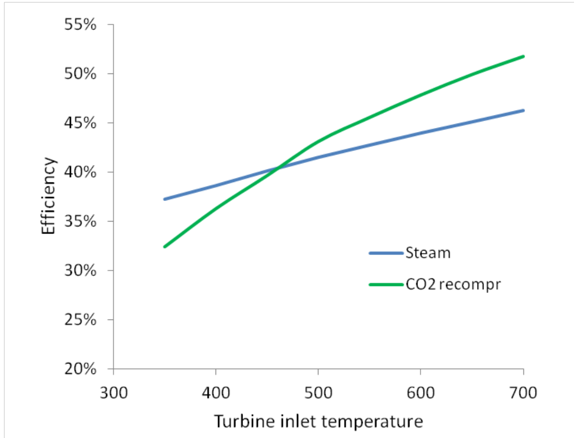
Supercritical CO_2-Based Power Cycles and Long-Duration Electrical Energy Storage – Status, Challenges and Opportunities

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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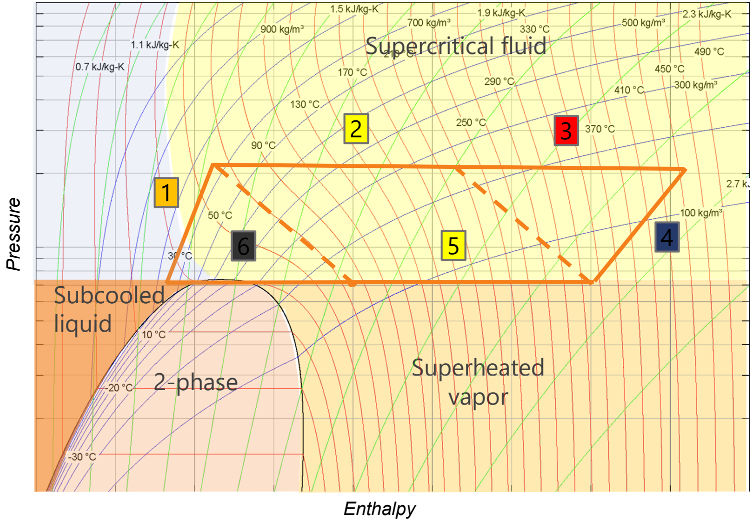
Supercritical CO_2 cycle example (simple recuperated)



1 Compressor

2 Recuperator

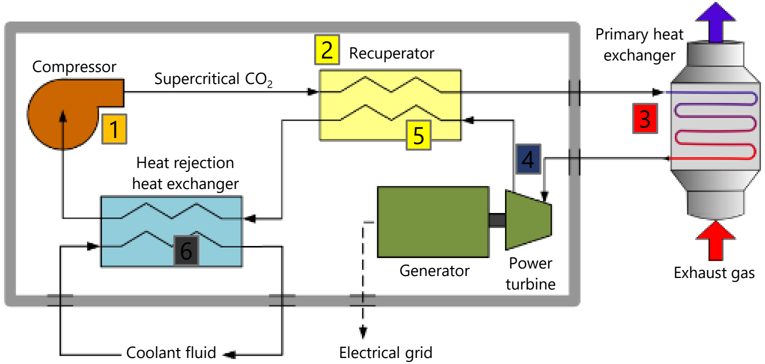
3 Primary HX

4 Turbine

5 Recuperator

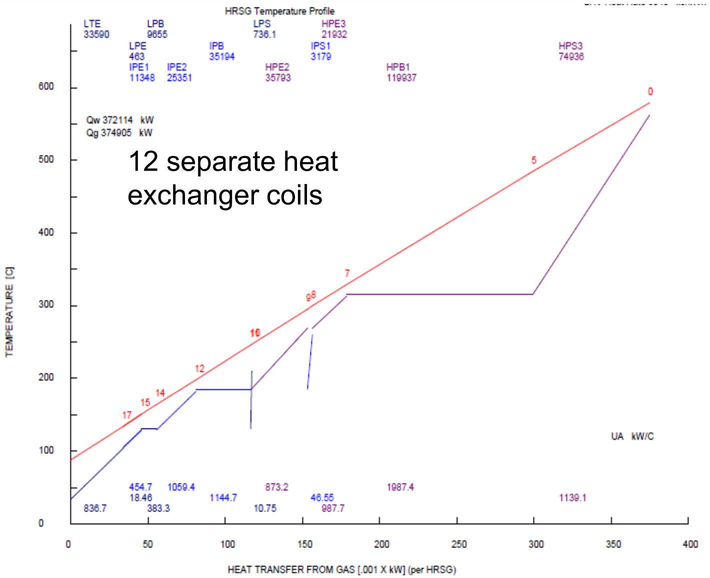
6 Heat rejection HX

CO_2 becomes supercritical above 31°C, 74 bar. Above the critical pressure, there is no constant-temperature phase change when adding heat

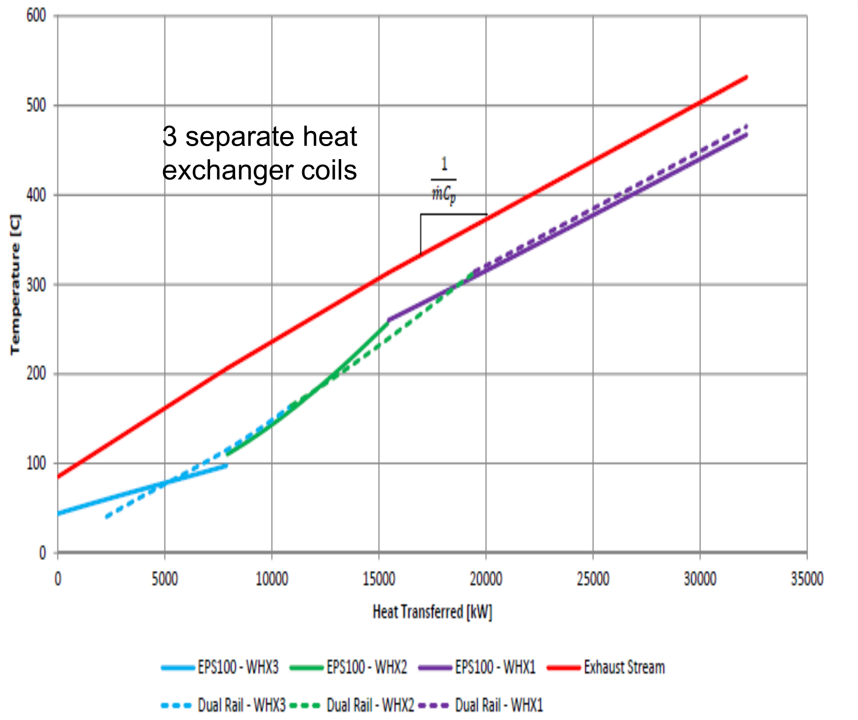


1. High-density CO_2 compressed
2. CO_2 preheated at recuperator
3. External heat added at primary heat exchanger
4. High energy CO_2 expanded at turbine drives generator
5. Expanded CO_2 is pre-cooled at recuperator
6. CO_2 is cooled to high density at heat rejection HX

Simple exhaust heat extraction process



Single phase – no drums, no concerns over “economizer steaming”, etc.



Advantages of an sCO_2 power cycle

- Simple waste heat exchanger
- High density fluid = small equipment
- CO_2 properties
- Cycle flexibility
- Compact, modular
- Low maintenance
- Dry operation

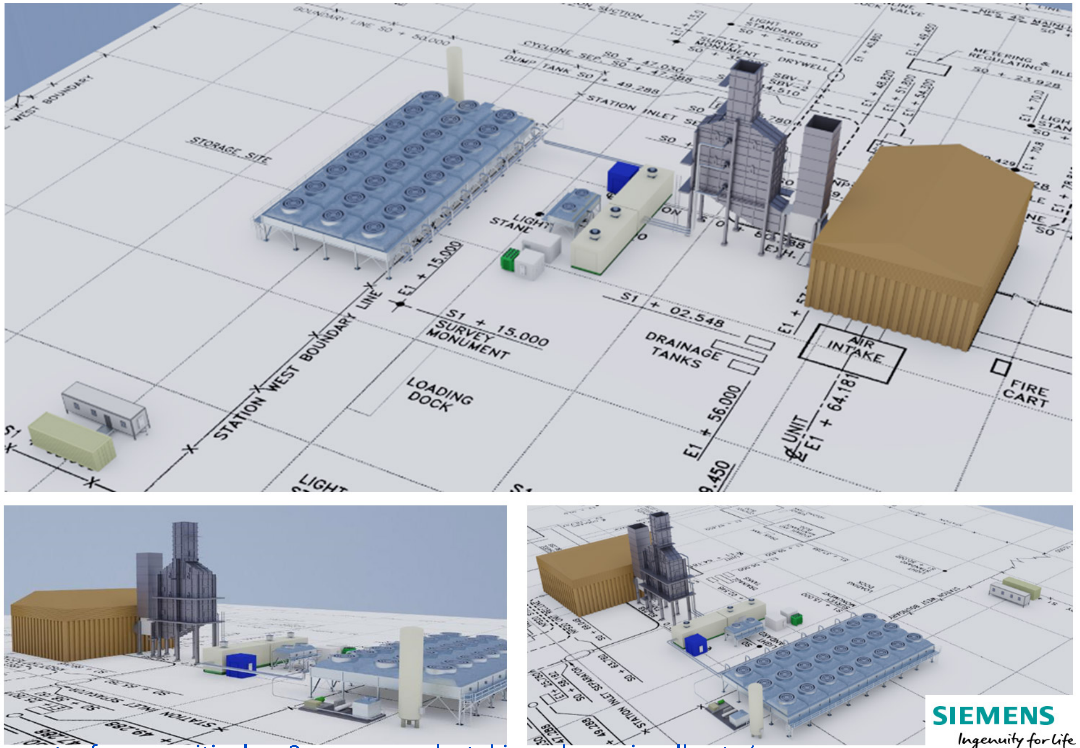
Echogen Power Systems background

- Founded in 2007
- 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
- Developing a CO_2-based electrical energy storage system

TC Energy / Siemens project

- Announced by TransCanada in March 2019
- EPS120 (uprated EPS100) on an RB211
- Partially-funded by ER Alberta
- FEED study completed, currently under financial review

Supercritical CO2 Pilot Project - Concept Plan

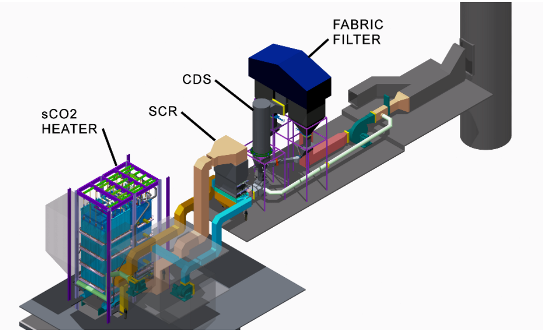


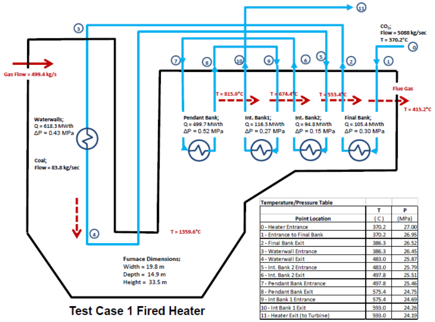
SIEMENS
Ingenuity for life

https://www.powermag.com/first-commercial-deployment-of-supercritical-co2-power-cycle-taking-shape-in-alberta/

Power cycle R&D and commercialization

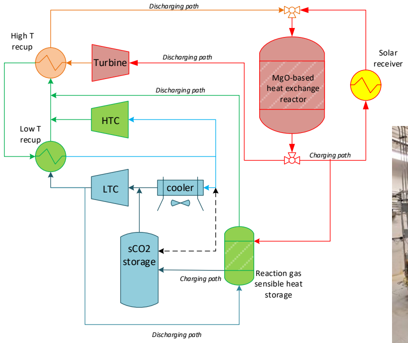
- Multiple DOE- and industry-funded projects in:
  - Nuclear – Micro-reactor and large-scale power plants
  - Fossil –10 MWe indirectly-fired power plant FEED study, utility-scale oxy-coal conceptual studies, gas turbine/sCO_2 control system simulations
  - Solar – thermochemical energy storage (with Southern Research)

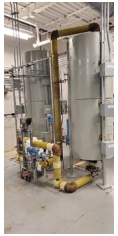




Test Case 1 Fired Heater

Temperature/Pressure Table		
Point Location	T (C)	P (MPa)
0 - Heater Entrance	370.2	27.00
1 - Entrance to Final Bank	370.2	26.95
2 - Final Bank Exit	386.3	26.52
3 - Waterwall Entrance	386.3	26.45
4 - Waterwall Exit	483.0	25.87
5 - Int. Bank 2 Entrance	483.0	25.79
6 - Int. Bank 2 Exit	497.8	25.51
7 - Pendant Bank Entrance	497.8	25.46
8 - Pendant Bank Exit	575.4	24.75
9 - Int Bank 1 Entrance	575.4	24.69
10 - Int Bank 1 Exit	593.0	24.26
11 - Heater Exit (to Turbine)	593.0	24.19





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STEP facility

- GTI-led project at SwRI
- Goal – 700°C RCB demonstration at 10 MWe scale

STEP DEMO

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sCO_2 cycle overview

There is no single “sCO_2 Power Cycle”

- Variation by
  - Application
  - Size
  - Temperature

	Power output	Temperature	ΔT main HX
Application	(MW)	(°C)	
Exhaust/Waste Heat Recovery	1-300	300-600	Large
Indirect-Fired Power	300-1000	550-750	Moderate
Concentrated Solar	10-150	550-750	Moderate
Advanced Nuclear	1000+	550-750	Small
Fired cycle (Allam-Fetvedt)	25-300	1150	N/A

- sCO_2 cycle flexibility is one of its strengths

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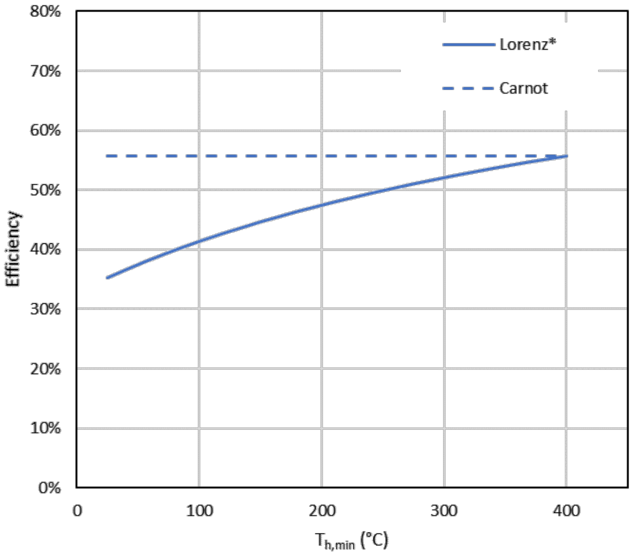
Carnot vs Lorenz

- Carnot cycle: Heat addition and rejection at constant temperature, constant pressure

$$\eta_{Carnot} = 1 - \frac{T_c}{T_h}$$

- Lorenz* cycle: Heat addition over range of temperatures

$$\eta_{Lorenz} = 1 - \frac{T_c}{\frac{T_{h,max} - T_{h,min}}{ln\left(T_{h,max}/T_{h,min}\right)}}$$



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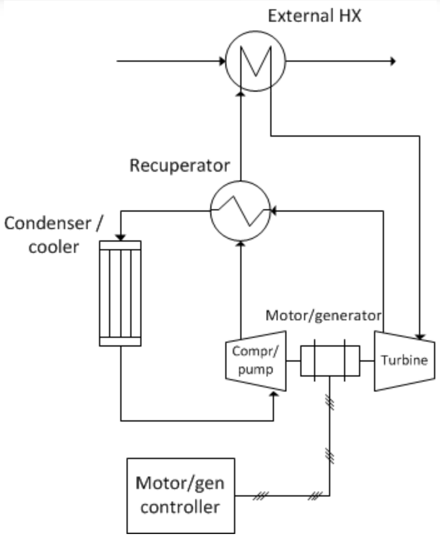
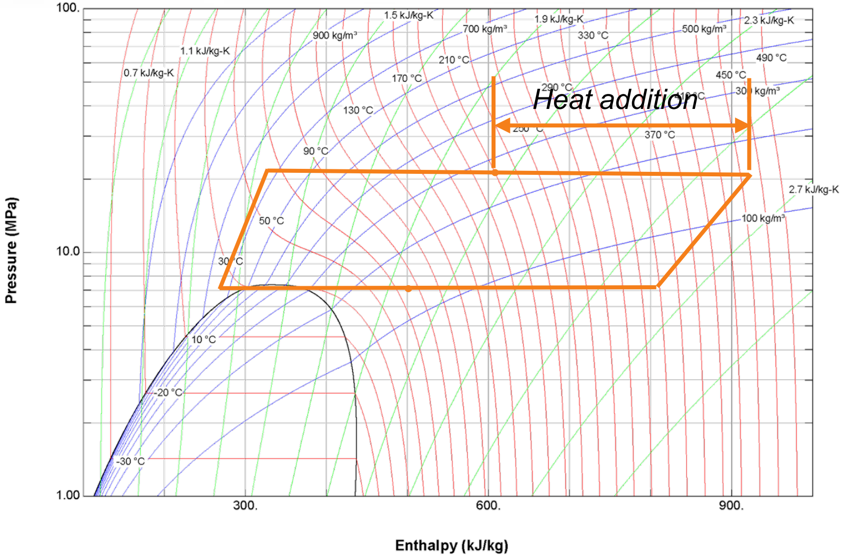
Simple recuperated cycle





Simplest practical version of sCO_2 cycle
Recuperation limits temperature range of heat extraction

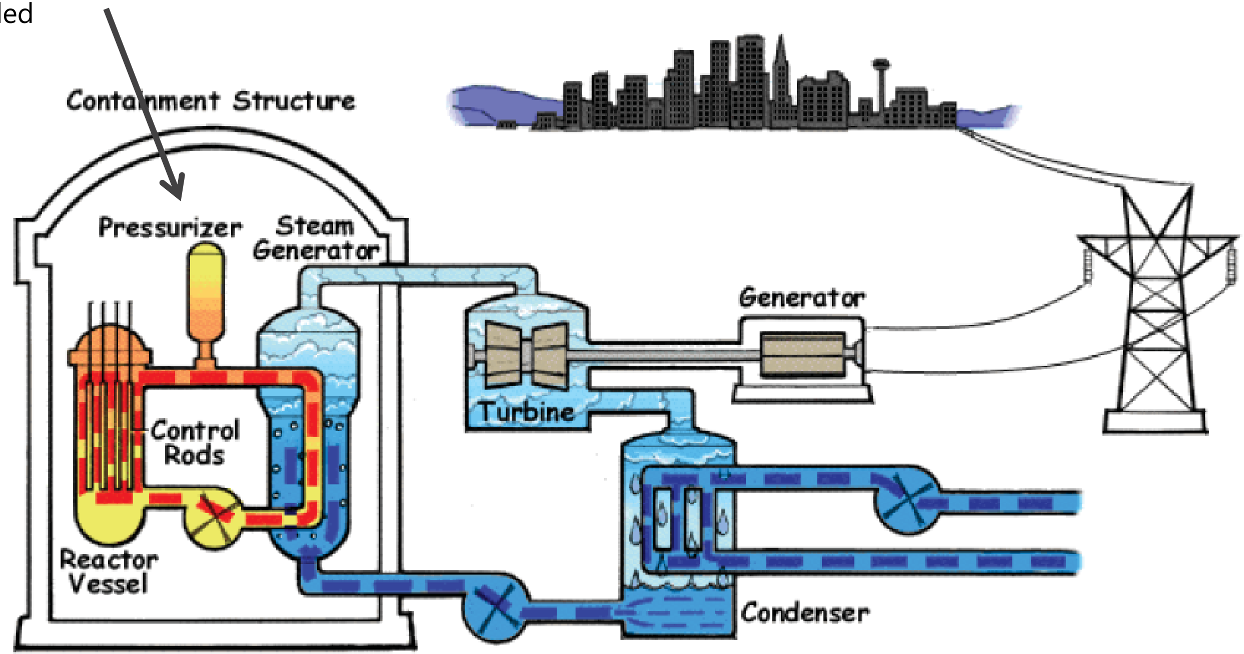
13

Types of heat sources

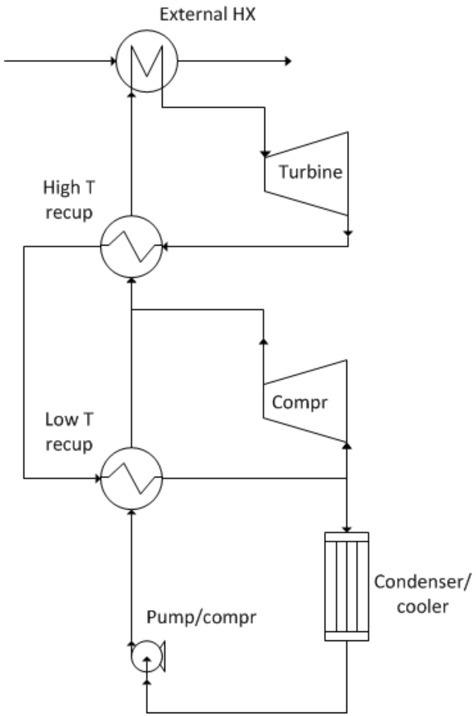
- Heat flux limited
  - Primary examples – Nuclear, CSP
  - Main characteristic is that unrecovered heat is recycled back to the main process
  - $T_{h,max}$-$T_{h,min}$ can be small, results in higher efficiency cycle
- Sensible enthalpy-based
  - Primary example – WHR, CCGT
  - Main characteristic is that unrecovered heat is lost to the environment
  - $T_{h,max}$-$T_{h,min}$ needs to be large, results in lower efficiency cycle
- Intermediate
  - High-temperature indirectly-fired cycle, CSP
  - Unrecovered heat partially recycled via air preheating
  - Cost impact of low $T_{h,max}$-$T_{h,min}$ is important to consider

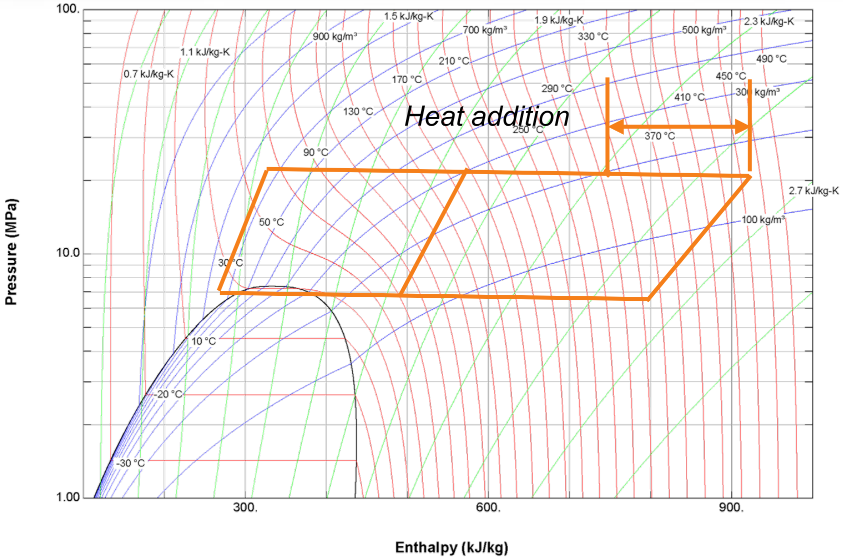
Nuclear application

Recirculated heat transfer fluid fully recycled



Recompression cycle yields high heat to power efficiency, but very low ΔT





Closer to constant temperature heat addition – Approximates Carnot cycle
Works well for heat flux limited source

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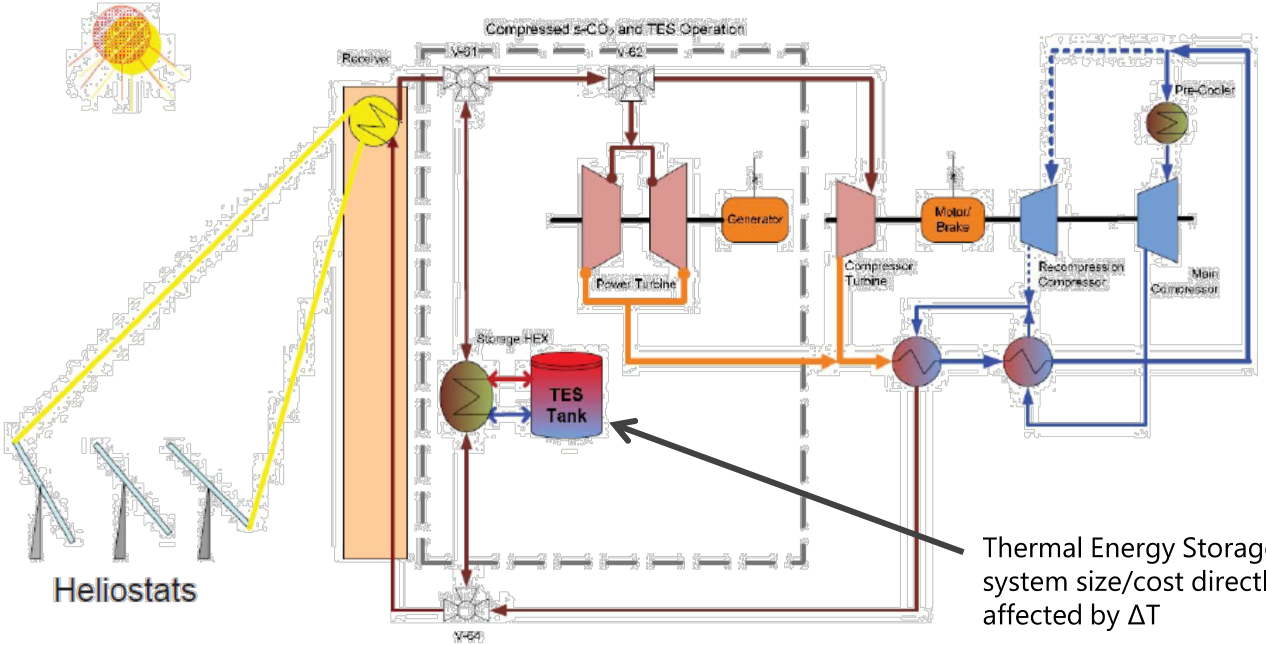
CSP application



Thermal Energy Storage system size/cost directly affected by ΔT

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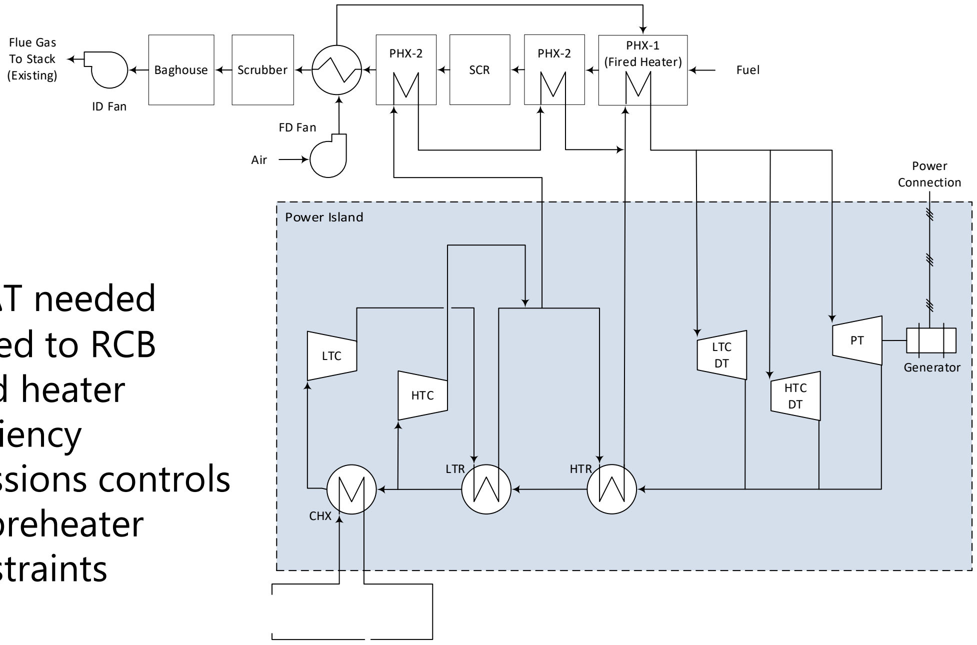
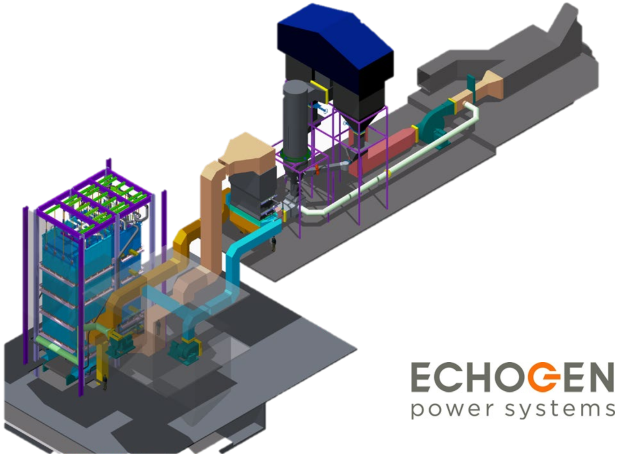
Integration with coal-fired power plant – LSP program



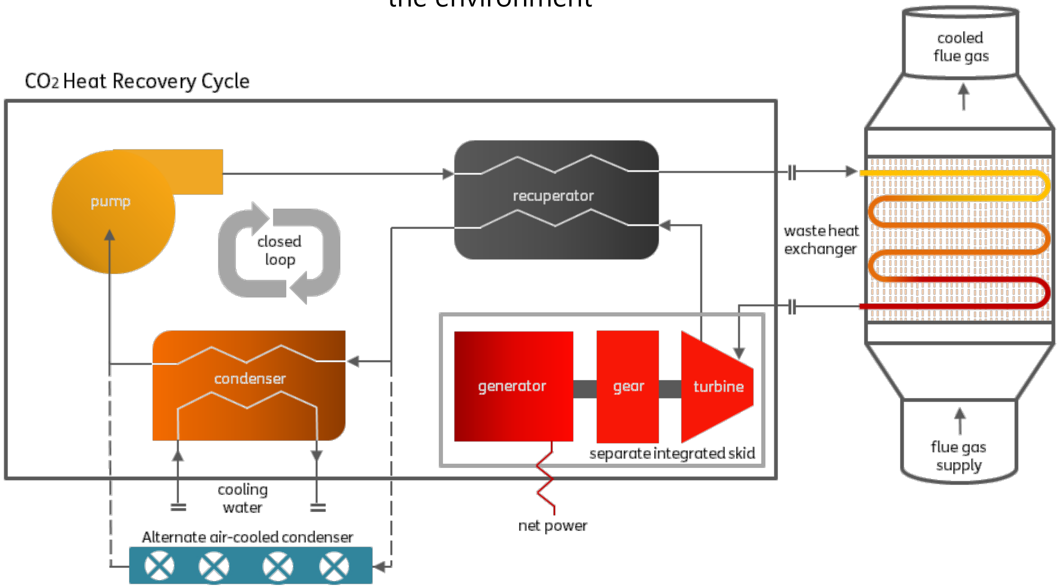


Larger ΔT needed compared to RCB

- Fired heater efficiency
- Emissions controls
- Air preheater constraints

Heat recovery application

Unrecovered heat lost to the environment



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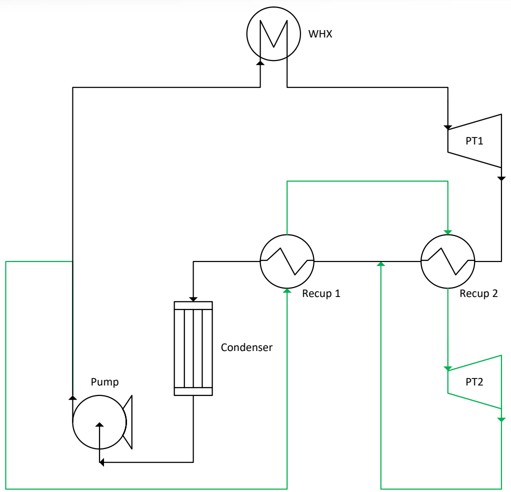
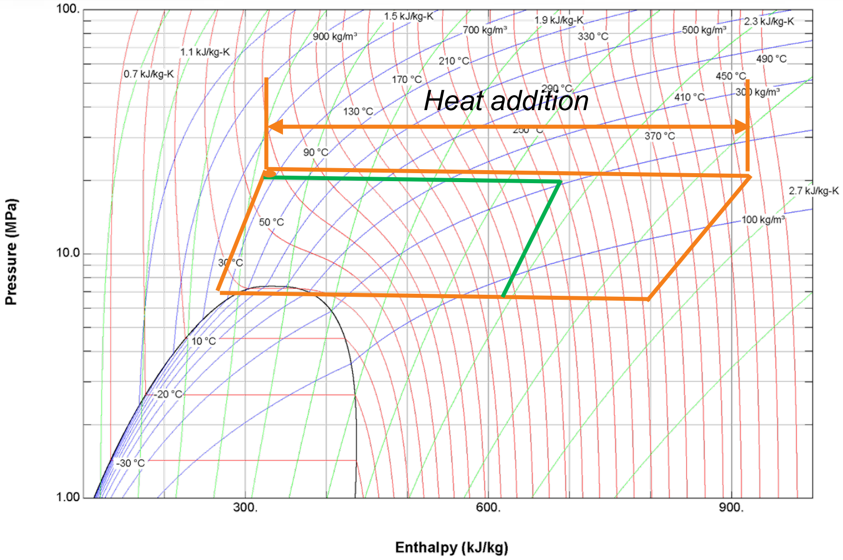
WHR architectures – increase available ΔT





Heat extraction limitations of simple recuperated cycle mitigated

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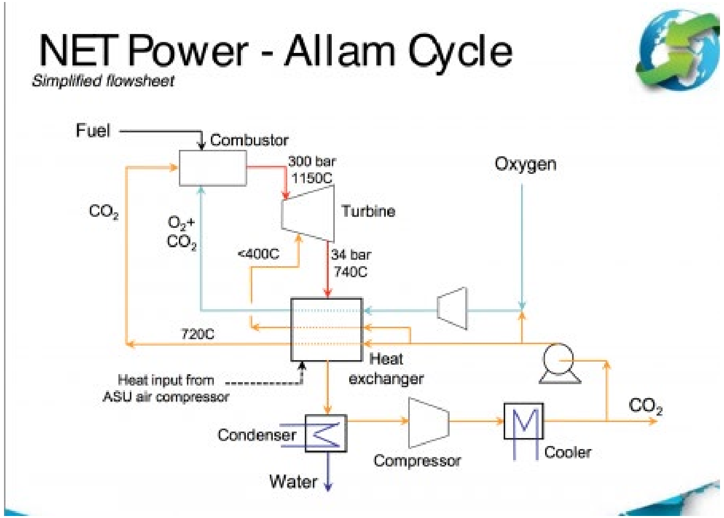
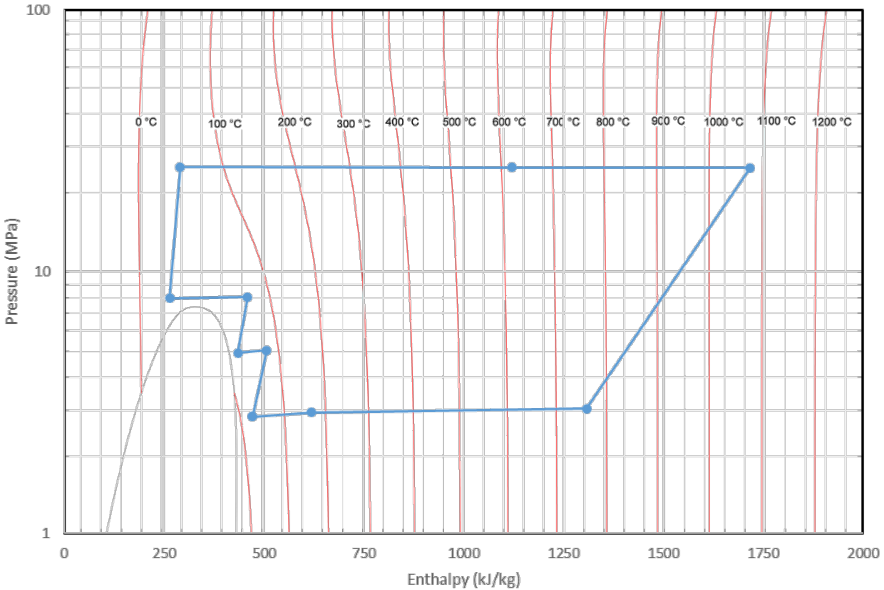
Direct-fired, Allam-Fetvedt cycle (simplified)



From http://www.21stcentech.com/mit-top-10-picks-2018-breakthrough-technologies/



Key features – zero emissions, extraction of produced CO_2 at pipeline pressure, co-production of other gases in ASU

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Technical challenges with sCO_2 power cycles

- Materials
  - WHR – 500-600°C, SS good enough
  - Advanced nuclear, CSP, indirectly-fired – 700°C… is the performance benefit worth the extra cost?
- Heat exchangers
  - Represent 20-40% of the total equipment cost
  - Diversity of primary heat exchangers
- Turbomachinery
  - Rotordynamic stability (high density fluid)
  - Non-ideal fluids (compressors only)
- Direct-fired cycle
  - Combustor design, operation and control
  - Turbine cooling
  - Recuperator design, materials and cost

Heat exchanger development programs

- Testing- and Model- Based Optimization of Coal-fired Primary Heater Design for Indirect Supercritical CO_2 Power Cycles (DE-FE0031928)
  - BYU (prime), REI, Riley Power and Echogen
  - Key outcome is heat flux modeling and measurement under severe conditions with CO_2 as coolant/working fluid
- Low-Cost Particle-to-CO_2 Moving Bed Heat Exchanger (DE-SC0021717)
- ARPA-E HITEMMP program
  - Multiple programs developing high-temperature heat exchangers for sCO_2 applications

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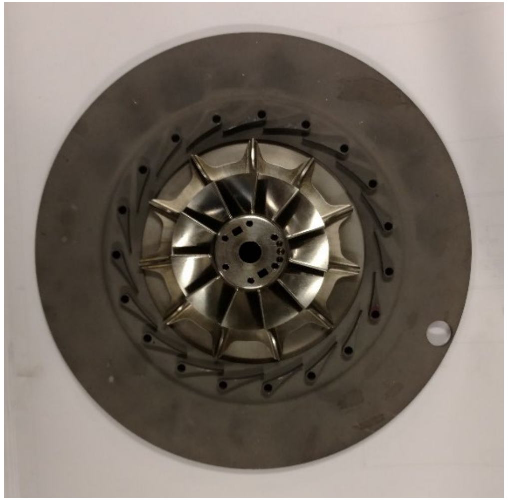
Metal parts - Echogen turbomachinery in practice

24.7 cm diameter

10 MW, 30 kRPM
EPS100 power turbine

16.0 cm diameter



3 MW, 25-35 kRPM
EPS100 turbocompressor

13.0 cm diameter

3 MW, 25-30 kRPM
EPS100 compressor

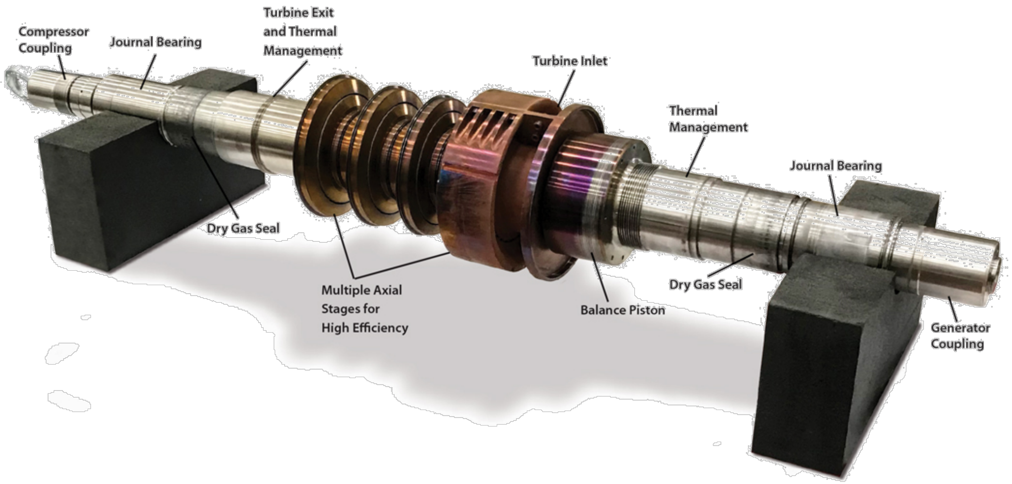
0.4MW, 40 kRPM
DMLS turbine

Metal parts – GE/SwRI SunShot turbine

First operating axial sCO_2 turbine

Max operating conditions, 27,000 rpm, 715 C and 250 bar

Forms basis of STEP turbine design



https://www.swri.org/technology-today/extreme-turbine-technology

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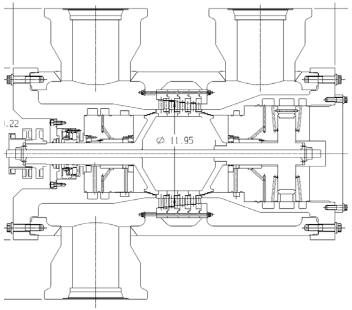
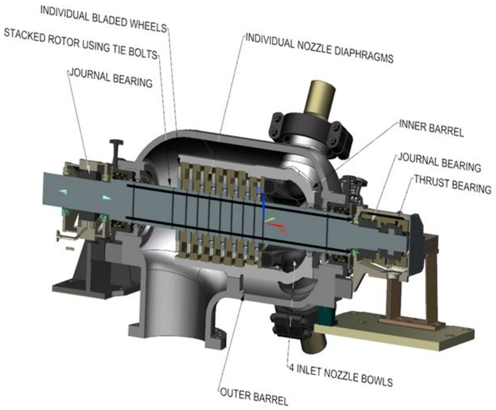
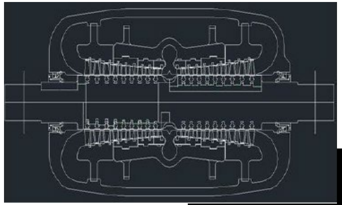
Paper parts - Larger-scale turbine designs are axial



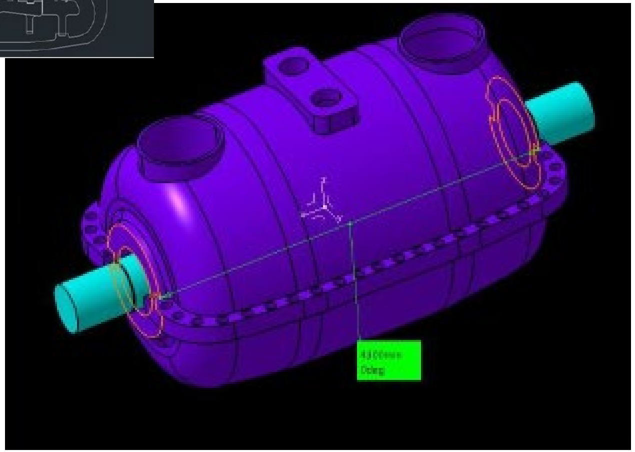
10 MW design
DE-FE00031585

Siemens 100 MW design
DE-FE00025959





DHI 750 MW design
DE-FE00025959



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Turbine design challenges

- Thrust management
- High fluid density
  - Rotordynamics, cross-coupled stiffness
  - Blade dynamics, especially at scale
- Case & rotor thermal growth / ramp rate limitations
- System architecture – single vs multiple shaft, cost vs controllability vs performance
- Bearings and seals – thermal management, internal vs external bearings, seals
- Axial vs radial

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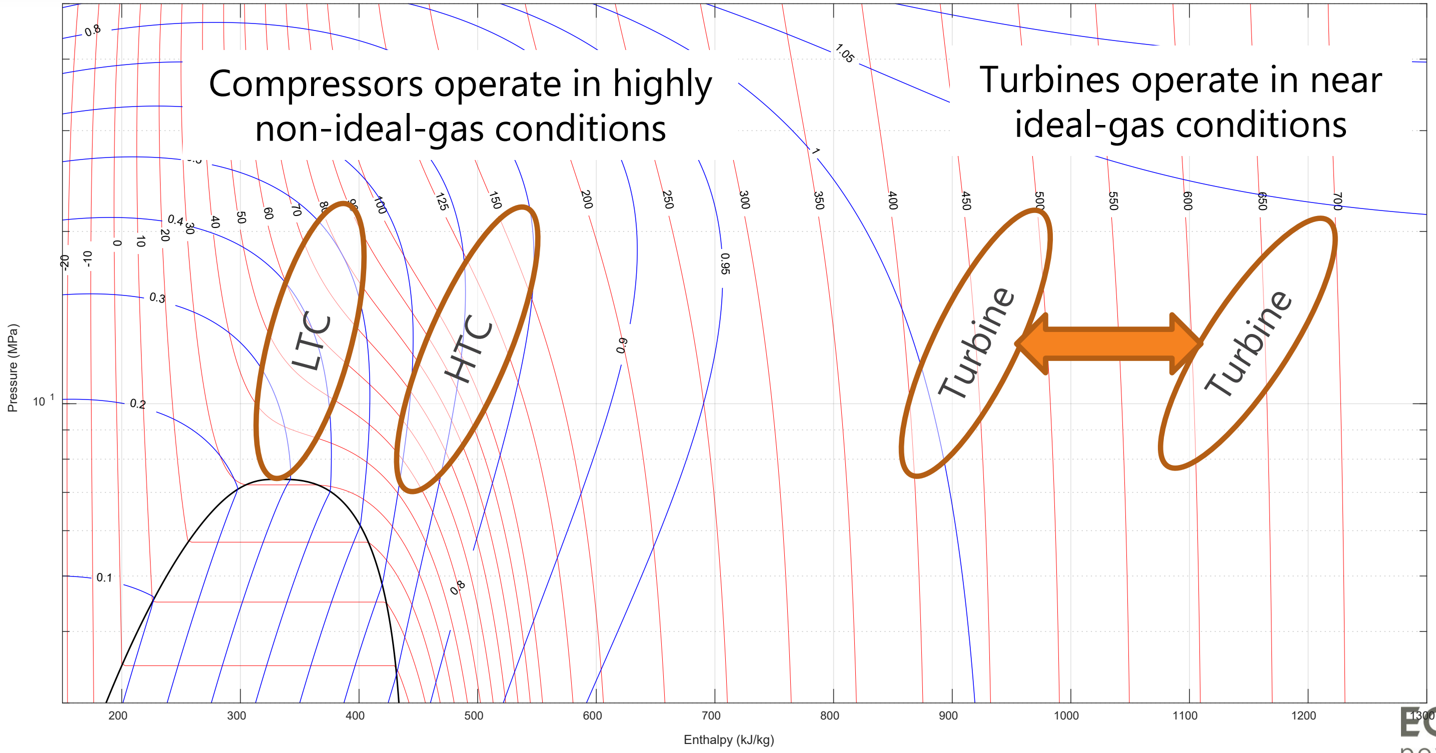
Aero design challenges – non-ideal gas behavior – Z(H,P)



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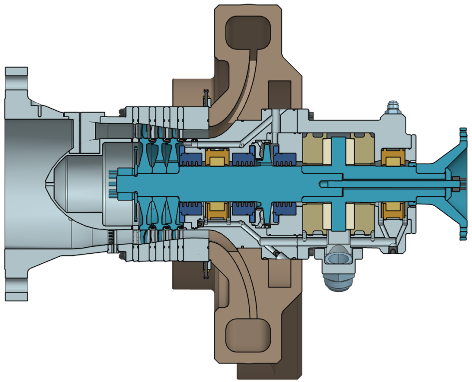
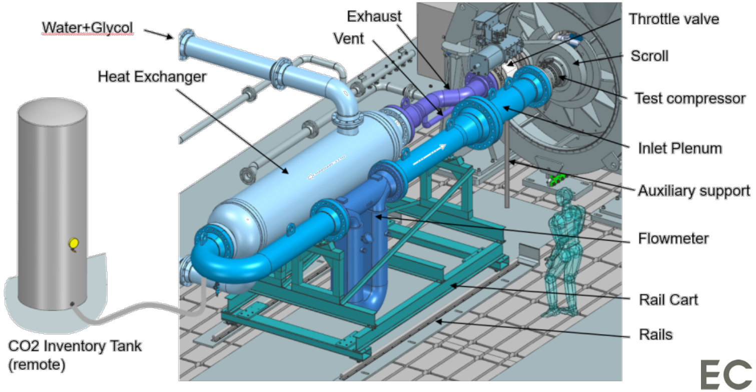
HTC compressor aero strongly affected by real gas effects

- Advanced compressors for CO_2-based power cycles and energy storage (DE-EE0008997)
- Echogen, University of Cincinnati and University of Notre Dame
- Design and test of 3-D Aero optimized axial CO_2 compressor





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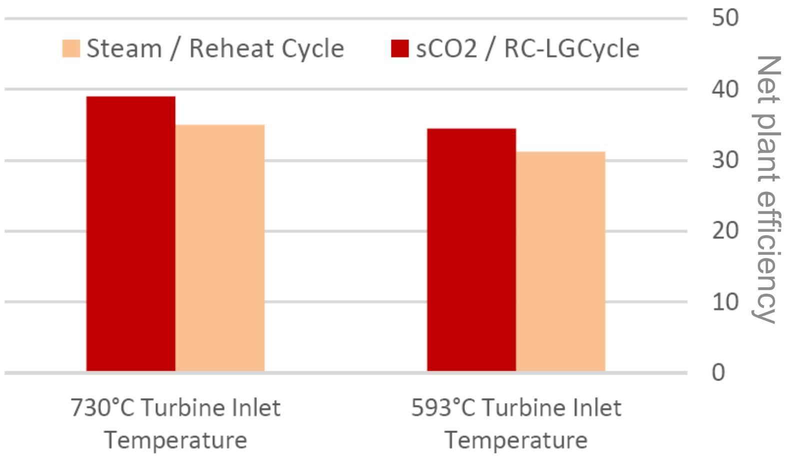
Market and application challenges & opportunities

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
- International applications more likely



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.

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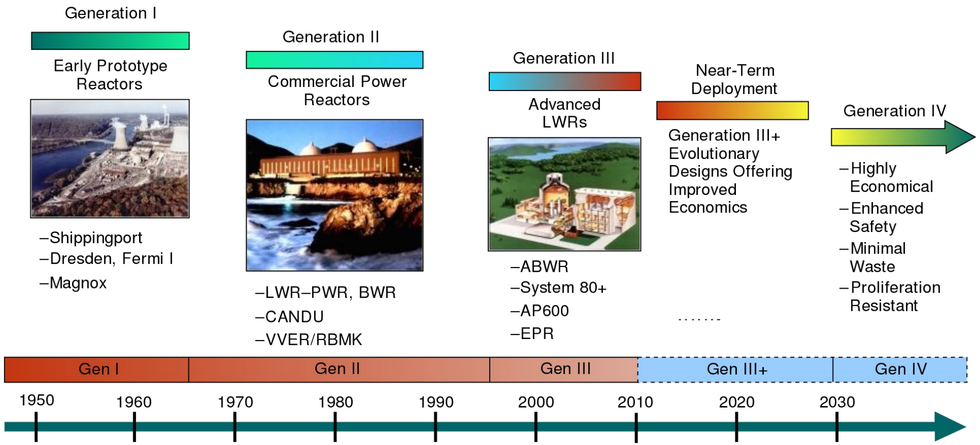
Advanced nuclear

sCO$_2$ cycles offer limited advantages for LWR (low heat source temperature)

Several Gen IV high-temperature reactors will operate at temperatures where sCO$_2$ gives significantly better efficiency

Timeline for introduction…

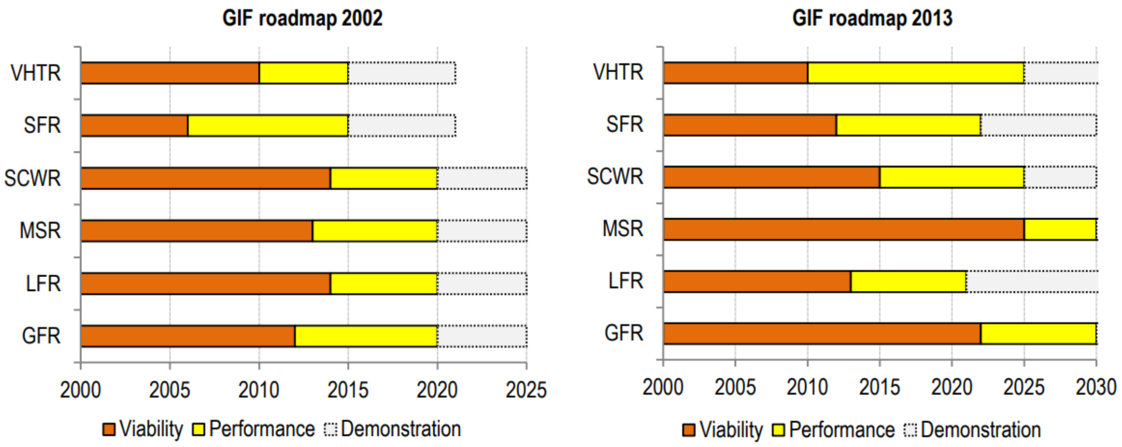
Generation IV: Nuclear Energy Systems Deployable no later than 2030 and offering significant advances in sustainability, safety and reliability, and economics



DOENE (USDOE Office of Nuclear Energy, Science and Technology (NE)), 2002, *A Technology Roadmap for Generation IV Nuclear Energy Systems*, GIF-002-00, 859029.

Gen IV timeline

In 11 years between Tech Roadmaps, timelines moved out 2 to 10 years



OECD Nuclear Energy Agency, 2014, *Technology Roadmap Update for Generation IV Nuclear Energy Systems.*

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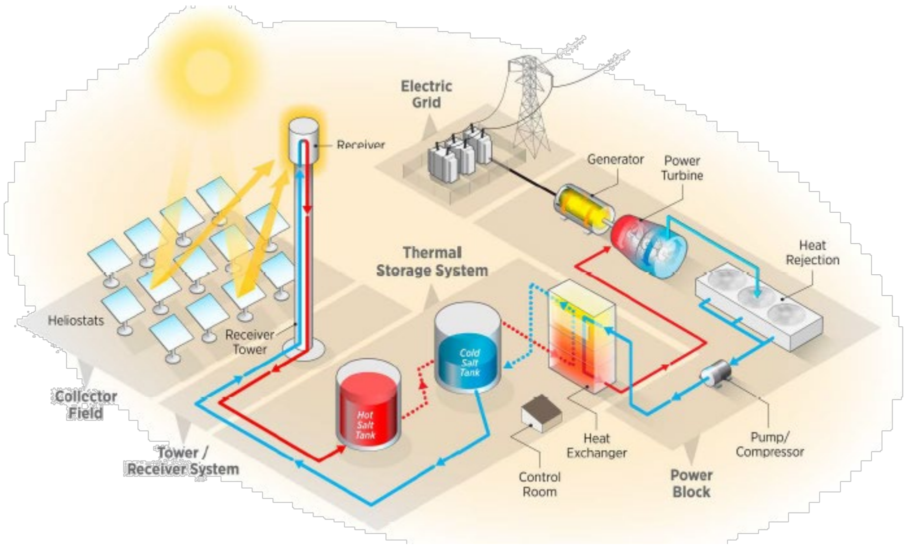
Concentrating Solar Power

CSP's primary value stems from integration with thermal storage

Current nitrate salt systems limited to 565°C – sCO_2 advantages are limited, reduced ΔT increases storage cost

Higher-temperature Gen3 applications are better fit for sCO_2



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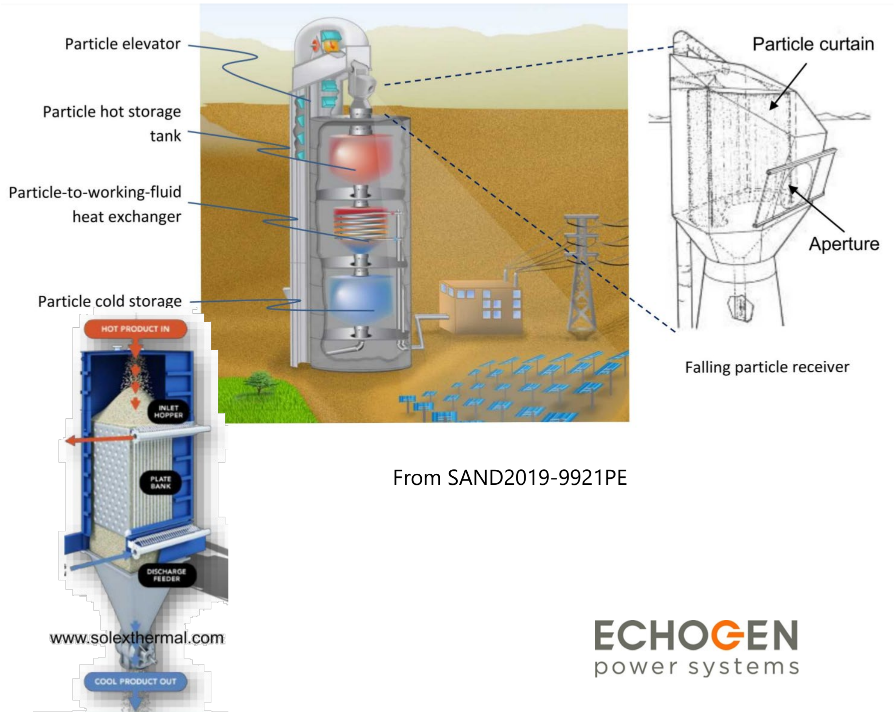
Gen3 Particle-based CSP

Receiver uses falling "curtain" of particles (bauxite) to both collect and store thermal energy at ~ 750°C

sCO_2 power cycle is integral part of technology

Key challenge – particle to CO_2 heat exchanger

Timeline to a commercial product…



From SAND2019-9921PE

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CSP – Heliogen Integrated TESTBED

SETO award to demonstrate thermal storage with sCO_2 power cycle at 5 MWe scale

Turbine inlet temperature = 600°C

Other project details (e.g., storage media) not disclosed

From https://heliogen.com

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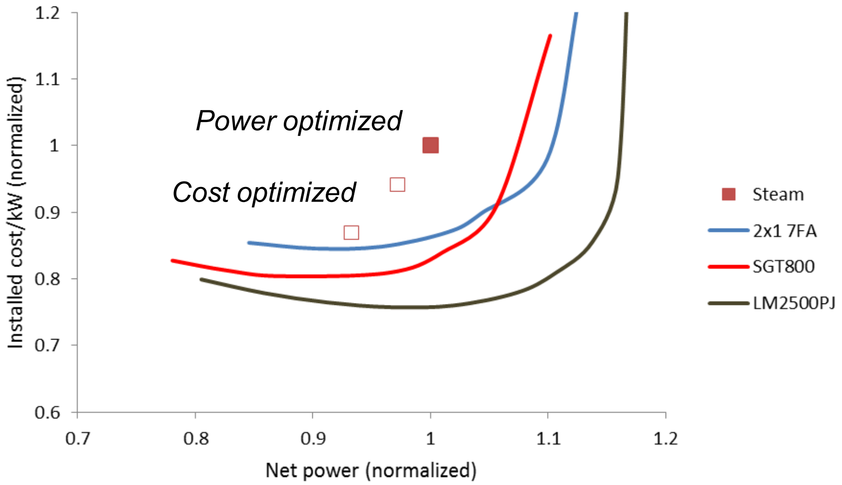
CCGT applications - sCO_2 vs steam

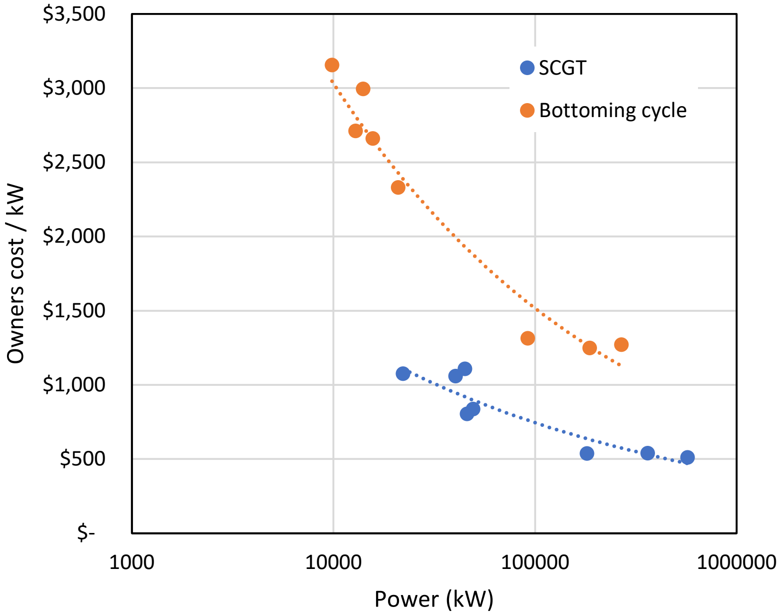


Held, T. J., 2015, "Supercritical CO_2 Cycles for Gas Turbine Combined Cycle Power Plants," Power Gen International, Las Vegas, NV.

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

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



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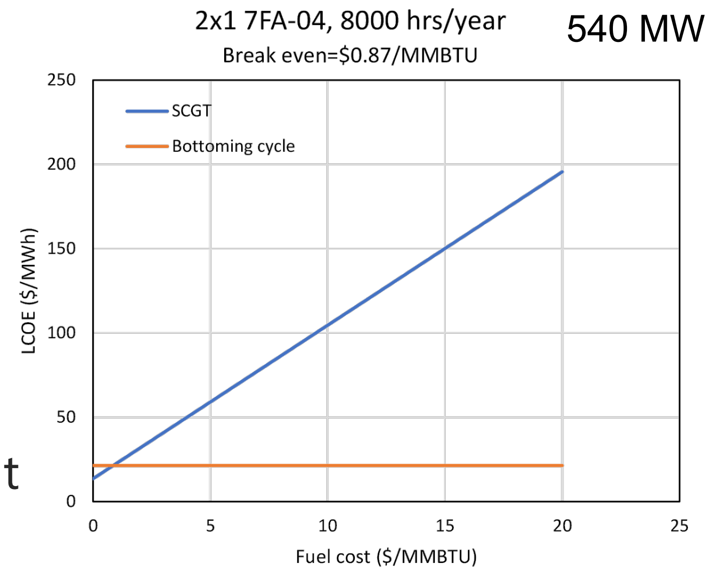
LCOE analysis

- 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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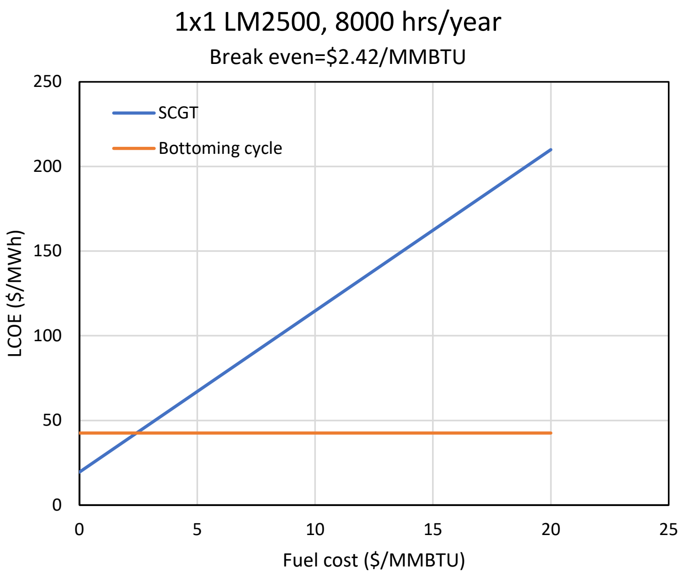
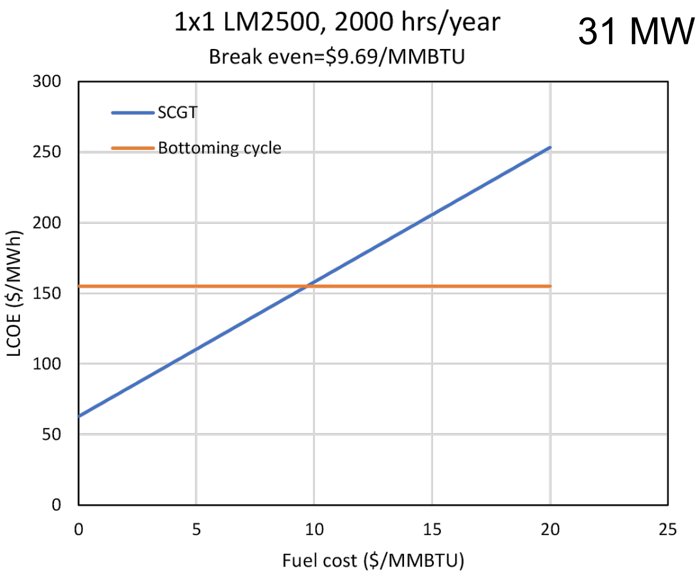
LCOE analysis, continued





31 MW

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

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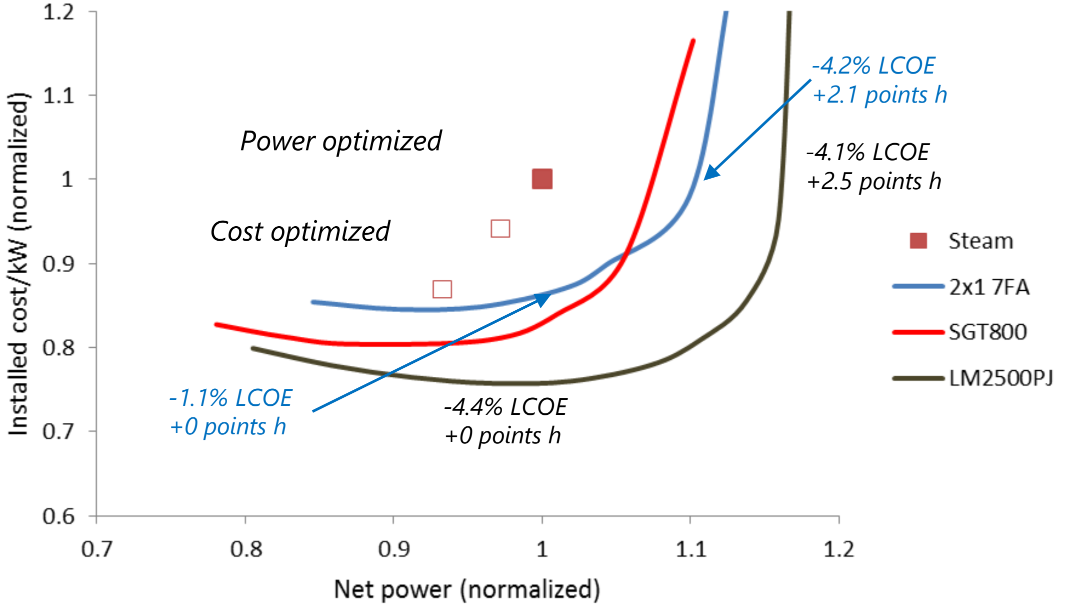
Improvements with sCO_2 bottoming cycle



All at $5/MMBTU, 8000 hrs/year

sCO_2 power cycles can deliver improved LCOE across the board

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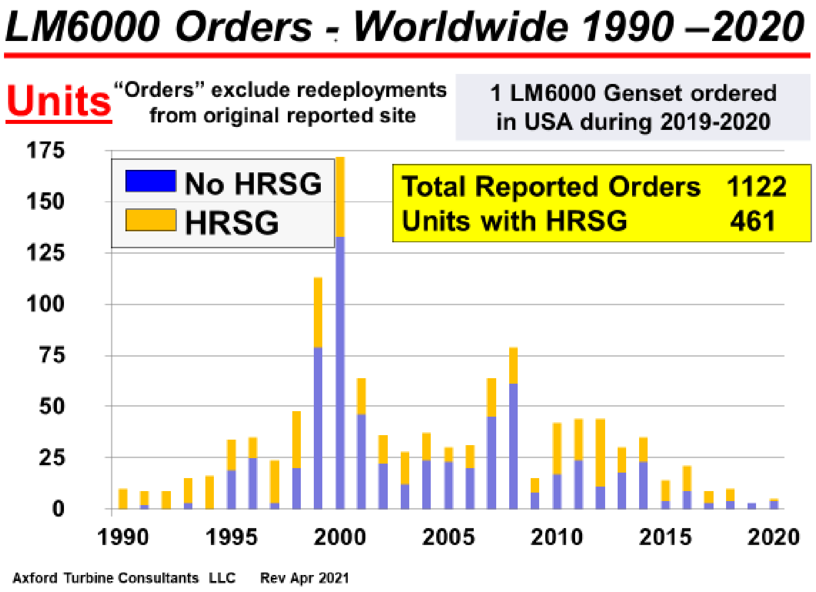
CCGT applications – a difficult market

- GT orders have fallen significantly
- NG costs have remained ~ $2-4 per MMBTU since 2010, reduces economic incentive to improve efficiency
- Hydrogen-fired GTs offer a potential long-term opportunity
  - $1/kg (DOE target) is equivalent of ~ $8/MMBTU
  - Will significantly improve value proposition of bottoming cycle, even at shorter firing hours



ECHOGEN power systems

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

ECHOGEN power systems

Long-duration Energy Storage with CO_2

Electro-Thermal Energy Storage: Electricity stored as heat & cold

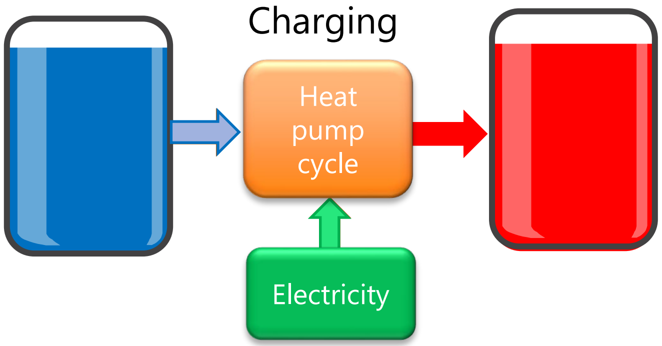
Thermodynamic cycles transform energy between electricity and heat

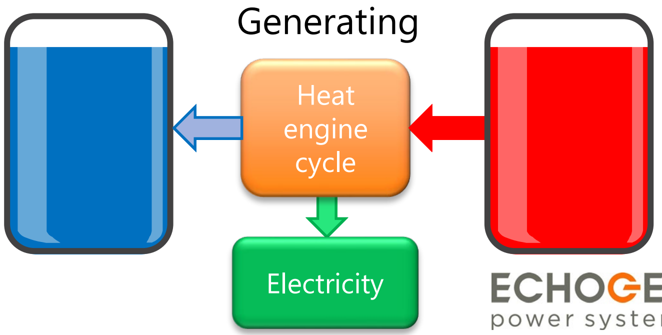
Charging cycle

- 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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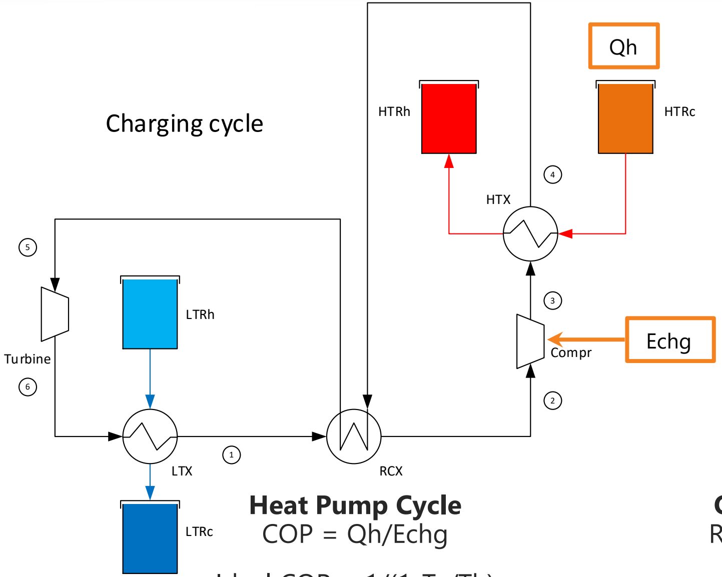
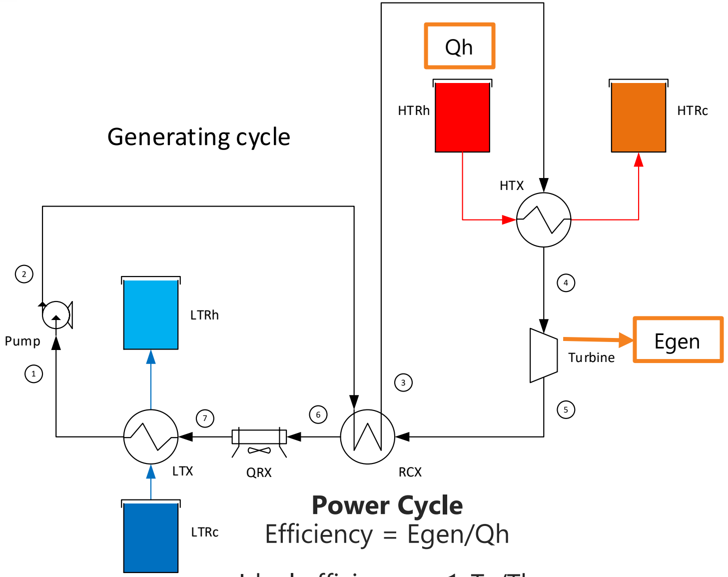
Pumped Thermal Energy Storage basics





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

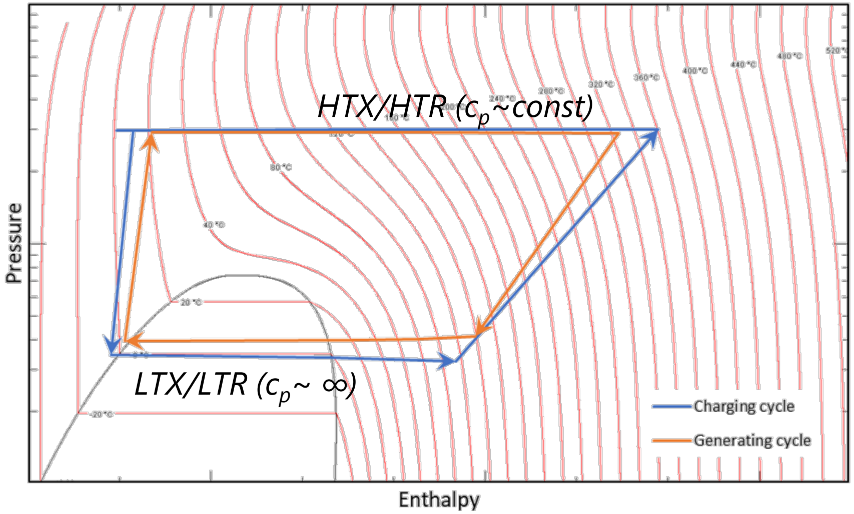
Ideal cycle RTE = COP_{Carnot} x η_{Carnot} = 100%

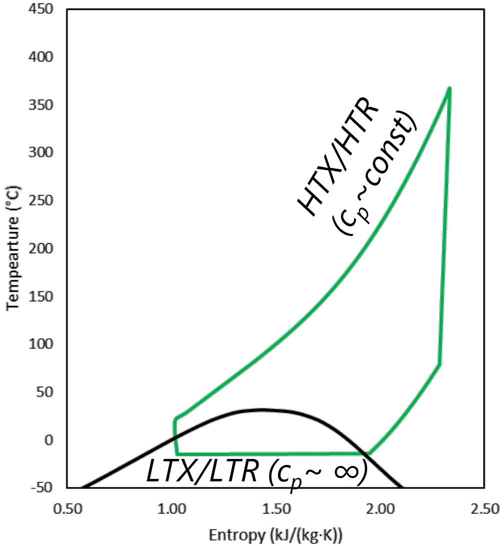
Non-ideal processes result in RTE ~60%, even at modest temperature ratio

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

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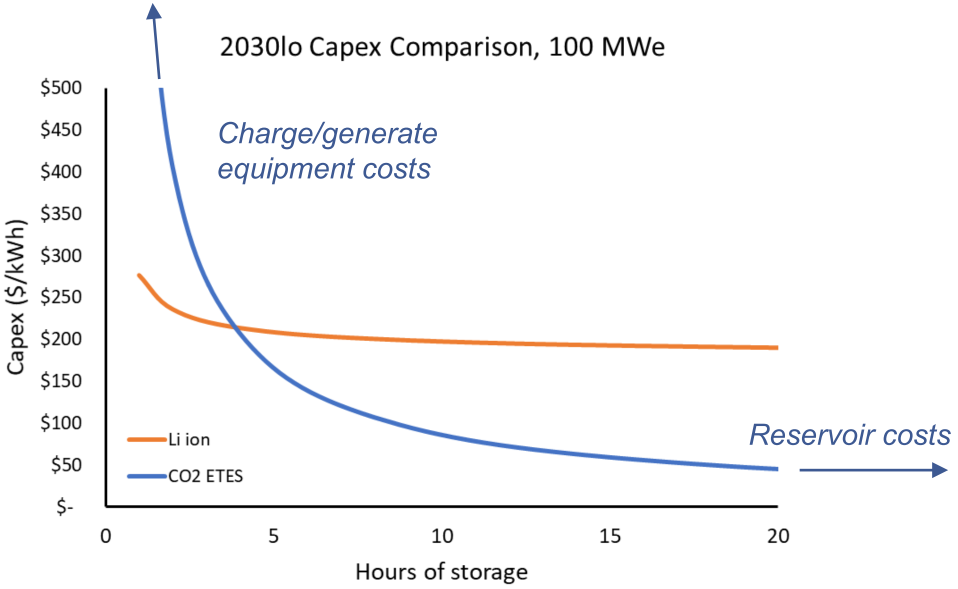
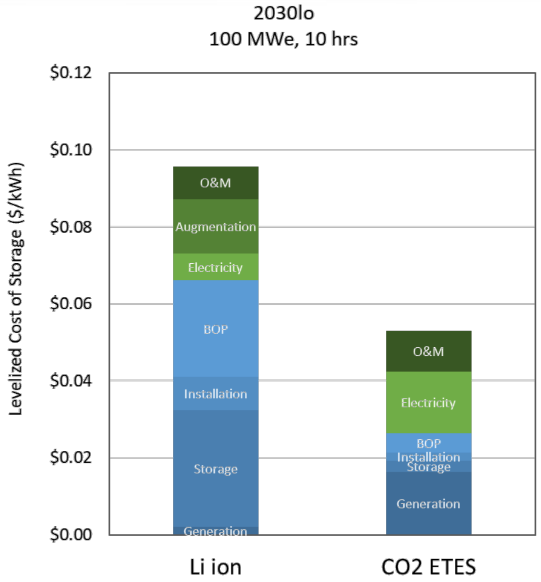
Low $/kWh reservoir costs drive competitive advantage





Lower Capex, no augmentation costs => Lower LCOS

ECHOGEN power systems

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)

Initial build

- 2-tank heat transfer fluid HTR
- Ice slurry LTR
- Commissioning end of Sept 2020
- Complete testing October 2020

- Build and test sand HTR system
- Complete April 2022

Primary developmental focus:

- HTR and heat exchanger (TRL 4)
- LTR performance (TRL 4)
- Operation and controls

25 MW, 8–10-hour system in prelim design

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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 hindered commercialization
- Future developments in high-temperature sCO_2 indirect cycles, oxy-fired sCO_2 cycles, energy storage in the works

Thank you!

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