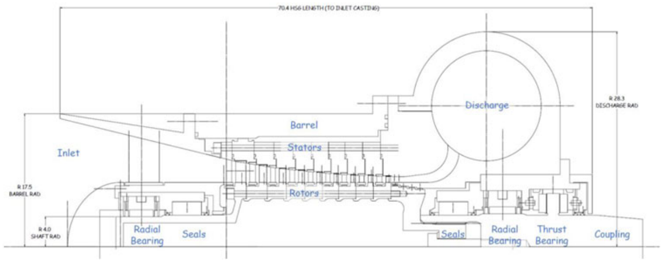
Generate pump and charge expander in liquid / supercritical / 2-phase region

Charge compressor and generating turbine moderately non-ideal gas

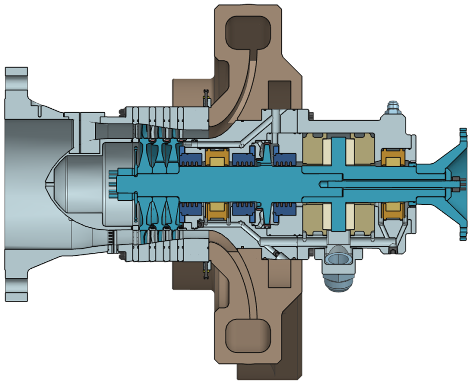
DOE award: DE-EE0008997

HTC compressor aero strongly affected by real gas effects

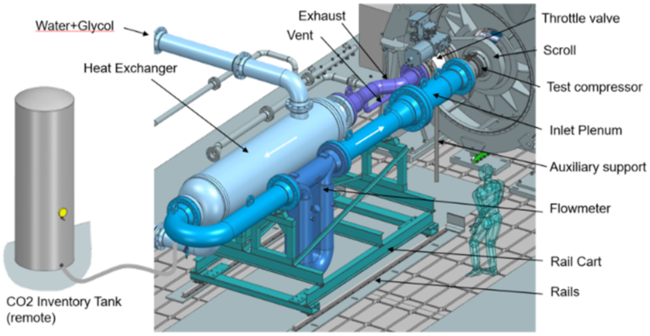
- Advanced compressors for CO_2-based power cycles and energy storage
- Echogen, University of Cincinnati and University of Notre Dame
- Design and test of 3-D Aero optimized axial CO_2 compressor



100 MW compressor



Subscale, 10 MW compressor



Other PTES activities

- Advanced passive ice/water slurry generation (SETO – with SPF and AES)
- Liquid expander development (SETO – SwRI / Flowserve / Echogen joint project)
- Low-cost moving-bed heat exchanger (SBIR)

Key takeaways

- Significant development effort in sCO_2 power cycles and systems has addressed many of the technical risks, and more continues
- Economics of market entry, low fuel prices, and long advanced application development time scales have challenged commercialization
- Long-duration energy storage may prove to be the first large-scale commercial introduction for sCO_2 systems

Acknowledgments and disclaimers

The information, data, or work presented herein was funded in part by the U.S. Department of Energy, award numbers:

DE-AR0000996, DE-AR0001125 Advanced Research Projects Agency-Energy
DE-EE0008126, DE-EE0008997 Energy Efficiency and Renewable Energy, Solar Energy Tech Office
DE-FE0025959, DE-FE00031585, DE-FE0031621, DE-FE0031928 Fossil Energy Office
DE-SC0021717 Office of Science

Thank you!

sCO_2 trivia contest

Who first proposed an sCO_2 power cycle?

☐ V. Dostal

☐ G. Angelino

☐ E.G. Feher

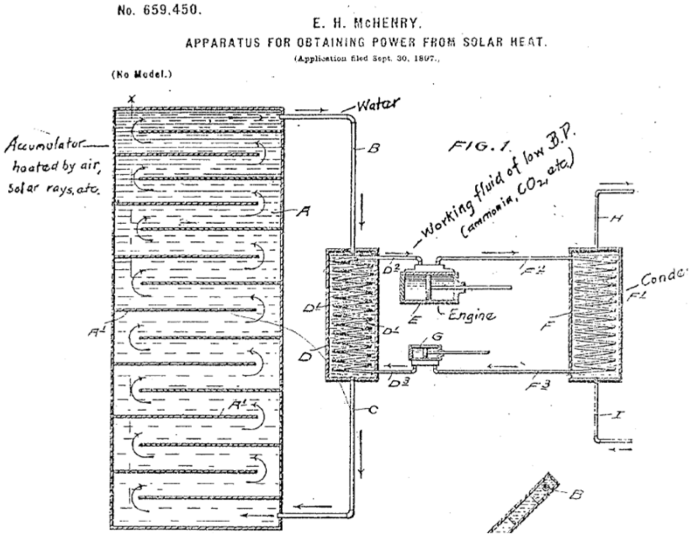
☐ None of the above

sCO$_2$ trivia contest

Who first proposed an sCO$_2$ power cycle?

☒ V. Dostal (2004)
☒ G. Angelino (1968)
☒ E.G. Feher (1967)
☑ E.H. McHenry (1897)

Not just sCO$_2$, but a “CSP” application!



No. 659,450.

E. H. McHENRY.

APPARATUS FOR OBTAINING POWER FROM SOLAR HEAT.

(Application filed Sept. 30, 1897.)

(No Model.)

sCO_2 trivia contest

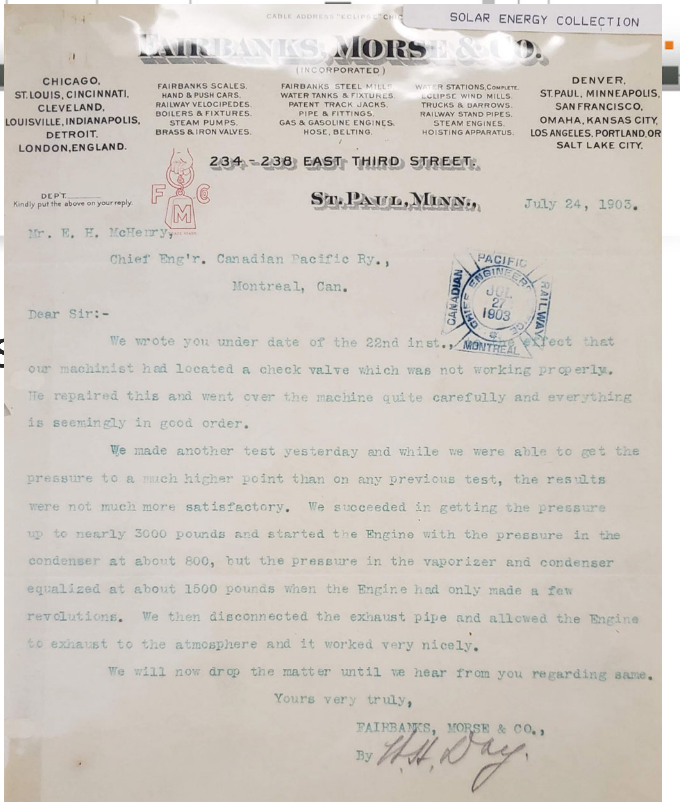
Who built the first operational sCO_2 power system?

- ☐ Sandia
- ☐ Barber Nichols
- ☐ KAPL
- ☐ Echogen
- ☐ None of the above

sCO_2 trivia contest

Who built the first operational sCO_2 power s

- ☒ Sandia (2011)
- ☒ Barber Nichols (2010)
- ☒ KAPL (2012)
- ☒ Echogen (2009)
- ☑ E.H. McHenry (1903)



SOLAR ENERGY COLLECTION

CABLE ADDRESS "ECLIPSE" CHIC

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(INCORPORATED)

CHICAGO,
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OMAHA, KANSAS CITY,
LOS ANGELES, PORTLAND, OR
SALT LAKE CITY.

234 - 238 EAST THIRD STREET.

DEPT. ____
Kindly put the above on your reply.

F & C M

ST. PAUL, MINN., July 24, 1903.

Mr. E. H. McHenry,
Chief Eng'r. Canadian Pacific Ry.,
Montreal, Can.

CANADIAN PACIFIC RAILWAY CHIEF ENGINEER'S OFFICE MONTREAL
JUL 27 1903

Dear Sir:-

We wrote you under date of the 22nd inst., [illegible] the effect that our machinist had located a check valve which was not working properly. He repaired this and went over the machine quite carefully and everything is seemingly in good order.

We made another test yesterday and while we were able to get the pressure to a much higher point than on any previous test, the results were not much more satisfactory. We succeeded in getting the pressure up to nearly 3000 pounds and started the Engine with the pressure in the condenser at about 800, but the pressure in the vaporizer and condenser equalized at about 1500 pounds when the Engine had only made a few revolutions. We then disconnected the exhaust pipe and allowed the Engine to exhaust to the atmosphere and it worked very nicely.

We will now drop the matter until we hear from you regarding same.

Yours very truly,

FAIRBANKS, MORSE & CO.,
By H.H. Day.

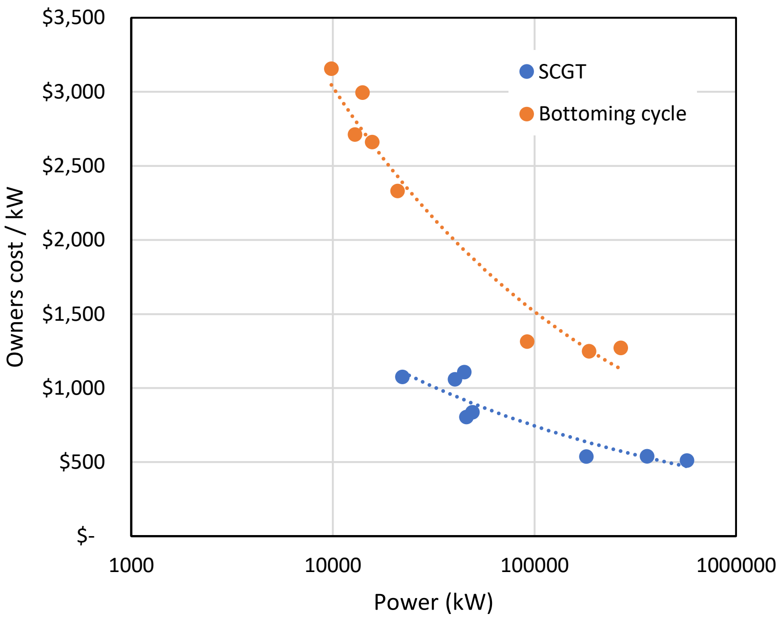
"We succeeded in getting the pressure up to nearly 3000 pounds and started the Engine with the pressure in the condenser at about 800, but the pressure in the vaporizer and condenser equalized at about 1500 pounds when the Engine had only made a few revolutions"

ECHOGEN
power systems

Thanks again!

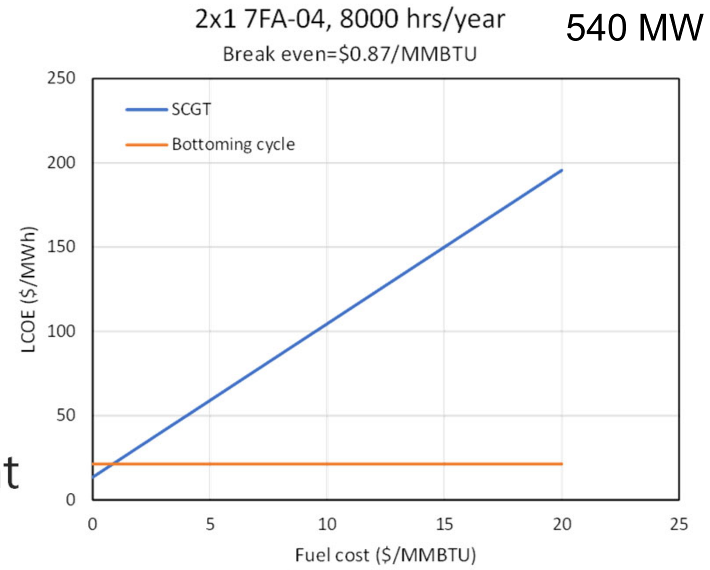
CCGT value proposition – can we get from 10 MW to 100+?

- Installed-cost analysis of existing SCGT and CCGT systems
- Significant drop in cost/kW for bottoming cycles
- Need to establish technology at smaller scales to make the leap to larger scales



LCOE analysis

- LCOE components:
  - Amortized capital cost
  - Fuel cost
  - Other O&M
  - Usage (hours / year)



- LCOE linear in fuel cost for SCGT
- Bottoming cycle LCOE independent of fuel cost
- Breakeven point = fuel cost below which power from CCGT costs more than from SCGT

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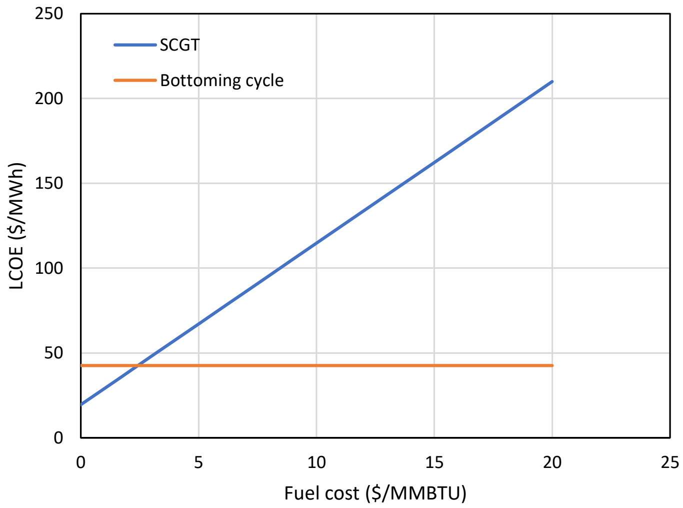
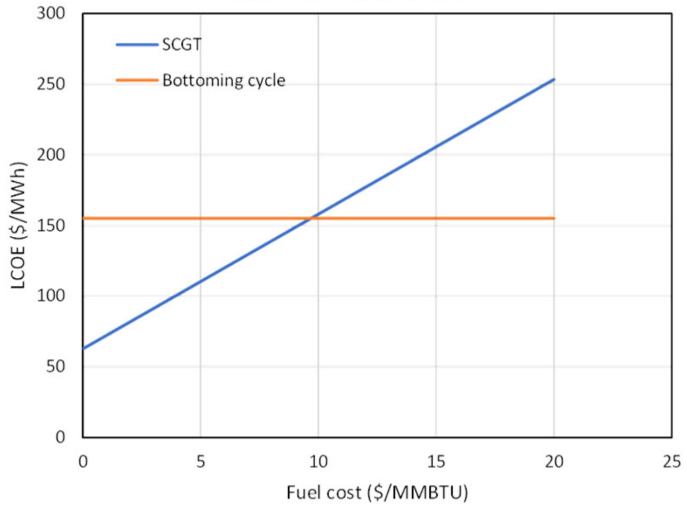
LCOE analysis, continued


1x1 LM2500, 8000 hrs/year

Break even=$2.42/MMBTU


1x1 LM2500, 2000 hrs/year

Break even=$9.69/MMBTU

31 MW

- Smaller systems have higher relative bottoming cycle capex, drives breakeven cost higher
- Impact of usage on breakeven fuel cost is critical