Supercritical CO2 Power Cycles: Design Considerations for Concentrating Solar Power

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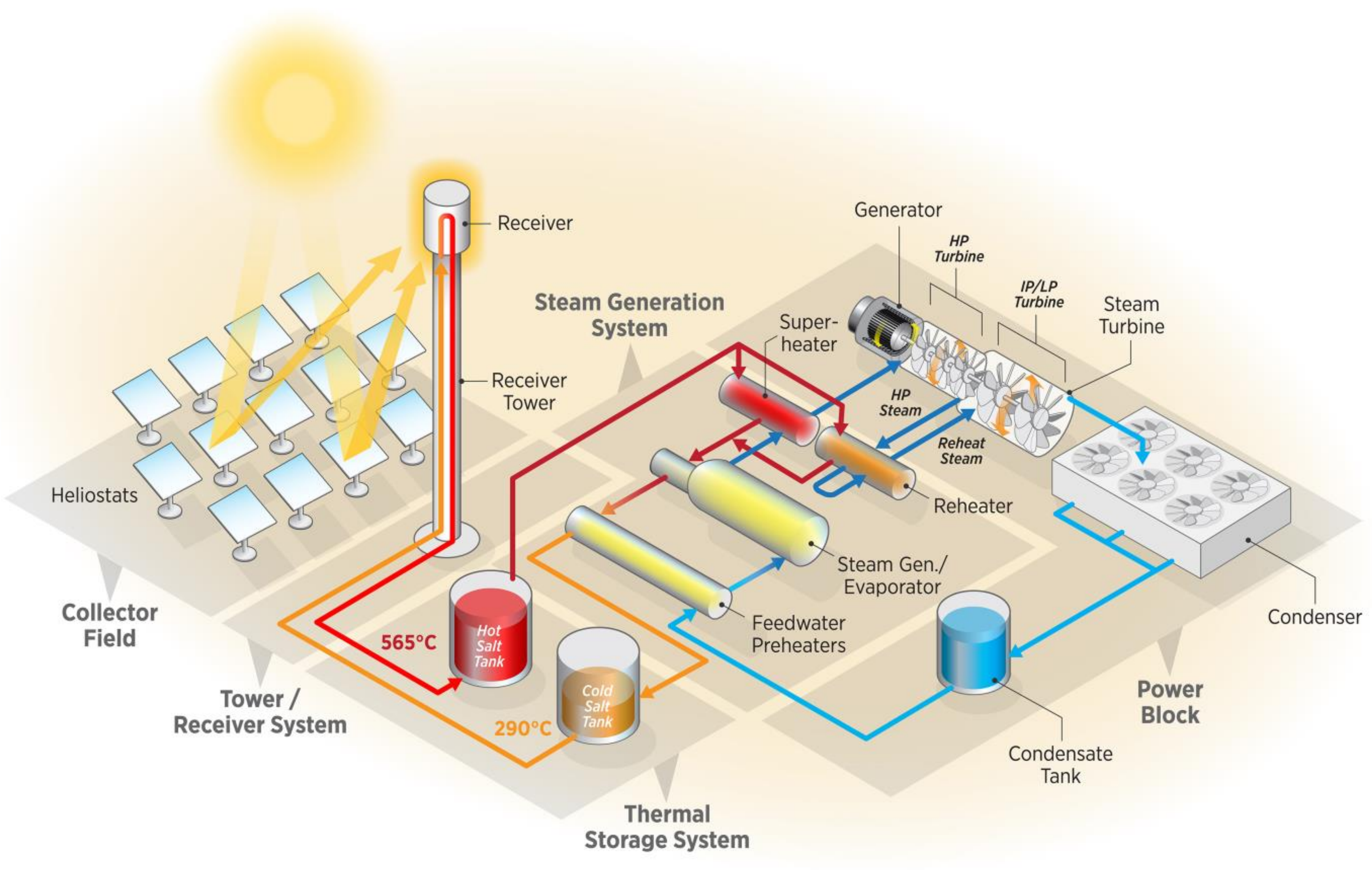
CSP Basics: the Molten-Salt Power Tower

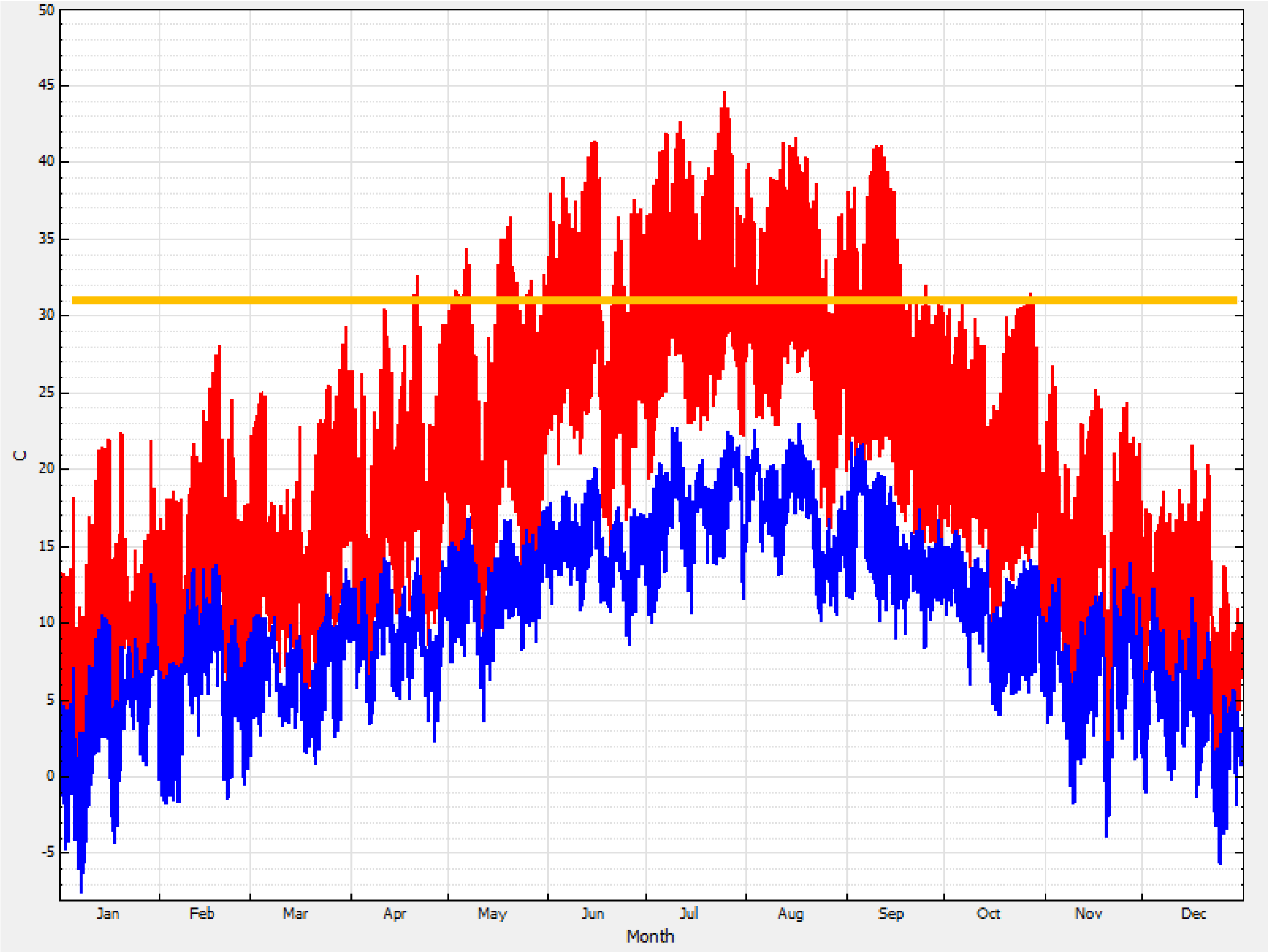


What Differentiates CSP?

Potential s-CO_2 Power System Applications

Application	Temp (°C)	Scale (MW)	Typical Cooling	Thermal Storage	Comments
Nuclear	550-650+	25-300+	Wet	Maybe	
Fossil (coal)	550	300+	Wet	No	
Fossil (Allam cycle)	1200	300+	Wet	No	
Marine Power	550	10-15	Wet	No	Rapid start and power ramping required
Waste Heat	<550	<50	Wet	No	Benefits from wide ΔT across primary HX
CSP	585-700	10-100	Dry	Yes	Off-design operation is common

Desert Temperatures for Southwest US



CO_2 critical temperature

Dry-bulb and wet-bulb temperatures for Daggett, CA

Considerations for CSP Integration

Factors for integrating s-CO2 power cycles into CSP plants

1. Superior performance vs. steam Rankine *at dry cooling*
2. Economic integration of TES

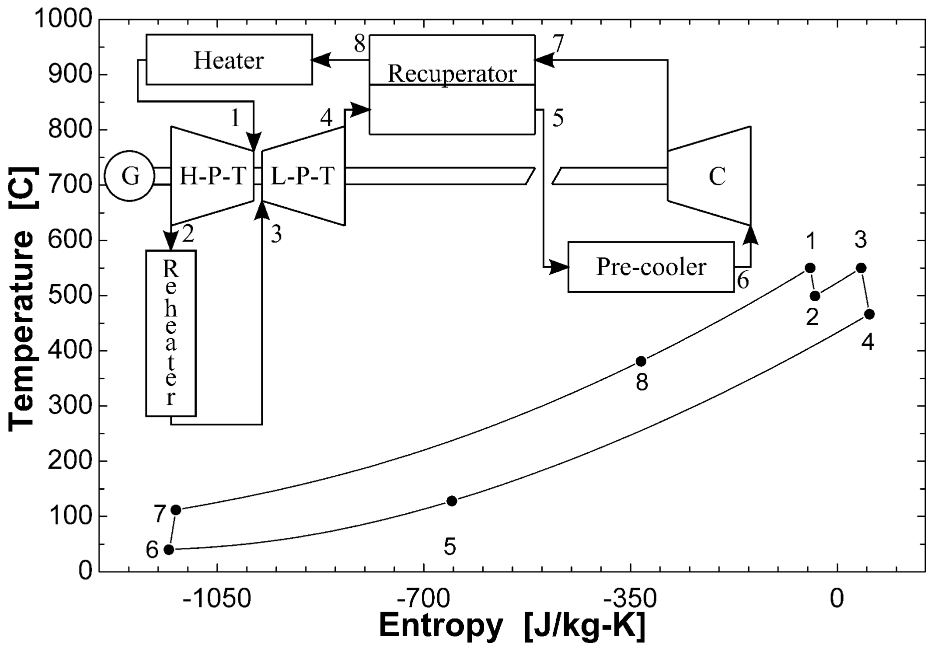
$$Energy_{TES} = mass * specific\ heat\ * (T_{hot} - T_{cold})$$

For sensible heat storage:

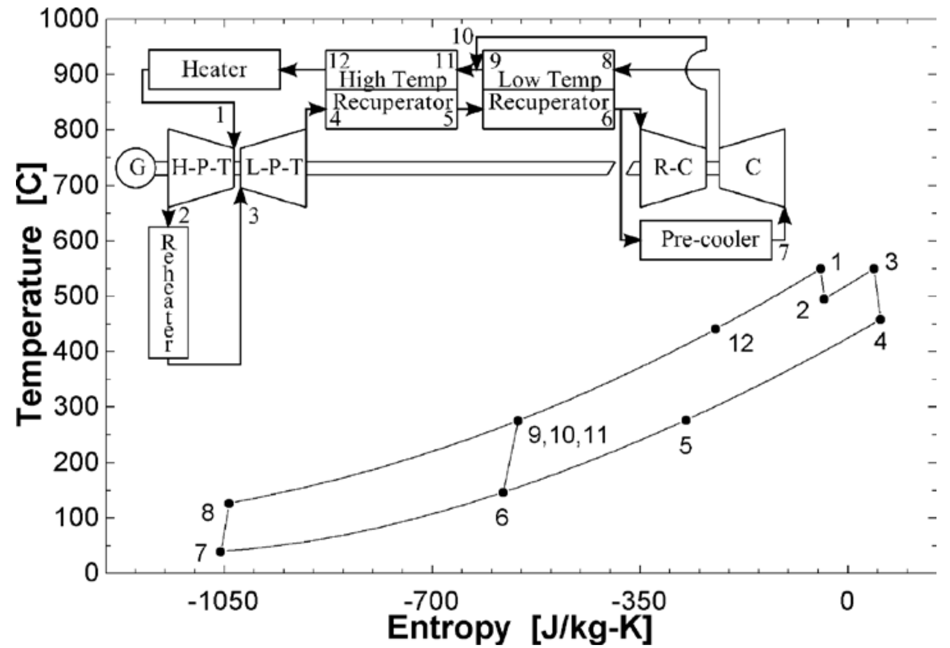
- The required mass of HTF is proportional to the hot and cold tank temperatures.
- All else equal, a cycle with a larger temperature difference is preferred to a cycle with a smaller temperature difference

Configurations

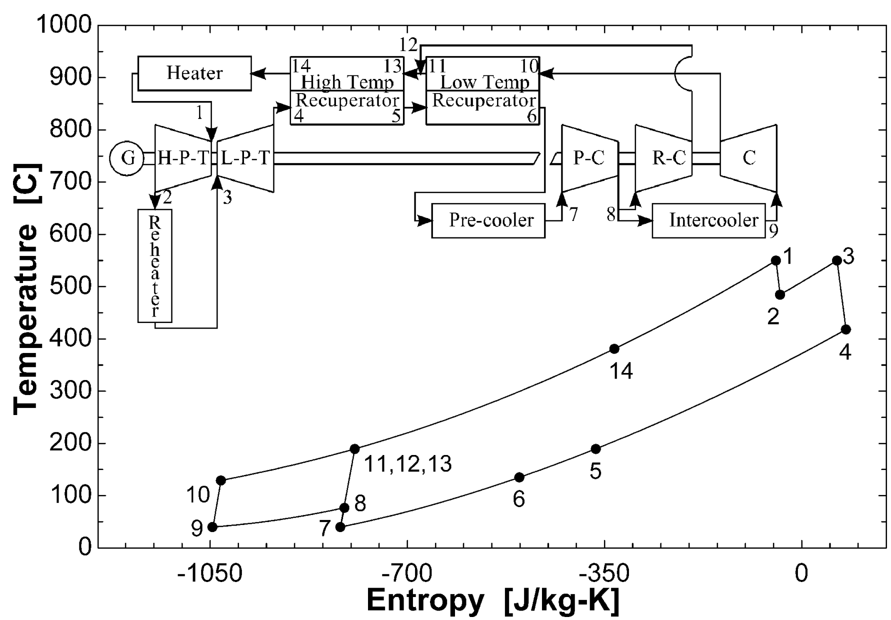
Simple



Recompression



Partial Cooling



Modeling Background and Research Objective

Modeling Background

- One reheat stage increased efficiency around 1.2% for a recompression cycle (Dostal, 2004)
- Partial cooling cycle achieves competitive efficiency with the recompression cycle while offering larger HTF temperature differences (Dostal, 2011)
- Dry-cooled partial cooling and recompression cycles have potential to achieve > 50% efficiency at 650°C (NREL, 2013)

Summary

- Recompression and partial cooling efficiencies are similar, but studies have not investigated the heat exchanger requirements

Objective

- Model the heat exchangers using a conductance (UA) model and compare the efficiency, HTF temperature difference, and other useful cycle performance metrics as a function of allocated conductance

Recuperator Modeling Approaches

1. Select HX effectiveness and minimum temperature difference
   - Simplest approach to approximate HX performance
   - Does not consider temperature profile within HX (e.g. pinch points)
   - Non-dimensional metric – does not correlate to HX size
2. Select HX conductance (UA)
   - Calculates HX performance based on approximation of HX size
   - Correlates performance and size without requiring specific physical dimensions – useful for relative comparisons
   - Does not capture effects of specific design decisions or varying fluid properties
3. Select a HX design
   - Requires realistic dimensions and heat exchanger material properties
   - Most complex and computationally expensive approach
   - Provides the best data with which to compare different cycles

Design and Optimized Parameters for Case Studies

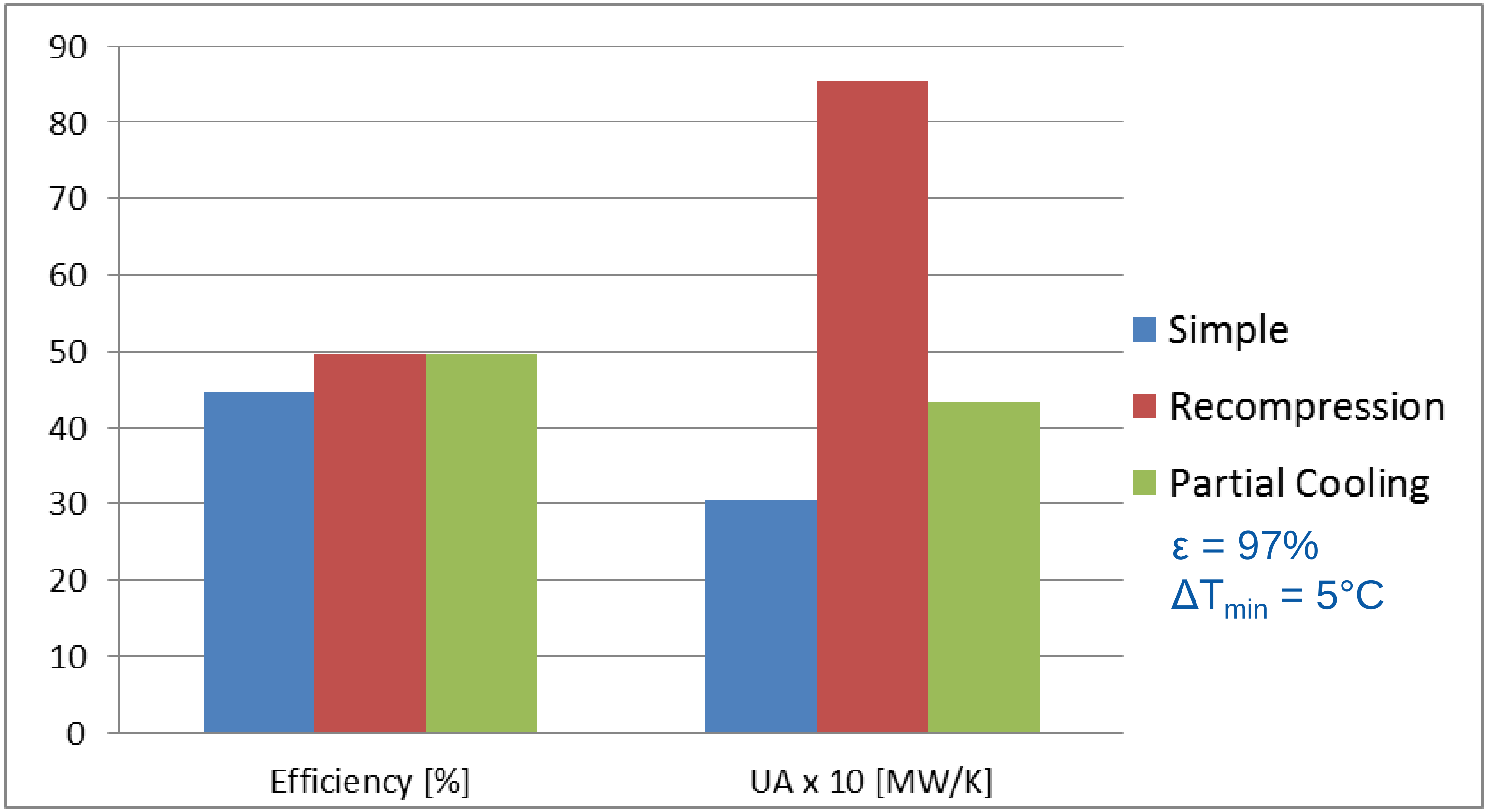
Design Parameters	Value	Comments
Turbine efficiency	93%	Projection of mature, commercial size axial flow turbine efficiency
Compressor efficiency	89%	Projection of mature, commercial size radial compressor
Heat exchanger effectiveness	97%	5°C minimum temperature difference, neglect pressure drops
Heat exchanger conductance (UA)	Varied MW/K	Neglect pressure drops
Turbine inlet temperature	650°C	SunShot target for CSP power tower outlet temperatures
Compressor inlet temperature	50°C	Possible under dry cooling with 35°C ambient temperature
Upper pressure	25 MPa	Upper limit given available and economic piping
Turbine Stages	2	One stage of reheat at average of high and low side pressures
Net power output	35 MW	Estimate of power cycle requirements for a 100 MW-thermal SunShot target power tower with a solar multiple of 1.5

Optimized Parameters	Relevant Cycles
Pressure ratio (PR)	All
Fraction of total UA allocated to HTR	Recompression, Partial Cooling (not applicable for effectiveness approach)
Ratio of pressure ratios (rpr)	Partial Cooling (sets intermediate pressure)

Results – Recuperator *Effectiveness* Model

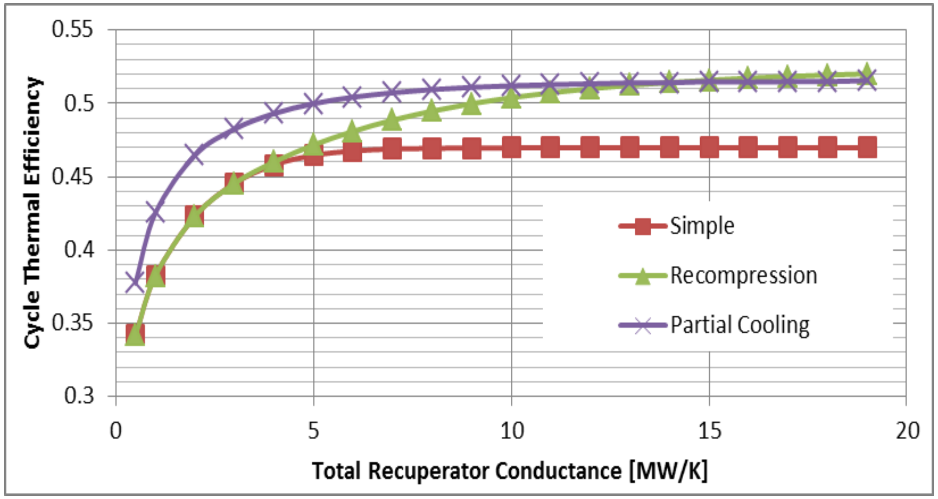
- Similar efficiencies for complex cycles
- Much larger recuperator conductance for the recompression cycle

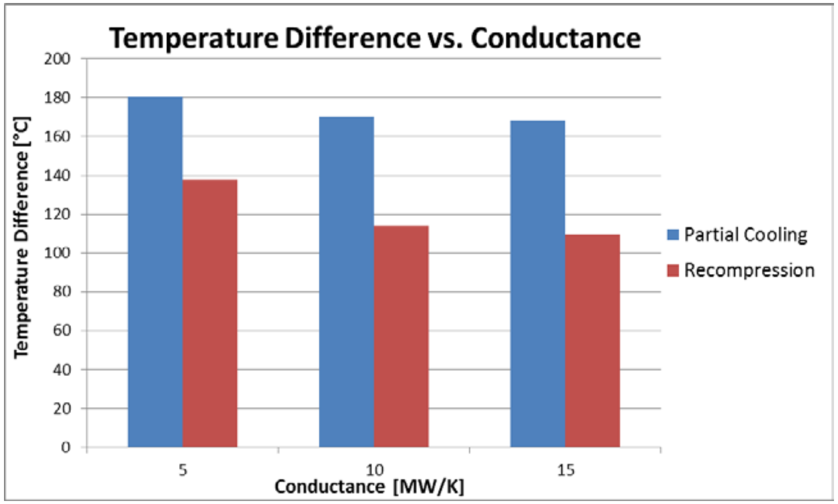
Effectiveness model does not give complete picture



Results – Recuperator *Conductance* Model

- Significantly different results when recuperator conductance is specified
- At smaller conductance values, the recompression cycle reverts to simple cycle behavior (Bryant 2011, Dyreby 2012)
- As conductance reaches largest values
  - Recompression cycle efficiency reaches partial cooling efficiency
  - Recompression PHX ΔT decreases more rapidly than partial cooling ΔT

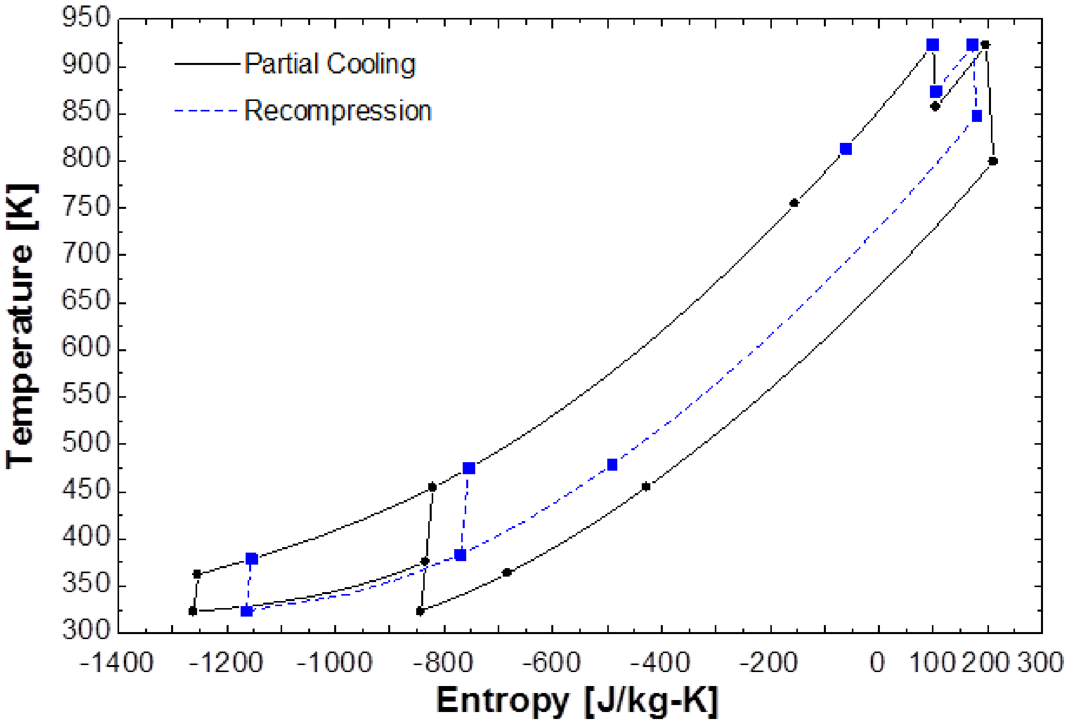




Recompression and Partial Cooling T-s Comparison

Partial cooling cycle optimizes at a higher pressure ratio:

- Lower turbine outlet temp & HTF inlet temp
- Lower compressor outlet temp & condenser inlet temp
- Smaller mass flow rate for a given power output, so more effective recuperators

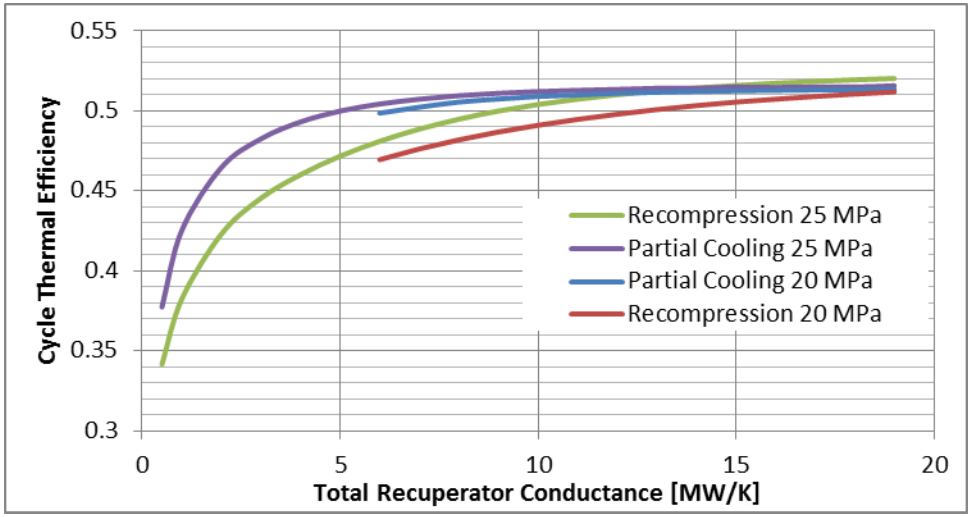


Modeling Limitations

- Neglecting pressure drops
  - Larger pressure difference in partial cooling cycle
  - Lower densities in partial cooling cycle may require more or larger channels
- Conductance HX model does not consider the impact of absolute pressures and pressure differentials
- Does not consider impact of varying fluid properties on heat transfer coefficients
  - One cycle may have favorable heat transfer coefficients in the recuperator

Integration with Direct CO2 Receivers

- Ongoing research of direct s-CO2 receivers
  - NREL, Brayton Energy, OSU/PNNL, CSIRO
- Potential advantages of integration with partial cooling cycle:
  1. Lower average temperature of receiver may help reduce thermal losses
  2. Enables longer flow paths in receiver
     1. Stabilizes mass flow rate through parallel tubes
     2. Reduces deviation of absorbed energy per tube
  3. Lower total mass flow rate reduces header piping sizes
  4. Greater potential to decrease the high pressure in the receiver

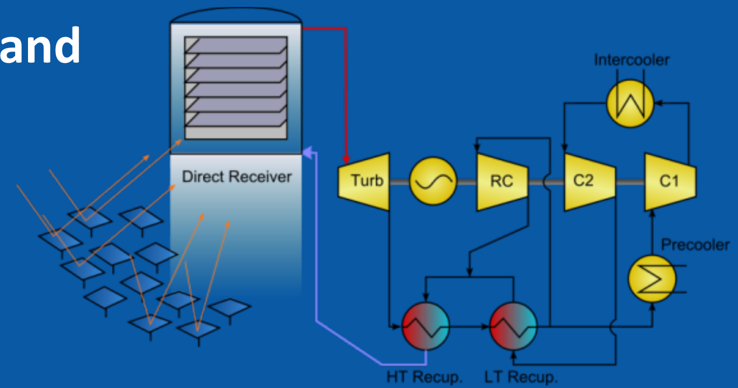


Conclusions

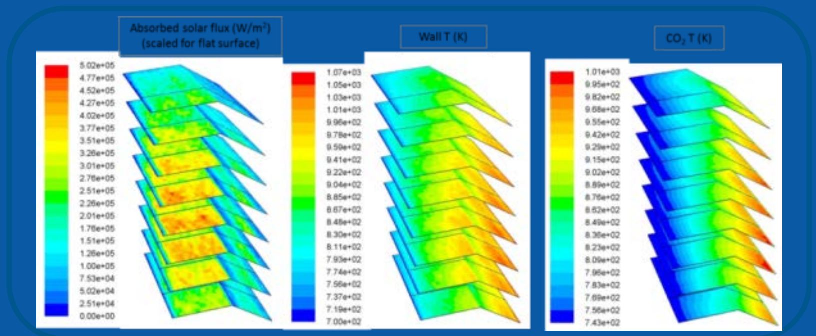
- A conductance model provides a more equivalent recuperator comparison than an effectiveness model
- The partial cooling cycle outperforms the recompression cycle until large quantities of conductance are modeled
- The partial cooling cycle offers a larger temperature difference across the primary heat exchanger, which is critical to economic TES integration in CSP systems. It also may offer benefits to direct receiver designs.
- Partial cooling cycles are reasonable candidates for CSP systems. Cycle off-design, system design, system off-design, and eventually cost of energy comparisons to the recompression cycle are required for a more thorough analysis.

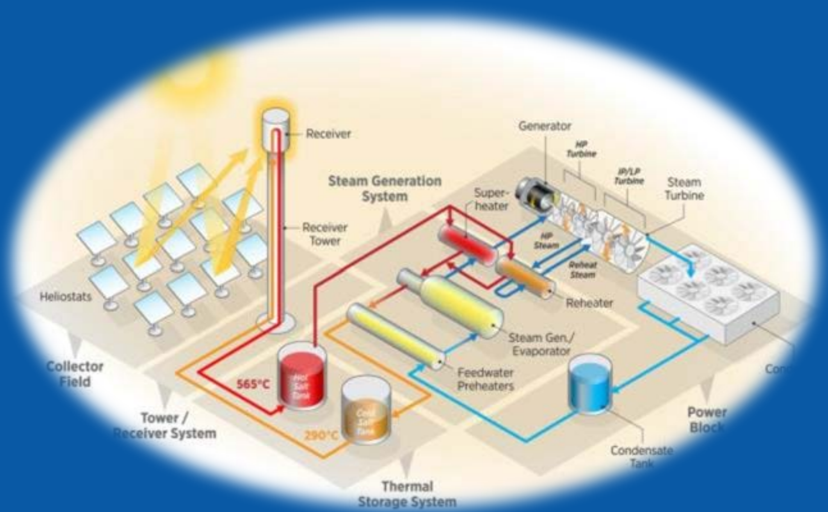
NREL's areas of focus for s-CO_2

Cycle modeling and optimization



Solar receiver design and optimization





CSP system integration and annual performance modeling

Heat transfer fluid testing, corrosion testing, and protective barrier coating development

THANK YOU!