CSP Gen3 System Integration Considerations

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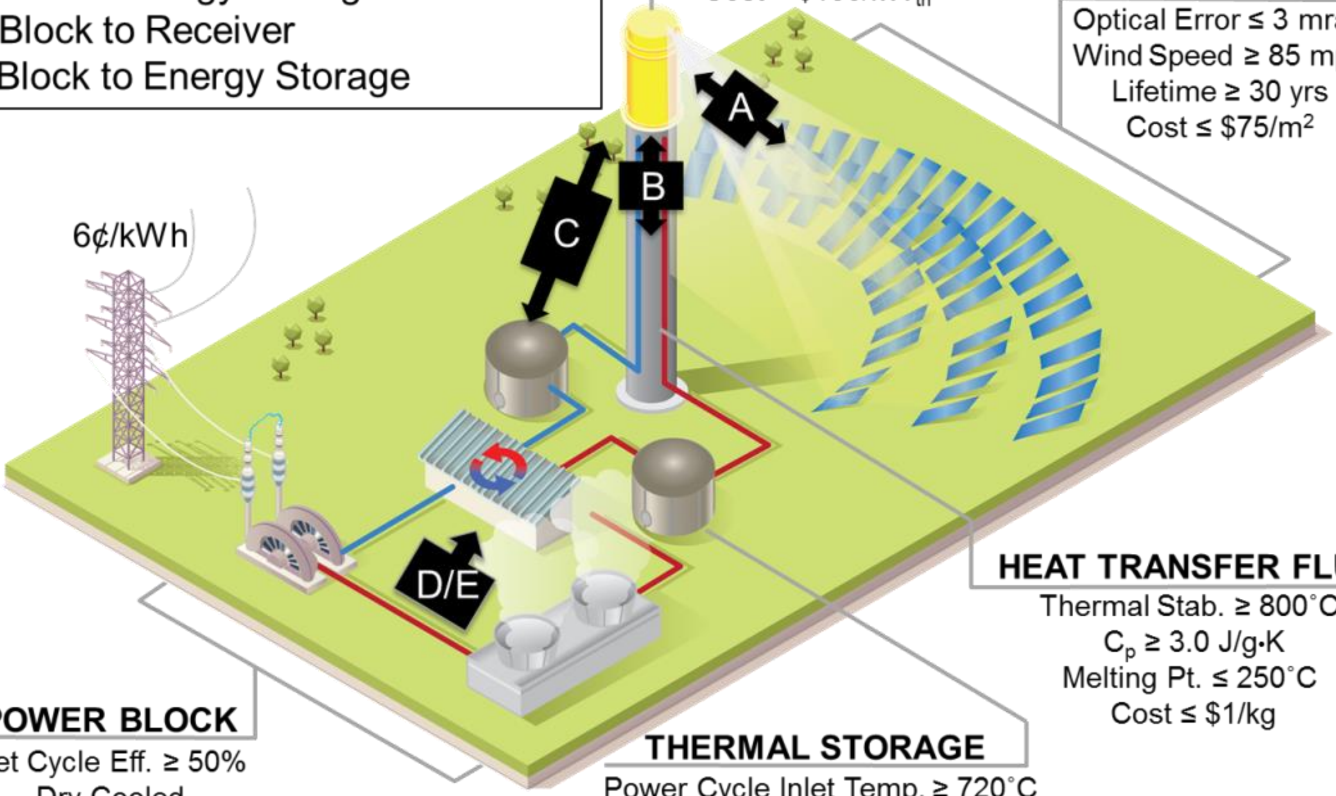
SunShot Metrics and Subsystem Integration

CSP Subsystem Interface Coupling
A: Solar Field and Receiver
B: Receiver and Heat Transfer Fluid System
C: Receiver and Energy Storage
D: Power Block to Receiver
E: Power Block to Energy Storage



RECEIVER
HTF Exit Temp. ≥ 720°C
Thermal Eff. ≥ 90%
Lifetime ≥ 10,000 cycles
Cost ≤ $\$150/\mathrm{kW}_{th}$

SOLAR FIELD
Optical Error ≤ 3 mrad
Wind Speed ≥ 85 mph
Lifetime ≥ 30 yrs
Cost ≤ $\$75/\mathrm{m}^2$

HEAT TRANSFER FLUID
Thermal Stab. ≥ 800°C
C_p ≥ 3.0 J/g·K
Melting Pt. ≤ 250°C
Cost ≤ $1/kg

POWER BLOCK
Net Cycle Eff. ≥ 50%
Dry Cooled
Cost ≤ $\$900/\mathrm{kW}_e$

THERMAL STORAGE
Power Cycle Inlet Temp. ≥ 720°C
Exergetic Eff. ≥ 95%
Cost ≤ $\$15/\mathrm{kWh}_{th}$

Outline

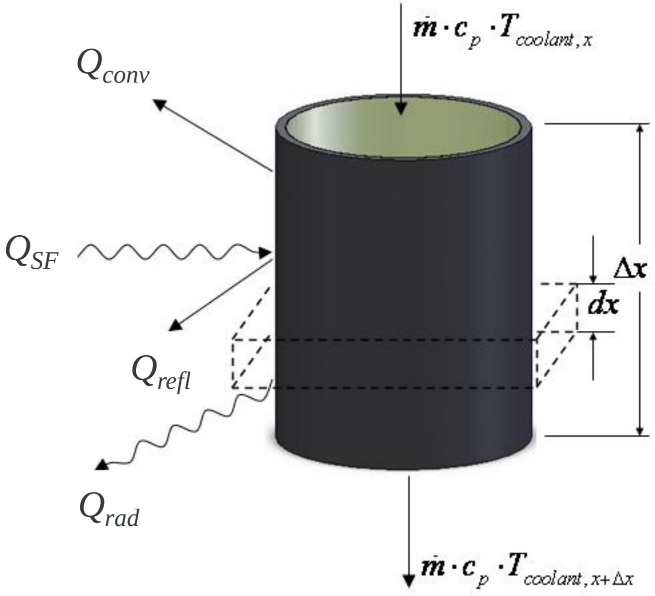
CSP Gen3 System Integration

- Receiver and heliostat performance definitions and design interactions
- STEP objectives and sCO_2 cycle design
- sCO_2 recompression Brayton cycle characteristics
  - Design point considerations
  - Impact of ambient temperature
  - Impact of part-load operation

Receiver Performance Metrics

Receiver efficiency is defined as the incident thermal flux from the solar field, less reflective, radiative, and convective thermal losses, divided by incident thermal flux:

$$\eta_{th} = \frac{Q_{SF} - Q_{refl} - Q_{conv} - Q_{rad}}{Q_{SF}} \geq 90\%$$



Where:

Q_{SF} = thermal flux from the solar field incident on the receiver aperture

Q_{refl} = thermal losses from reflection to ambient

Q_{conv} = thermal losses from convection to ambient $\propto A_{rec}T$

Q_{rad} = thermal losses from the radiation to ambient $\propto A_{rec}T^4$

Heliostat Performance Metrics

SunShot Heliostat Goals *	
Cost	≤ $75/m^2
Optical error (calm)	≤ 3.0 mrad
Optical error (windy)	≤ 4.0 mrad

* DOE-FOA-0001186 "APOLLO" 2015

SunShot optical error metrics are for total reflected image area, σ_{total}:

$$\sigma_{total} = \sqrt{4\left(\sigma_{el}^2 + \sigma_{az}^2 + \sigma_{s,x}^2 + \sigma_{s,y}^2\right) + \sigma_{r,x}^2 + \sigma_{r,y}^2}$$

Where:

σ_{el}	Elevation pointing error
σ_{az}	Azimuthal pointing error
$\sigma_{s,x}$	Surface slope error in X
$\sigma_{s,y}$	Surface slope error in Y
$\sigma_{r,x}$	Reflected beam error in X
$\sigma_{r,y}$	Reflected beam error in Y

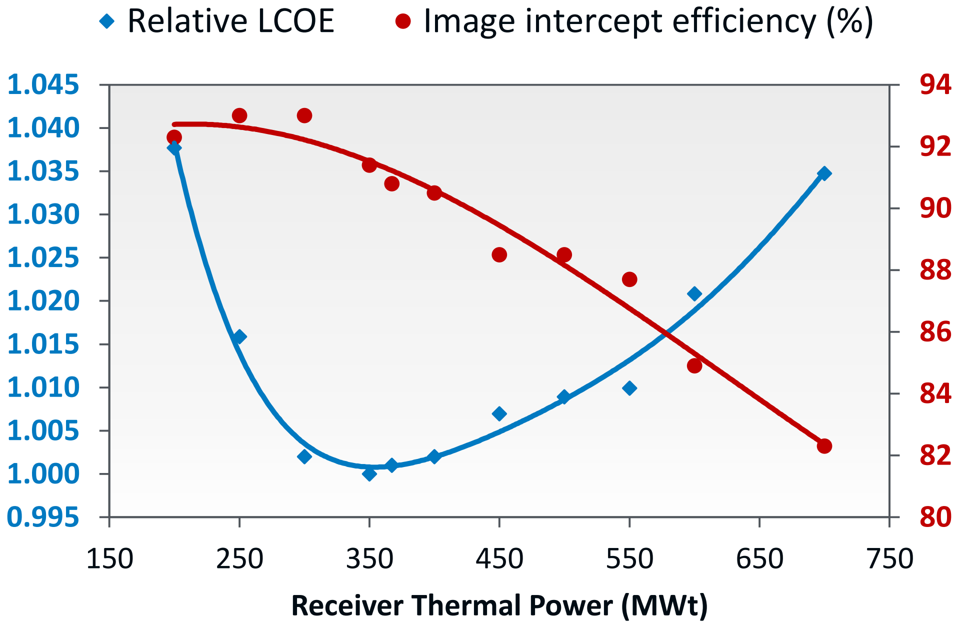
When modeling solar field/receiver interactions it is necessary to incorporate relevant receiver and heliostat metrics.

Heliostat/Receiver Interaction Example

Fixed Receiver Height Parametric

- Assumptions:
  - Receiver height: 10 m
  - Peak flux: 2 MW/m^2
  - Large, accurate heliostats (SAM default)
- Method:
  - Vary thermal power input
  - Optimize receiver diameter and tower height for each power
- Observation:
  - *Fixed receiver design attributes (such as receiver height) can influence overall system sizing due to optical performance effects*

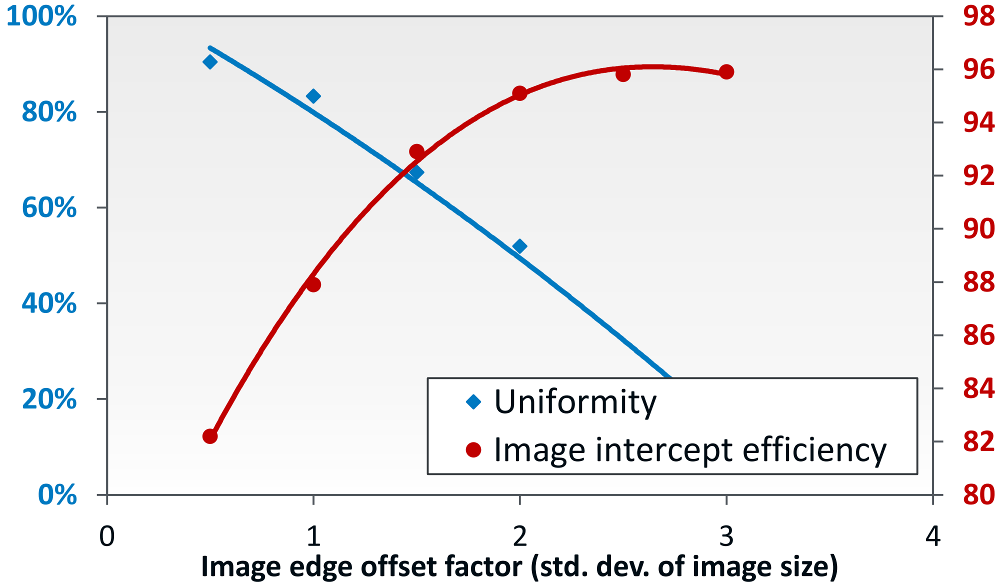
Optimal design for 10-m Receiver Height with Tower Height and Receiver Diameter optimized



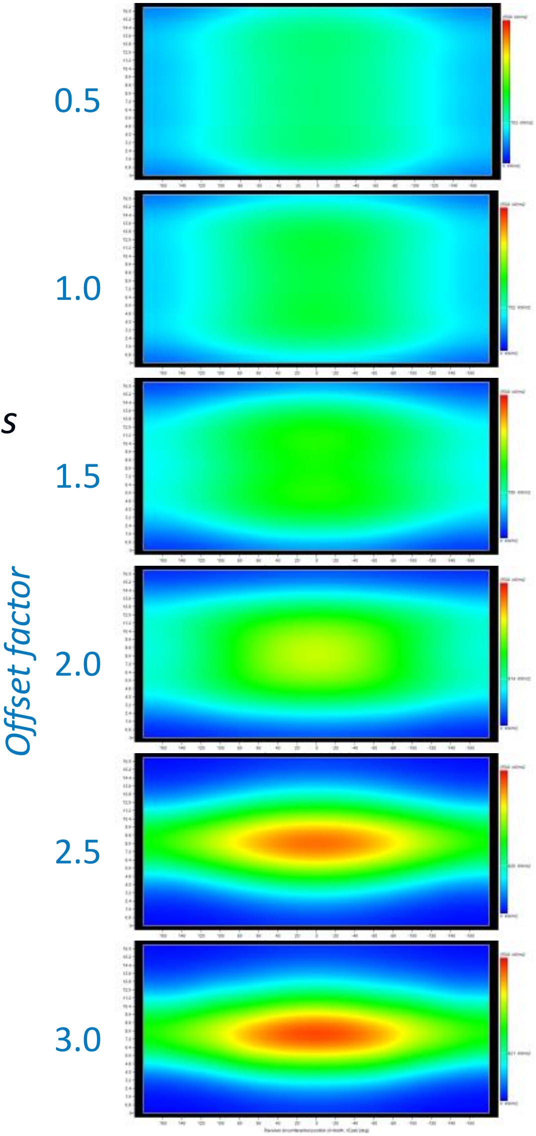
Heliostat/Receiver Interaction Example

Flux Uniformity Parametric

- Assumptions:
  - Flat heliostats, 6 m x 4 m, two facets, canted
  - Cylindrical receiver, 500 MW_t
- Method:
  - Vary allowable heliostat image-edge offset
  - Optimize receiver height, diameter, and tower height
  - Measure vertical flux uniformity
- Observation: *The ability to achieve flux uniformity on the receiver comes at the expense of image intercept efficiency*



Receiver flux profiles; horizontal axis is circumferential dimension



sCO$_2$ Cycle Development under STEP

DOE's "STEP" project will demonstrate a 10 MW$_e$ recompression cycle

- In negotiation with winning proposal team of GTI/SwRI/GE
- Operational in 2020

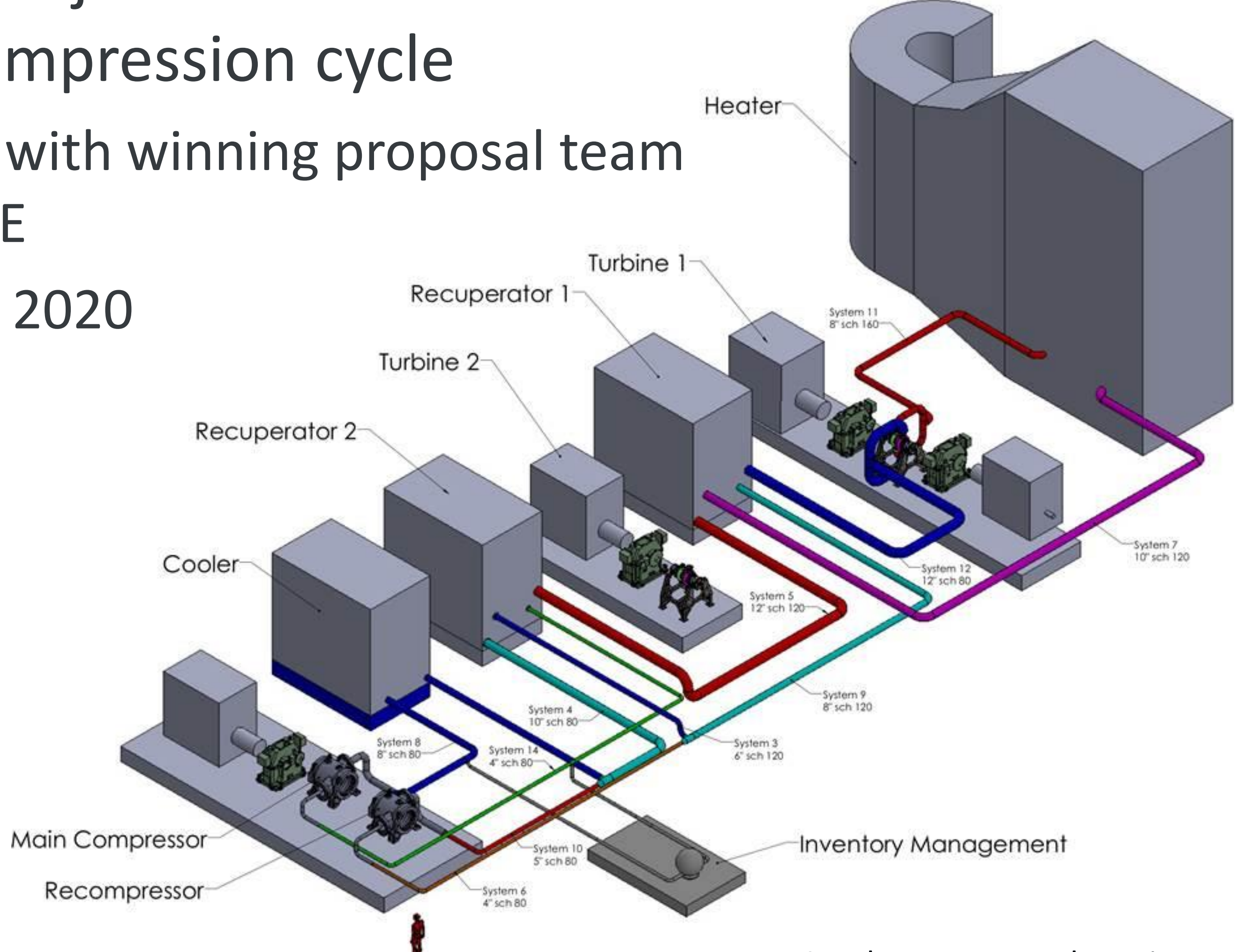


Image: Southwest Research Institute

Supercritical
Transformational
Electric
Power

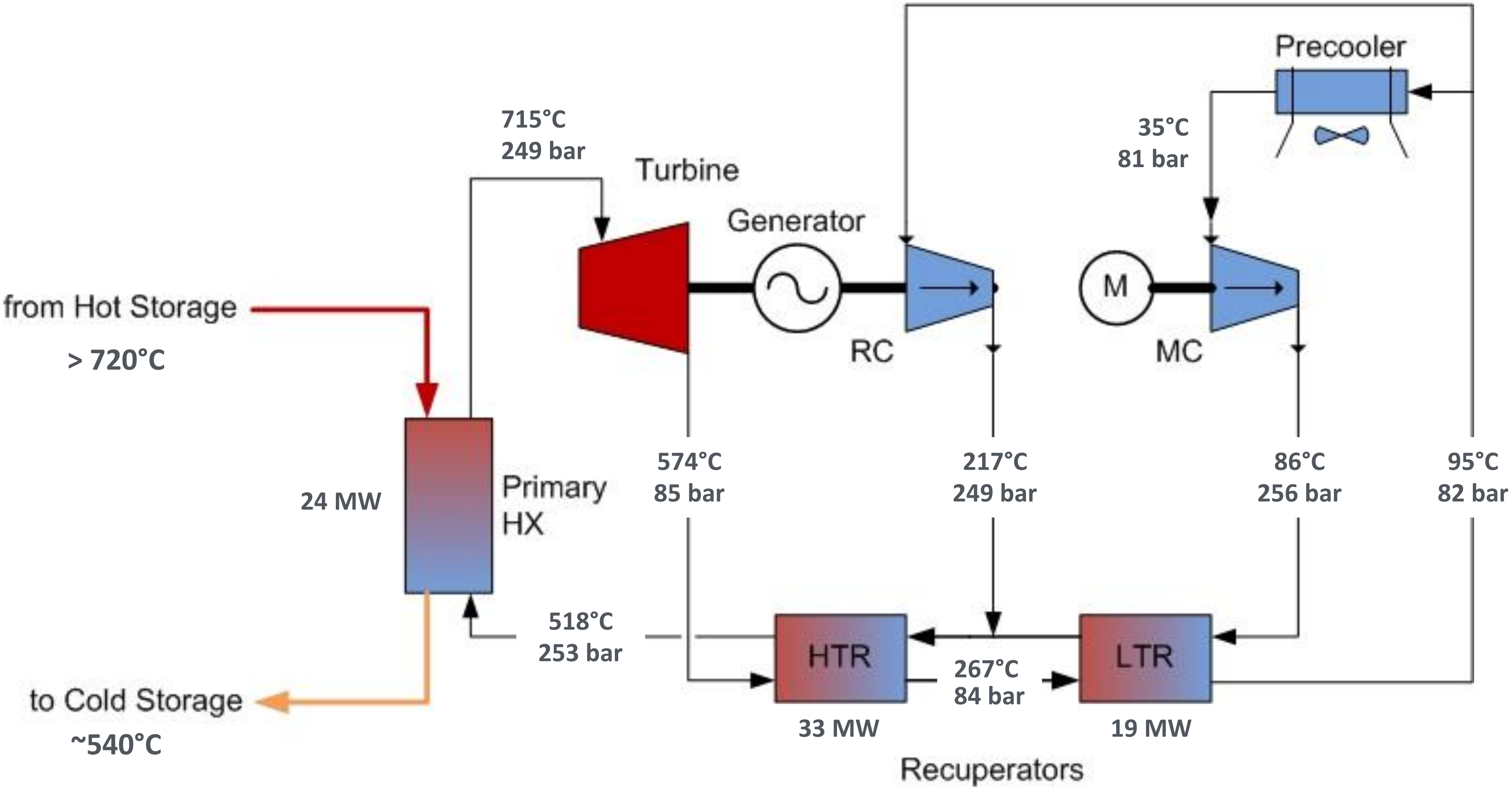
STEP Test Facility Attributes and Objectives

- 10 $MW_{e,net}$ sCO_2 recompression Brayton cycle
- Turbine inlet temperature of 700°C
- Demonstrate pathway towards an overall power cycle efficiency of 50% or greater
- Reconfigurable and can monitor and characterize primary components or subsystems (turbomachinery, heat exchangers, recuperators, bearings, seals, etc.)
- Demonstrate steady state, transient load following, and limited endurance operation.
- Capable of test campaigns to assess critical component degradation mechanisms to assess component life and cost

sCO$_2$ Recompression Cycle

Design-point values from Black & Veatch study

$T_{amb} = 22.5°C$



Note: SunShot CSP plants are assumed to be dry cooled, so a higher design-point ambient temperature is likely.

Effects of Ambient Temperature

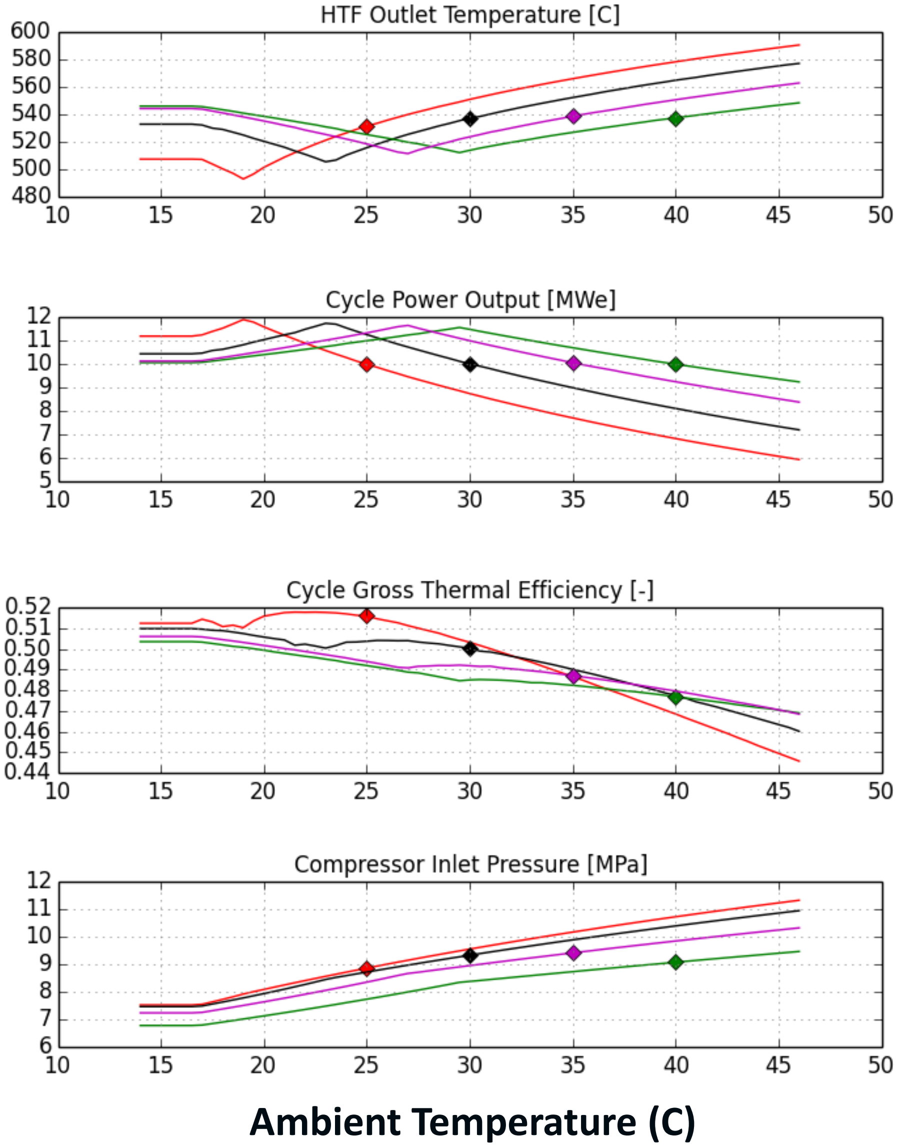
NREL Modeling

These changes affect the solar HTF temperature in the primary heat exchanger, which will propagate back to receiver operations.

Cycle power output varies in sync with thermal efficiency. Equipment limitations may constrain over-design operation.

(Actual operation strategy will seek to optimize revenue, which will depend on many factors, including market and dispatch signals from the grid.)

As T_{amb} rises, compressor-inlet pressure is increased to compensate.



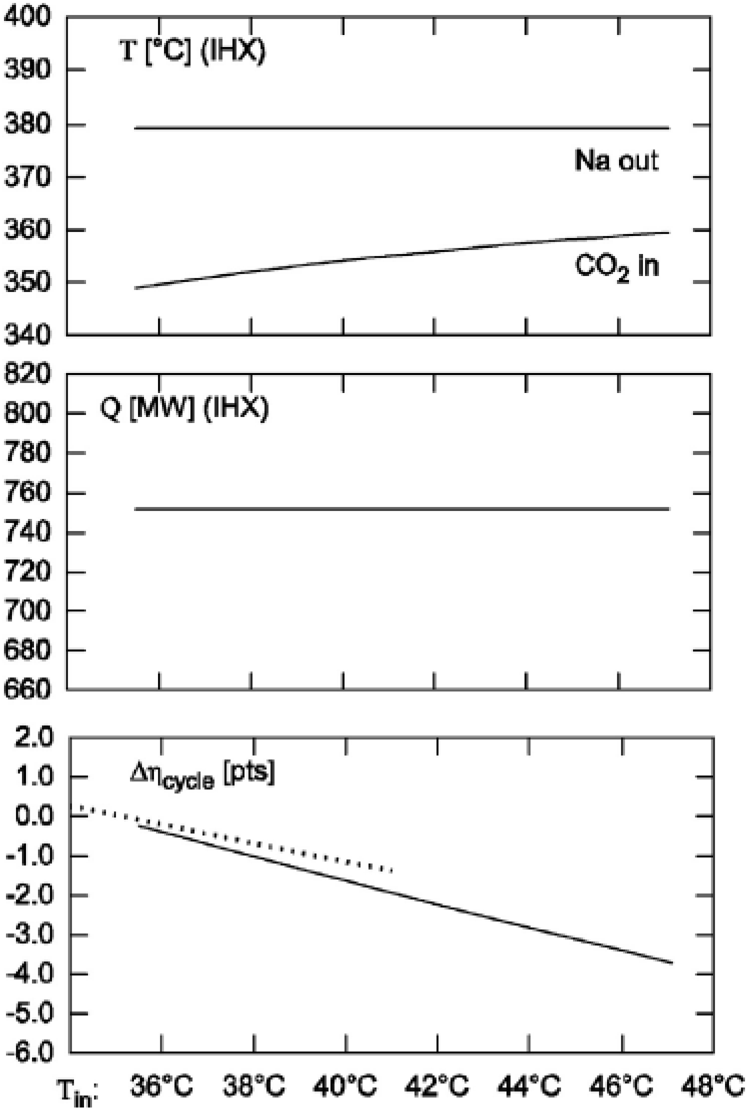
Ambient Temperature and Cycle Control

[Floyd et al., 2013]

HTF storage return temperature maintained

Heat transfer in Primary HX maintained

Speed control applied to main compressor as T_{amb} changes



Main compressor inlet temperature (T_{in})

HTF Temperatures at the Primary HX

Primary HX Power

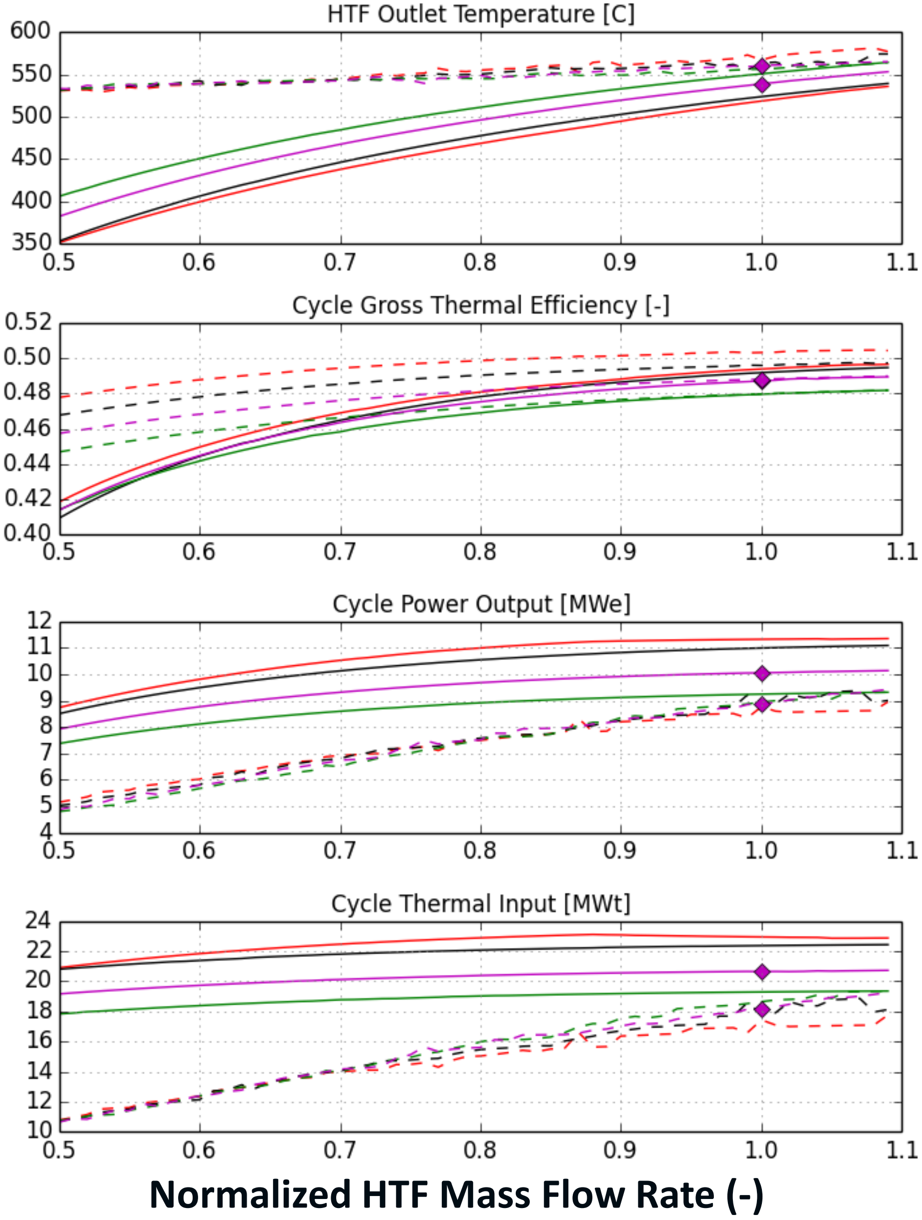
Change in Cycle Efficiency

Part-Load Operation

Optimizing for efficiency keeps the solar HTF temperature near it’s design point.

Under these conditions, one will normally optimize to cycle efficiency (dashed lines) rather than power output (solid lines)

For part-load operation, heat flow to the primary HX is reduced.



Summary

- Receiver and solar field should be modeled together to ensure optimal designs.
    - SolarPILOT can perform such analyses
- CSP Gen3 designs must be compatible with sCO_2 power cycle development under STEP
    - Variants, e.g., partial-cooling cycle, may be more favorable for CSP
- Off-design conditions will occur for changing ambient temperature and part-load
    - These changes will impact solar HTF mass flow and temperature in the primary HX
- Cycle operating strategy can maximize power output or cycle efficiency as necessary to optimize revenue.
    - These modes result in different demands on the thermal storage system

Thank you!

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