sCO_2 TES CSP Integration

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Overview

1) What are sCO2 cycle design options to integrate with a CSP salt power tower at ~565°C and TES, if:

a) The cycle is dropped into current tower systems such that the HTF cold temperature is ~300°C

b) The entire CSP system is redesigned to minimize LCOE

2) What are the expected operating conditions?

- Annual performance of an air-cooled cycle in CSP climates
- Dispatch to meet intermediate or peak electricity prices

Modeling Approach

sCO_2 Modeling Objectives

- Capture 1st order effects for design and annual simulation of CSP plants
  - Power, efficiency, HTF cold return temperature, cost estimates, design optimization
  - Off-design performance vs. ambient temperature, HTF mass flow rate, HTF hot temperature
- Do not require detailed component design or specialized/proprietary data
- Distribute freely and integrate with CSP models
  - Cycle option in CSP salt power tower model in SAM
  - Simulate cycle performance independently via Python scripts
    - Performance code in open-source C++

sCO_2 Model in Python

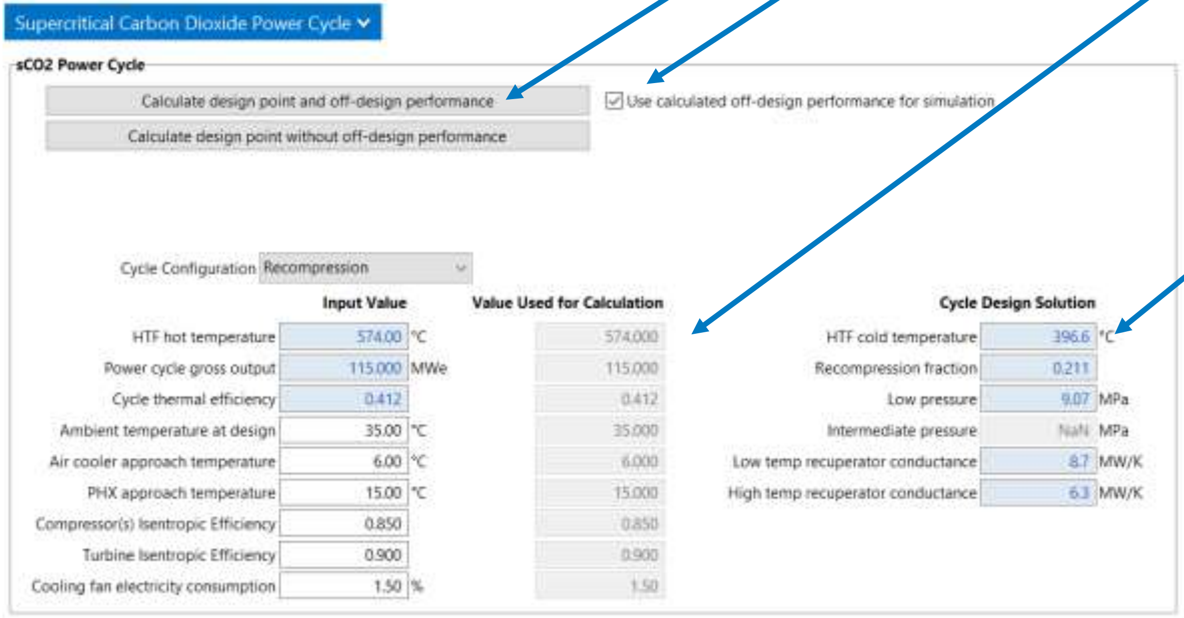
- Option to set a wide range of design parameters
  - e.g. choose recup design parameter, optimize/fix free parameters
- Control over off-design simulations
  - Shaft speed control, set compressor inlet conditions, sweep compressor inlet pressures
  - https://github.com/NREL/SAM/blob/develop/samples/CSP/sco2_analysis_python/examples/User%20Guide.pdf

```
    # LTR
des_par["LTR_design_code"] = 2       # 1 = UA, 2 = min dT, 3 = effectiveness
des_par["LTR_UA_des_in"] = 2200.0    # [kW/K] (required if LTR_design_code == 1 and design_method == 3)
des_par["LTR_min_dT_des_in"] = 8.0   # [C] (required if LTR_design_code == 2 and design_method == 3)
des_par["LTR_eff_des_in"] = 0.895    # [-] (required if LTR_design_code == 3 and design_method == 3)
des_par["LT_recup_eff_max"] = eff_max #[-] Maximum effectiveness low temperature recuperator
des_par["LTR_LP_deltaP_des_in"] = deltaP_recup_LP    #[-]
des_par["LTR_HP_deltaP_des_in"] = deltaP_recup_HP    #[-]
    # HTR
des_par["HTR_design_code"] = 2       # 1 = UA, 2 = min dT, 3 = effectiveness
des_par["HTR_UA_des_in"] = 2800.0    # [kW/K] (required if LTR_design_code == 1 and design_method == 3)
des_par["HTR_min_dT_des_in"] = 8.0   # [C] (required if LTR_design_code == 2 and design_method == 3)
des_par["HTR_eff_des_in"] = 0.943    # [-] (required if LTR_design_code == 3 and design_method == 3)
des_par["HT_recup_eff_max"] = eff_max #[-] Maximum effectiveness high temperature recuperator
des_par["HTR_LP_deltaP_des_in"] = deltaP_recup_LP    #[-]
des_par["HTR_HP_deltaP_des_in"] = deltaP_recup_HP    #[-]
```

sCO_2 in SAM's Salt Power Tower Model

- Reduced set of inputs to simplify use
- Designs cycle to hit a target efficiency (if possible)

Pre-process off-design performance and use until cycle design values change

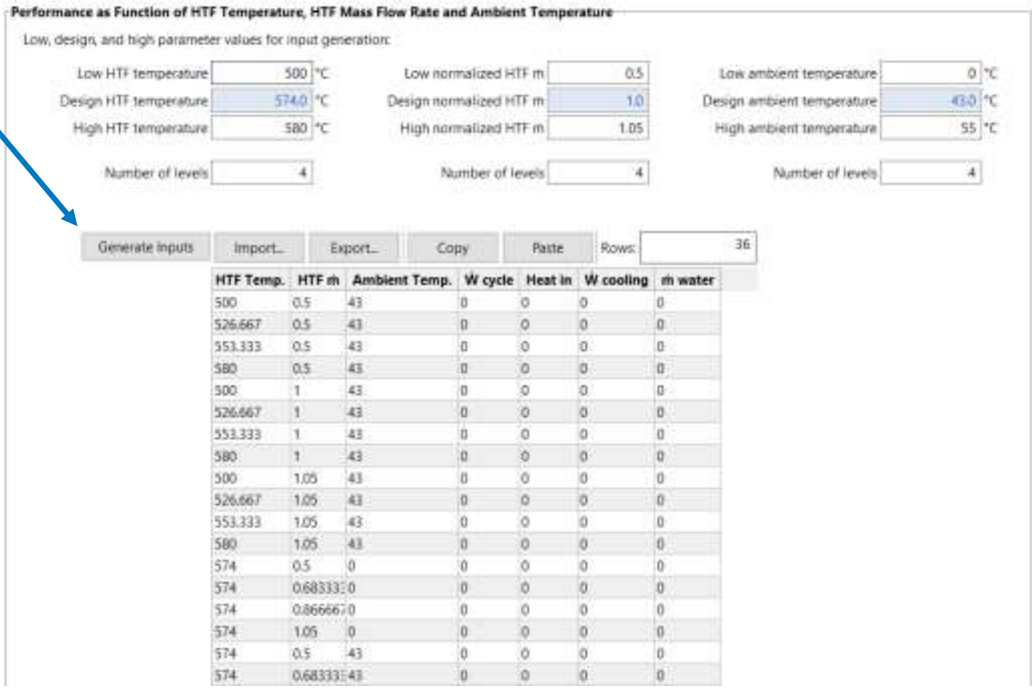


Modify the system design for new HTF cold temperature as necessary

- Number of receiver panels
- Cost of TES

User-Defined Cycle Data in SAM

- Input custom performance data for varying ambient temperature, HTF mass flow rate, HTF hot temperature
- Need to provided data in modified Design of Experiments format
  - Macro can generate independent variables

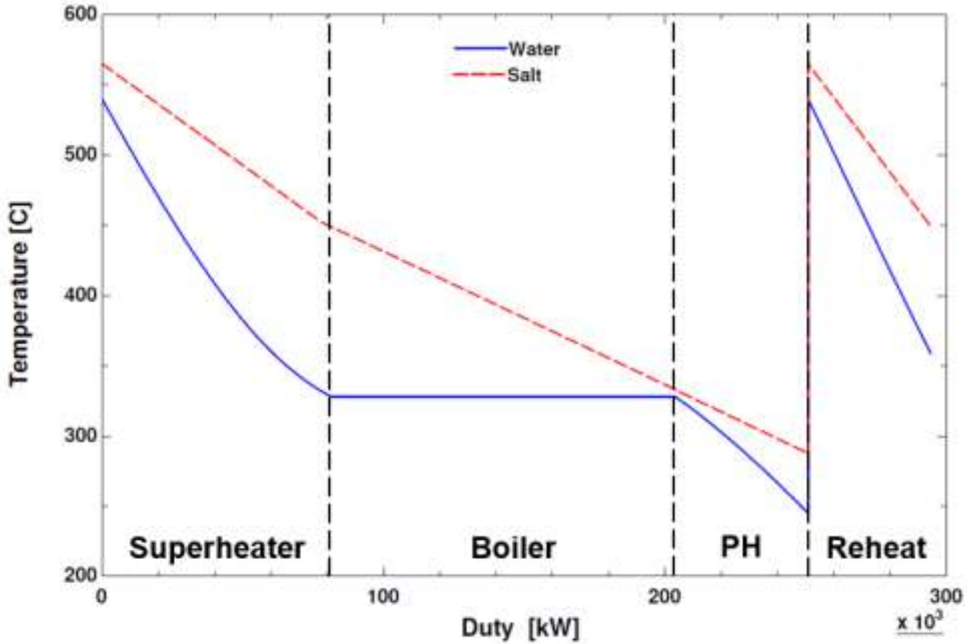


HTF Temp.	HTF ṁ	Ambient Temp.	Ẇ cycle	Heat in	Ẇ cooling	ṁ water
500	0.5	43	0	0	0	0
526.667	0.5	43	0	0	0	0
553.333	0.5	43	0	0	0	0
580	0.5	43	0	0	0	0
500	1	43	0	0	0	0
526.667	1	43	0	0	0	0
553.333	1	43	0	0	0	0
580	1	43	0	0	0	0
500	1.05	43	0	0	0	0
526.667	1.05	43	0	0	0	0
553.333	1.05	43	0	0	0	0
580	1.05	43	0	0	0	0
574	0.5	0	0	0	0	0
574	0.68333	0	0	0	0	0
574	0.86666	0	0	0	0	0
574	1.05	0	0	0	0	0
574	0.5	43	0	0	0	0
574	0.68333	43	0	0	0	0

Cycle Designs for Current Salt Power Tower Temperatures

Crescent Dunes TES and Power Cycle

- 565°C hot tank
- 290°C cold tank
- 222°C freeze temperature
- Designed for integration with steam Rankine cycle
  - 1 stage of reheat
  - ~42.5% efficiency at 35°C ambient temperature



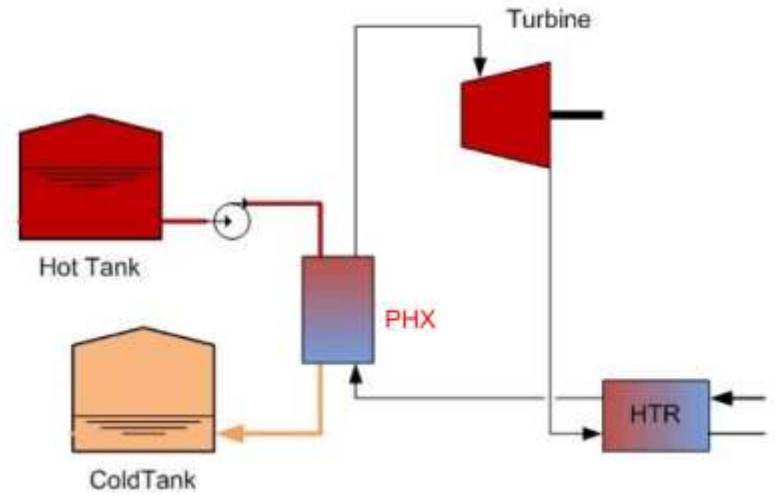
Credit: Bill Hamilton, Colorado School of Mines

Effect of Cold HTF Temperature

As temperature difference over the primary heat input increases:

- Cycle efficiency likely decreases
- Storage (sensible heat) cost decreases
- Receiver thermal losses decrease
- Pumping power decreases

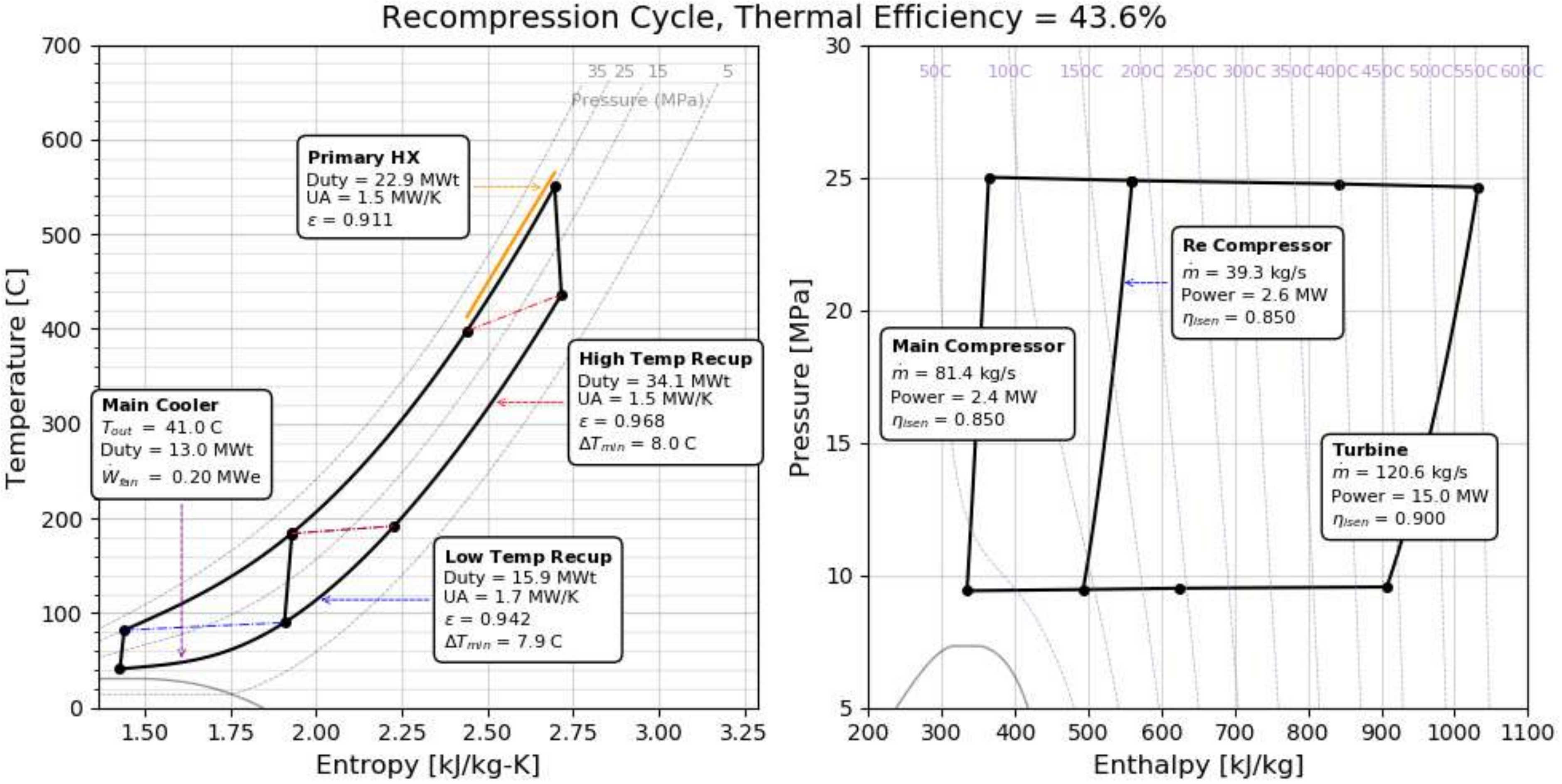
$$Volume_{tank} = \frac{Stored\ Energy}{c_p\ \rho(T_{hot} - T_{cold})}$$



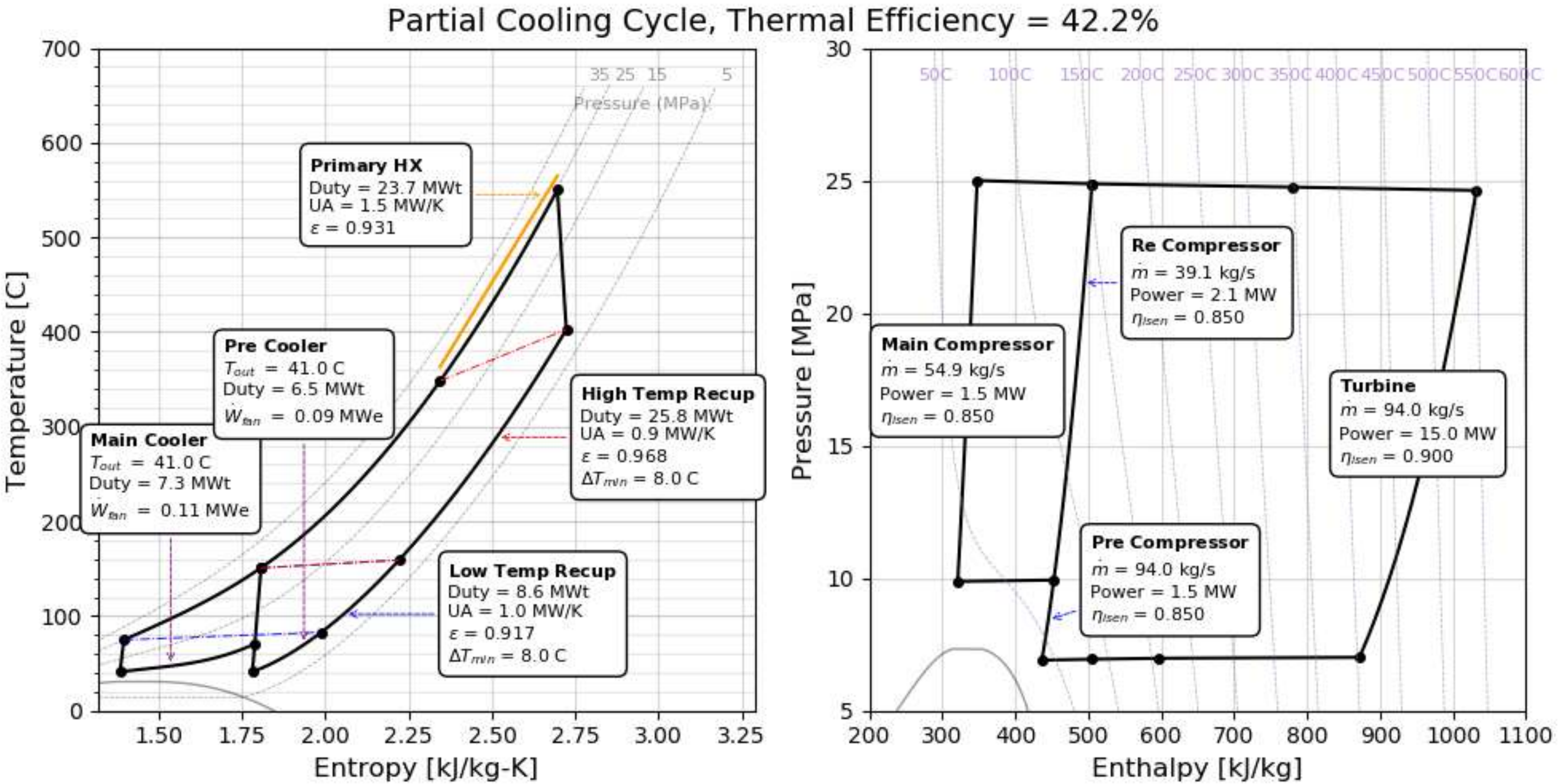
Cycle Configurations

Cycle	Description
Simple	Closed loop, recuperative Brayton cycle
Recompression	Adds bypass compressor upstream of cooler to improve recuperator effectiveness
Partial Cooling	Adds intercooling stage upstream of recompressor and increases pressure ratio across turbine.

RC Cycle - High Efficiency Design for Hot HTF Temp



PC Cycle - High Efficiency Design for Hot HTF Temp



Options to modify cycle for conventional tower w/ cold HTF temps ~300°C

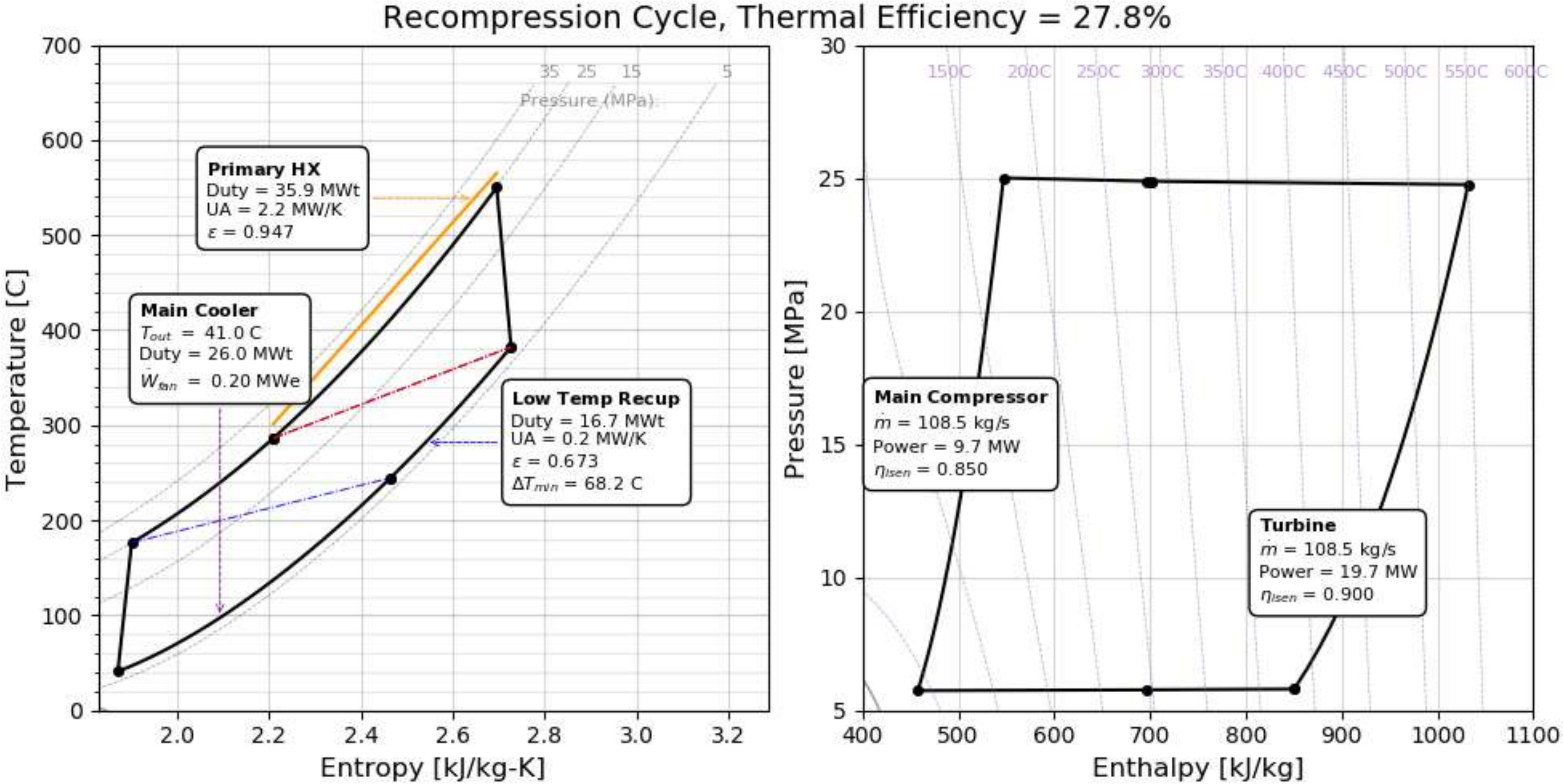
Options for simple, RC, or PC configurations

- Limit recuperation
- Decrease the turbine inlet temperature

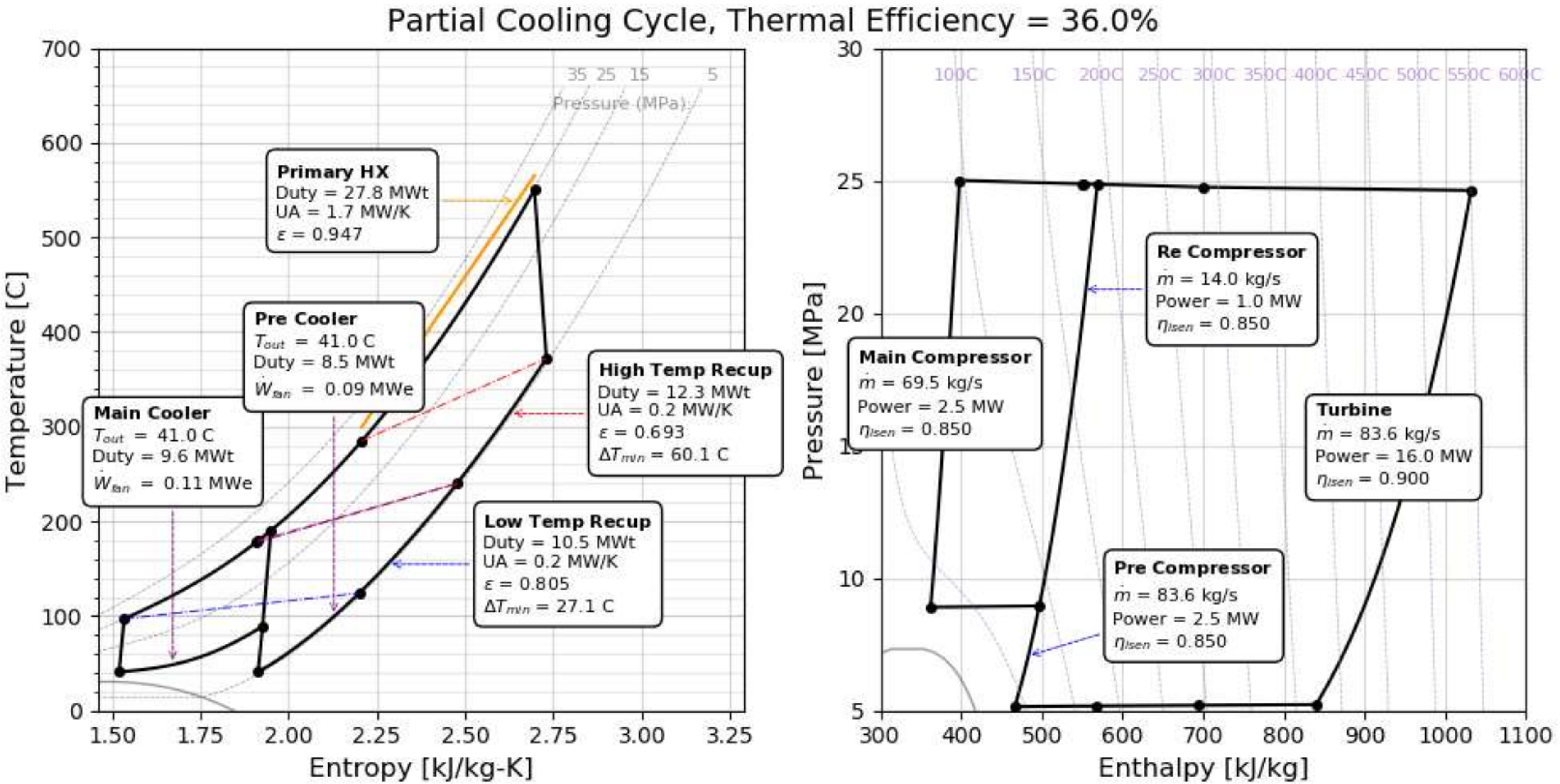
Options that create a new configuration

- Bypass some cold CO_2 around the high temperature recuperator and through a salt preheater
- Add intercooling stages to improve efficiency

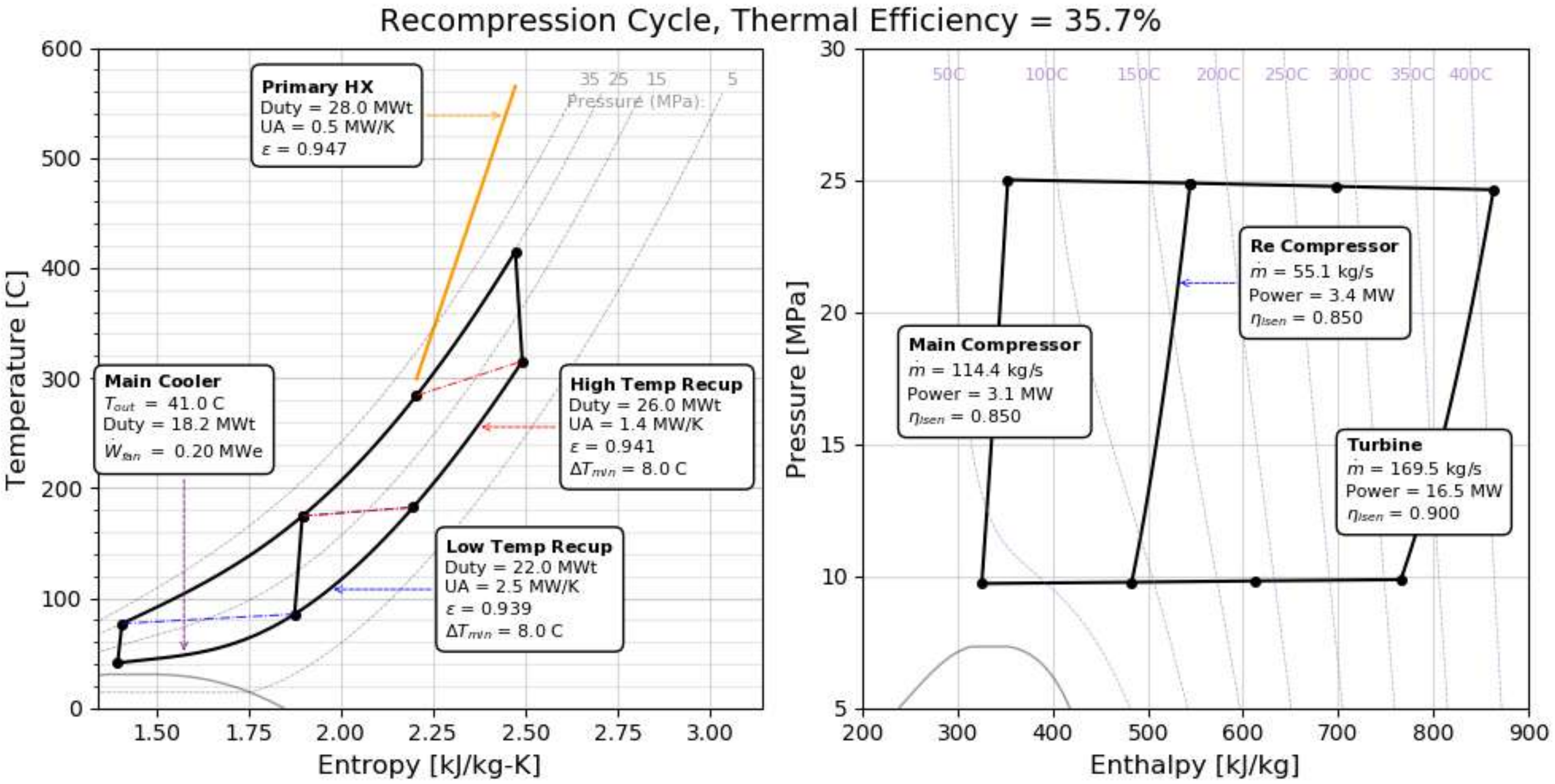
RC Cycle – 300°C Return, Limited Recuperation



PC Cycle – 300°C Return, Limited Recuperation

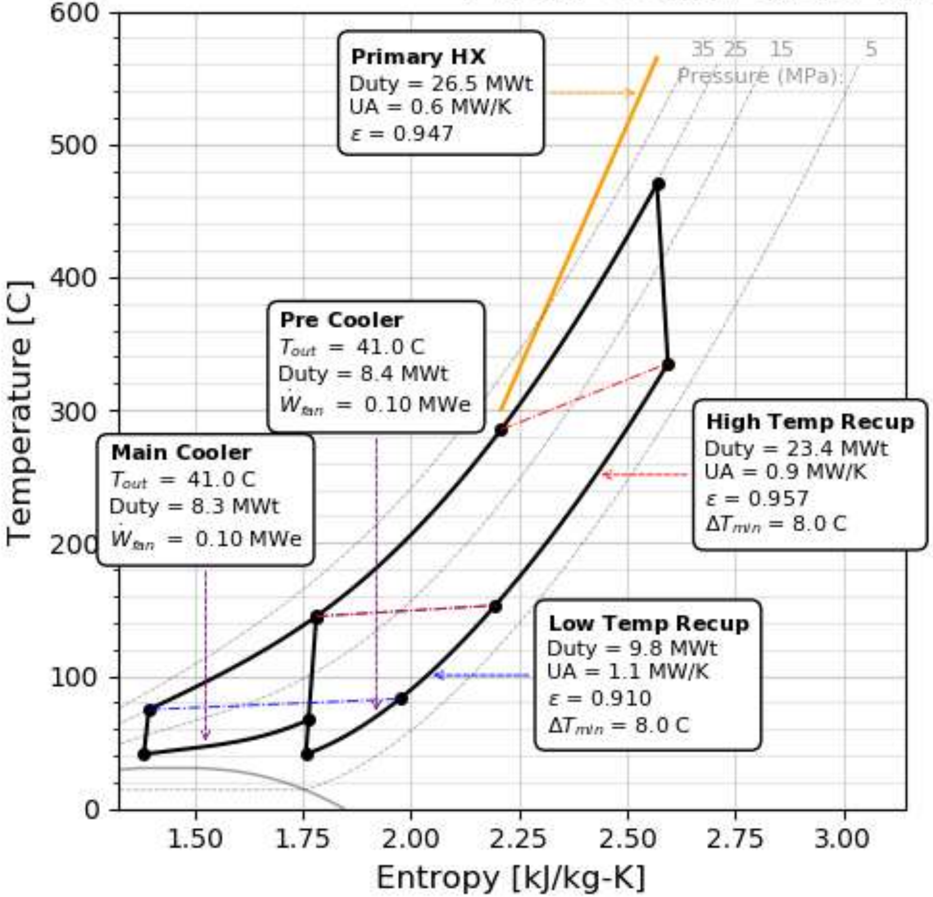


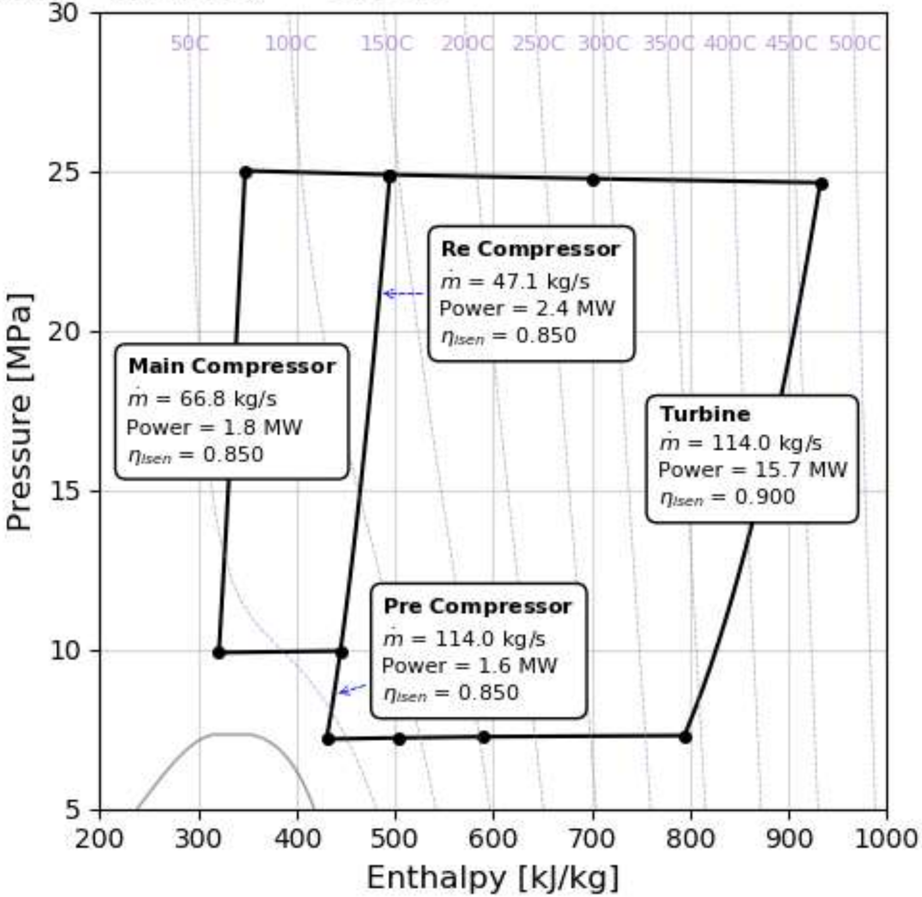
RC Cycle – 300°C Return, Large PHX Approach



PC Cycle – 300°C Return, Large PHX Approach

Partial Cooling Cycle, Thermal Efficiency = 37.8%





Cycle Design Comparison

Cycle Design	Efficiency [%]	Cold TES Temp [C]	Turbine Inlet Temp [C]	PHX UA [MW/K]	Turbine Out Temp [C]	Recup UA [MW/K]	# of comps, coolers
Recompression	43.6	415	550	1.5	440	3.2	2,1
Partial Cooling	42.2	360	550	1.5	400	1.9	3,2
Recompression	27.8	300	550	2.2	380	0.2	2,1
Partial Cooling	36	300	550	1.7	370	0.4	3,2
Recompression	35.7	300	415	0.5	315	3.9	2,1
Partial Cooling	37.8	300	470	0.6	335	2	3,2

- Highest efficiency designs significantly raise cold tank temps. Optimal design for a *new salt tower system* probably looks closer to the highest efficiency case that trades some efficiency for ΔT
- If desire to keep cold tank temperature around 300°C, then it’s more efficient to reduce turbine inlet than to limit recuperation
    - Also compatible w/ colder rec outlet temps at off-design

Shouhang – EDF Retrofit

- 10 MWe retrofit to salt tower
- 290°C – 530°C
- Recompression cycle with intercooling and preheating
  - Maximizing efficiency while hitting 290°C and maintaining supercritical pressures

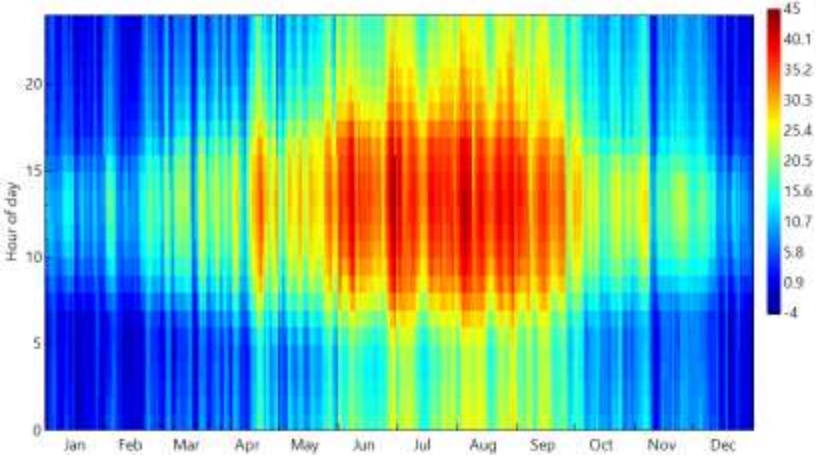
Y. Moullec *et al.*, "Shouhang-EDF 10MWe supercritical CO2 cycle + CSP demonstration project," in *3rd European Supercritical CO2 Conference*, 2019
https://duepublico2.uni-due.de/servlets/MCRFileNodeServlet/duepublico_derivate_00070565/LeMoullec_et_al_Shouhang-EDF_10MWe.pdf

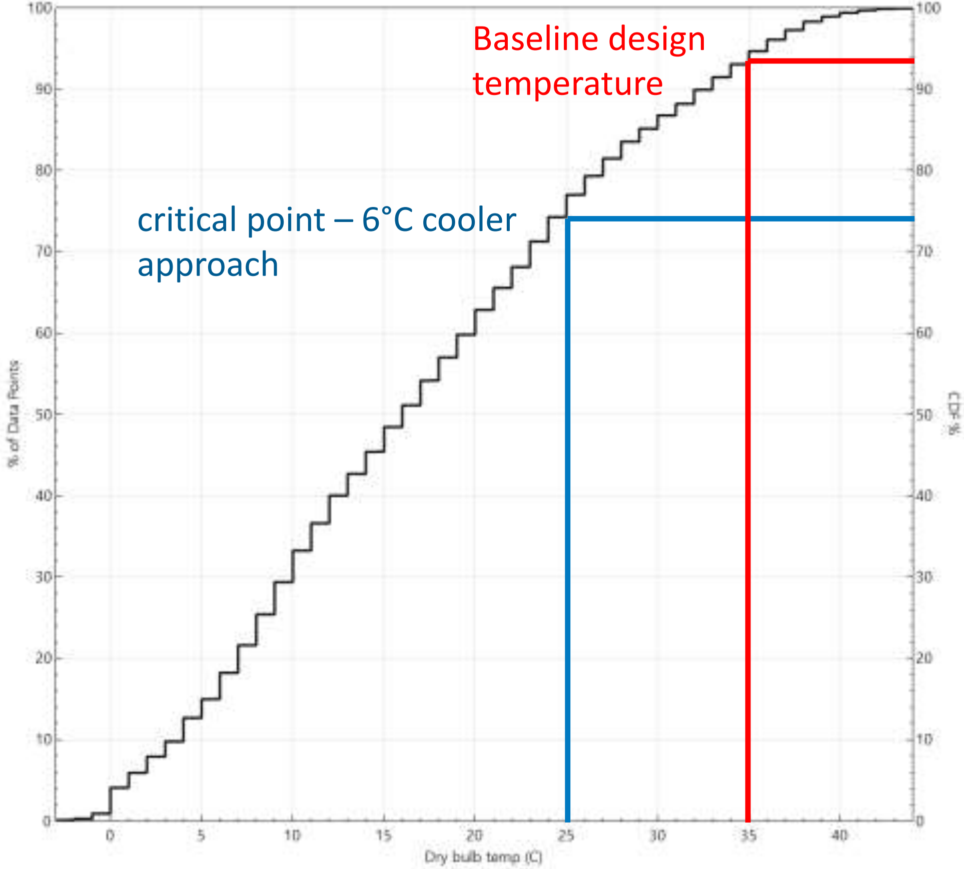
Cycle Operating Conditions

Ambient Temperature Variation

Data from Daggett, CA weather file

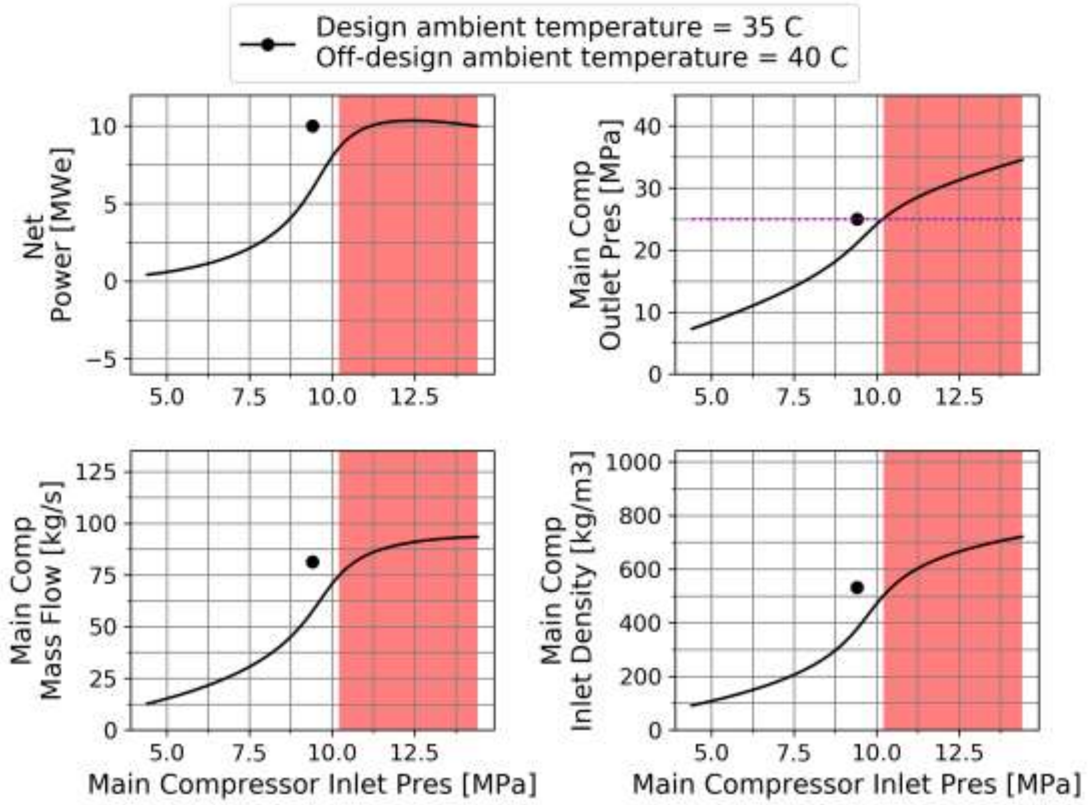
- Min = -3°C
- Max = 44°C
- Median = 16°C





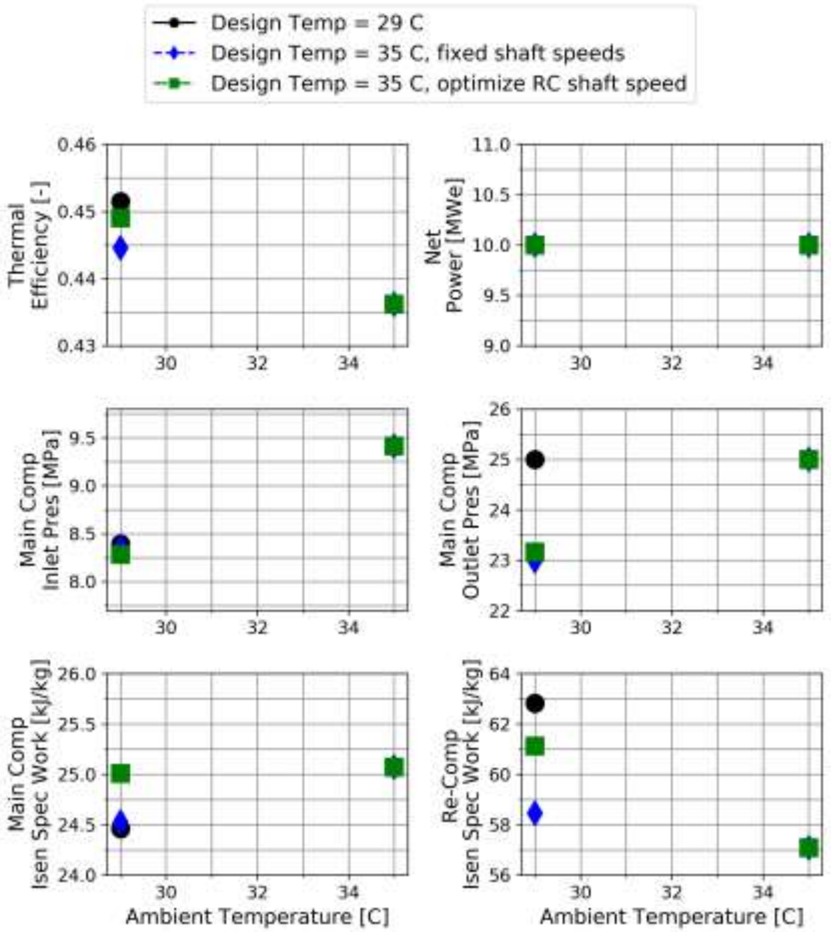
Performance at Hot Ambient Temperatures

- CO_2 density decreases at design compressor inlet pressure
- Results in less mass flow rate, less power
- Can increase inlet pressure, but exceed upper pressure limit before hitting design power
- Can design for a) higher pressures limits, b) at a hotter design point, or c) accept less output, but there's a cost



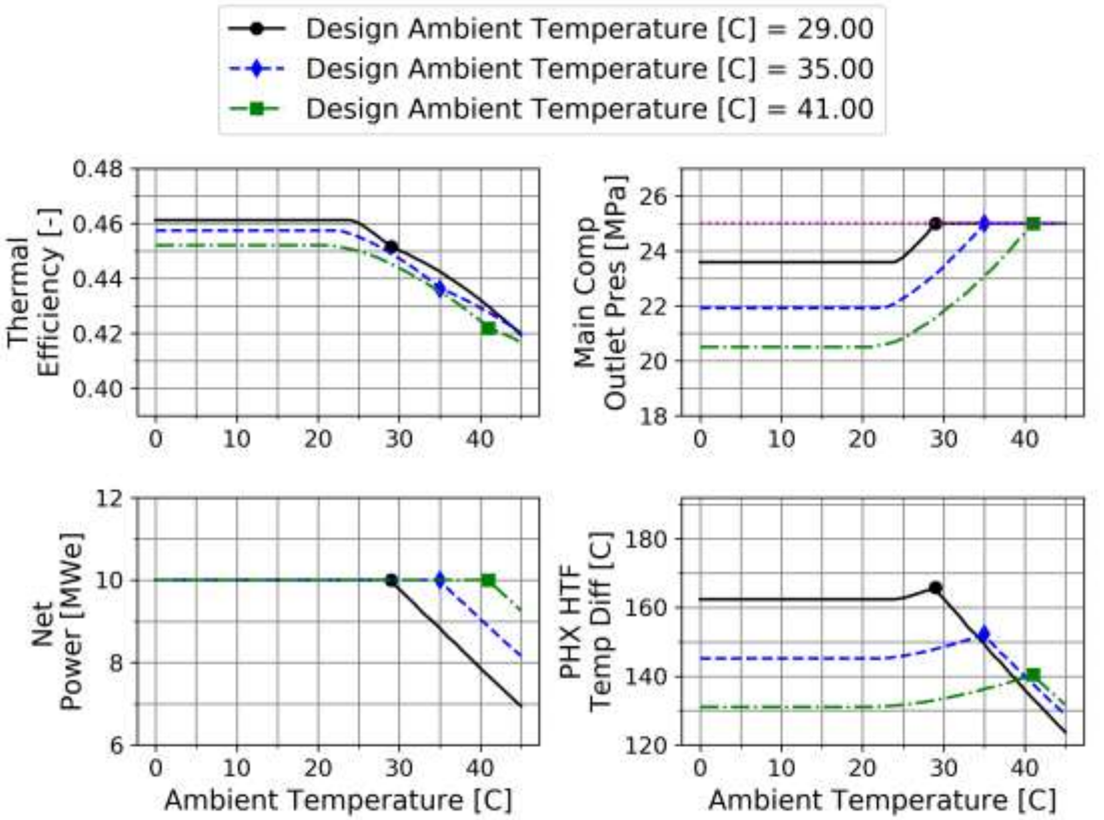
Performance at Cold Ambient Temperatures

- Max efficiency design points at 35°C vs 29°C are different!
- 35°C design operating at 29°C lowers main compressor inlet to approach 29°C design case
- 35°C design at 29°C recompressor requires more specific work than design
- Shaft speed control moves RC closer to design efficiency and cycle closer to 29°C design case



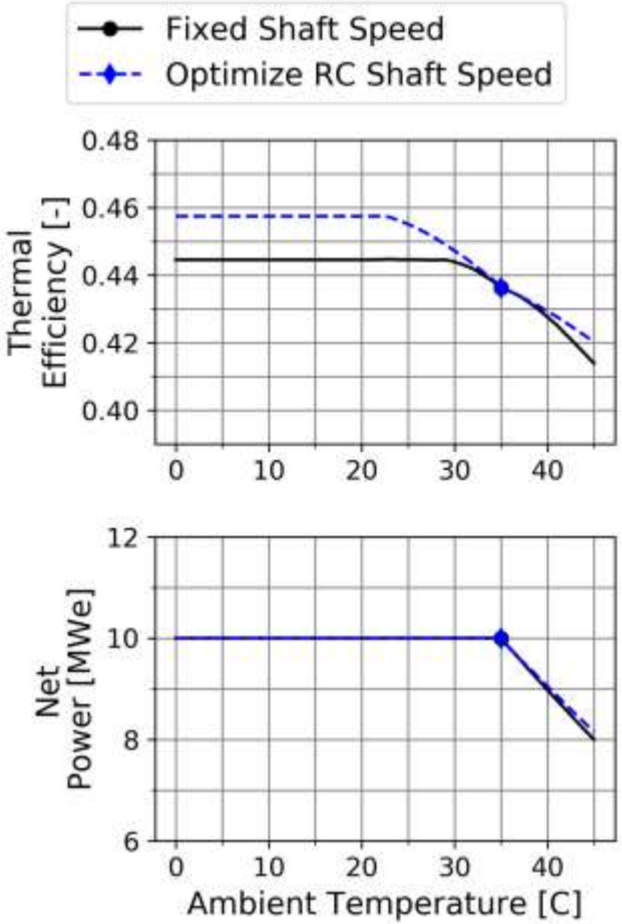
Influence of Design Point Ambient Temperature

- Warmer design points maintain design capacity on hot days, but can give up efficiency on cold days
- Potentially important gains at subcritical temperatures
  - Can cycle control achieve more efficient operation?
  - Is it worth the cost/risk?



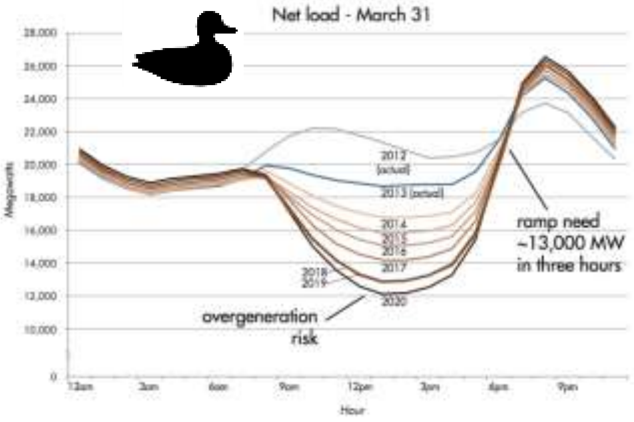
Cycle Control Options

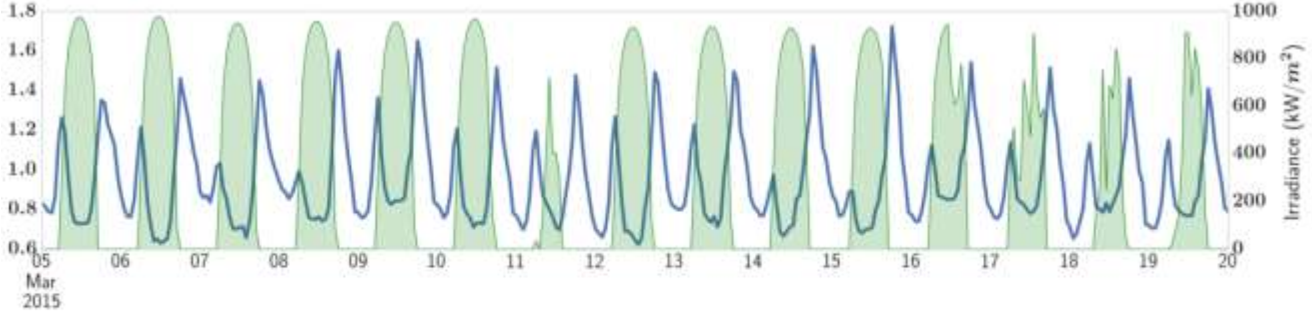
- Assume cycle will use inventory control
- More control can improve efficiency, especially on cold days
  - Shaft speed control
  - Variable inlet guide vane
- Can cycle operate at higher efficiencies at subcritical compressor inlet temperatures?
  - Is solution worth cost and complexity?



Dispatchability

- Electricity prices spike as solar resource & PV generation decline
- TES allows CSP to decouple generation from solar availability and target high electricity prices
- Ideally, cycle ramps “quickly” to respond to high prices





Operation as a Peaker

- Price *et al.*, studied a CSP peaker plant design for a 2017 APS RFP requesting a plant:
  - Capable of operating 4 hrs at 45.6°C at 100% capacity
  - Capable of load following
  - Capable of stable operation at 25%
- Designed to ramp from minimum to full load in under 10 minutes, capacity factor ~20%
- Whether the system is intended for intermediate or peak power, dispatch and system models need to understand cycle ramping and load following

H. Price, *et al.*, "Dispatchable Solar Power Plant," in *Proceedings of the 2017 SolarPACES International Symposium*.

http://www.solarpaces.org/wp-content/uploads/Hank-Price-Dispatchable-Solar-Power-Plant-.pdf

Summary

- NREL has open-source tools to help understand CSP-sCO_2 integration.
- The most efficient sCO_2 designs have cold HTF temp > 350°C.
- To maximize efficiency while, maintaining a cold HTF temp = 300°C, probably want to decrease turbine inlet temperature.
- Additional intercooling and/or PHX preheating may help for these conditions. But higher temperature, smaller ΔT systems (e.g. Gen3) are less likely to include these features.
- Cycle will operate often at subcritical ambient temperatures. Design + control challenge to achieve high efficiencies at cold temps while maintaining design power at hot temps.
- Important for CSP to understand cycle ramping and load following

Thank you!

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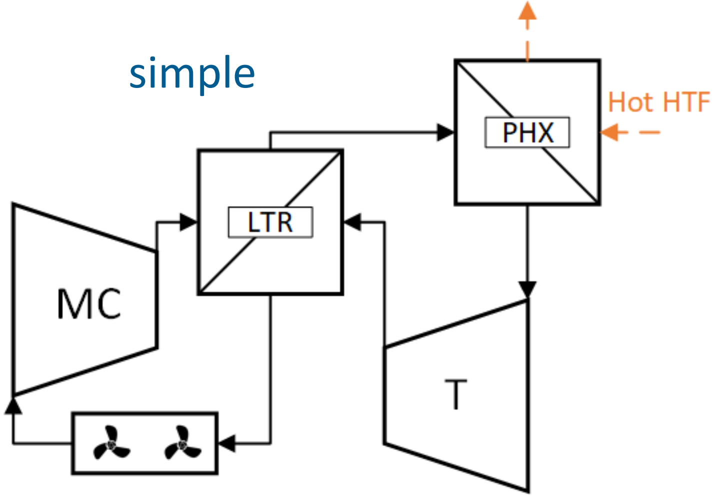
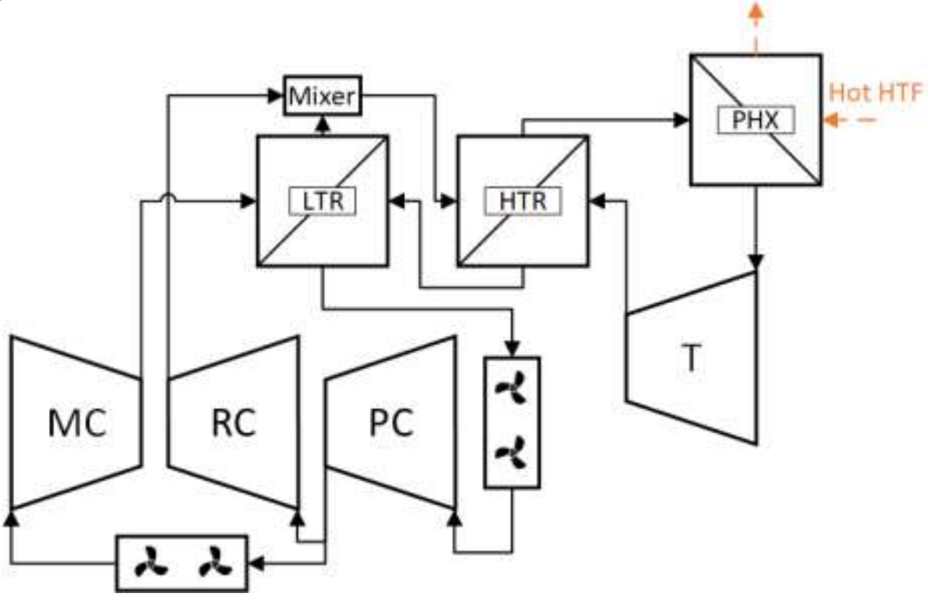
Supplemental Slides

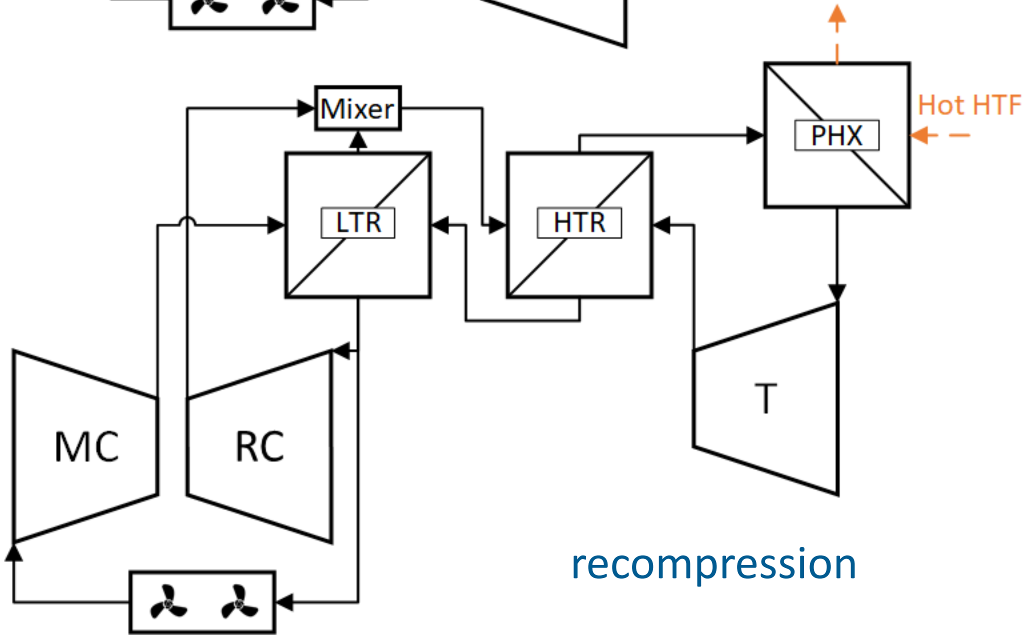
Cycle Configurations

simple





partial cooling



recompression

Cycle Modeling and Optimization

- Discretized counterflow recuperator model
- Discretized triple-pass air cooler model
- Fix compressor outlet pressure
- For *fixed recuperator conductance*, optimize free parameters to maximize efficiency

Nominal design assumptions

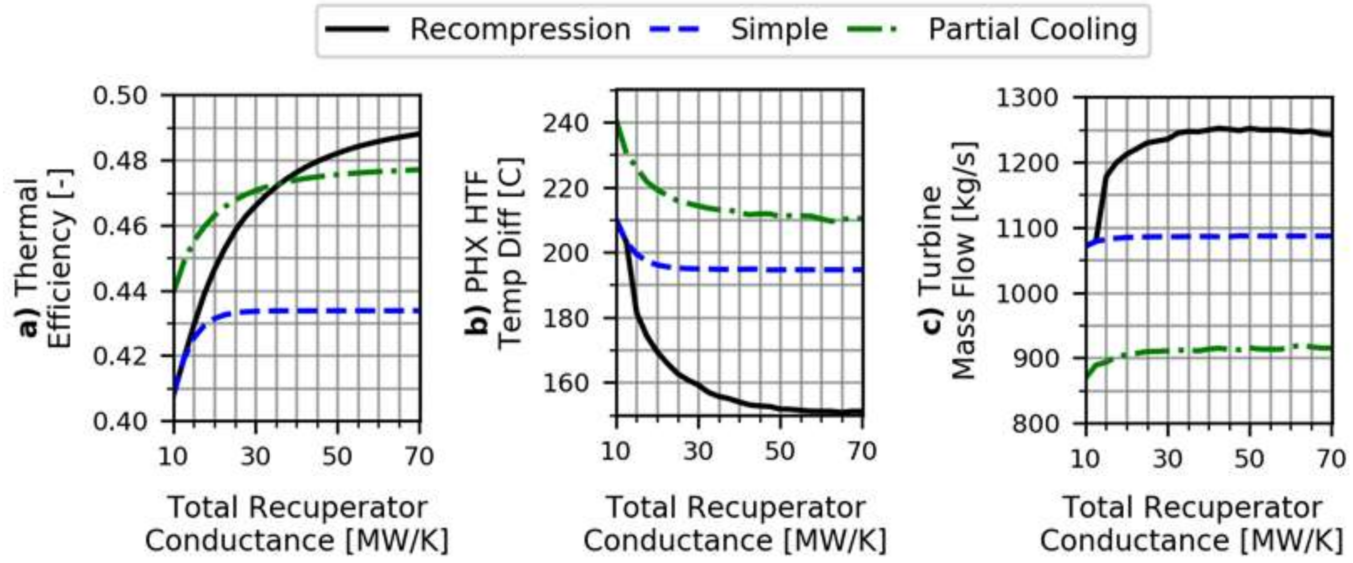
Cycle net output (MW_e)	115
Hot HTF temperature (°C)	650
Turbine inlet temperature (°C)	630
Ambient temperature (°C)	35
Compressor inlet temperature (°C)	45
Compressor isentropic efficiency	0.89
Turbine isentropic efficiency	0.9
Compressor outlet pressure (MPa)	25
Air cooler fan power % of gross (%)	2
Heat exchanger pressure drop (% of inlet pressure)	0.5
Total recuperator conductance (MW/K)	parametric
Main compressor inlet pressure (MPa)	optimized
Recompression fraction (-)	optimized
Fraction of recuperator conductance to LTR (-)	optimized
Precompressor inlet pressure (MPa)	optimized

T. Neises and C. Turchi, "Supercritical carbon dioxide power cycle design and configuration optimization to minimize levelized cost of energy of molten salt power towers operating at 650°C," ***Sol. Energy*****, vol. 181, pp. 27–36, 2019.**

https://www.sciencedirect.com/science/article/abs/pii/S0038092X19300908?via%3Dihub

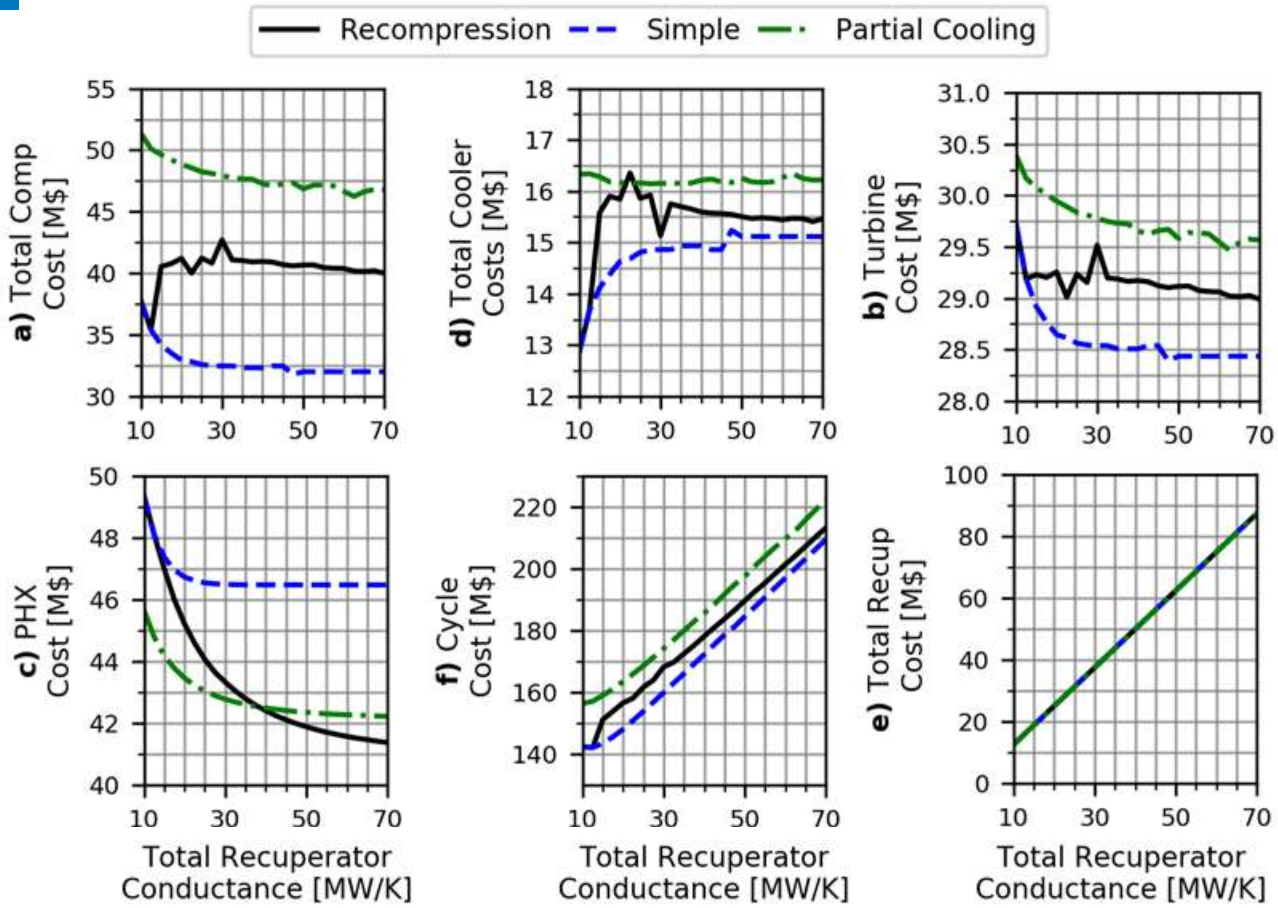
Cycle Performance vs Recuperator Conductance

- Recompression cycle has highest efficiency but requires the most conductance
- Partial cooling cycle has ~30% larger ΔT over heat input



Cycle Cost

- Costs from Carlson et al. 2017
- Partial cooling cycle ~5% more expensive

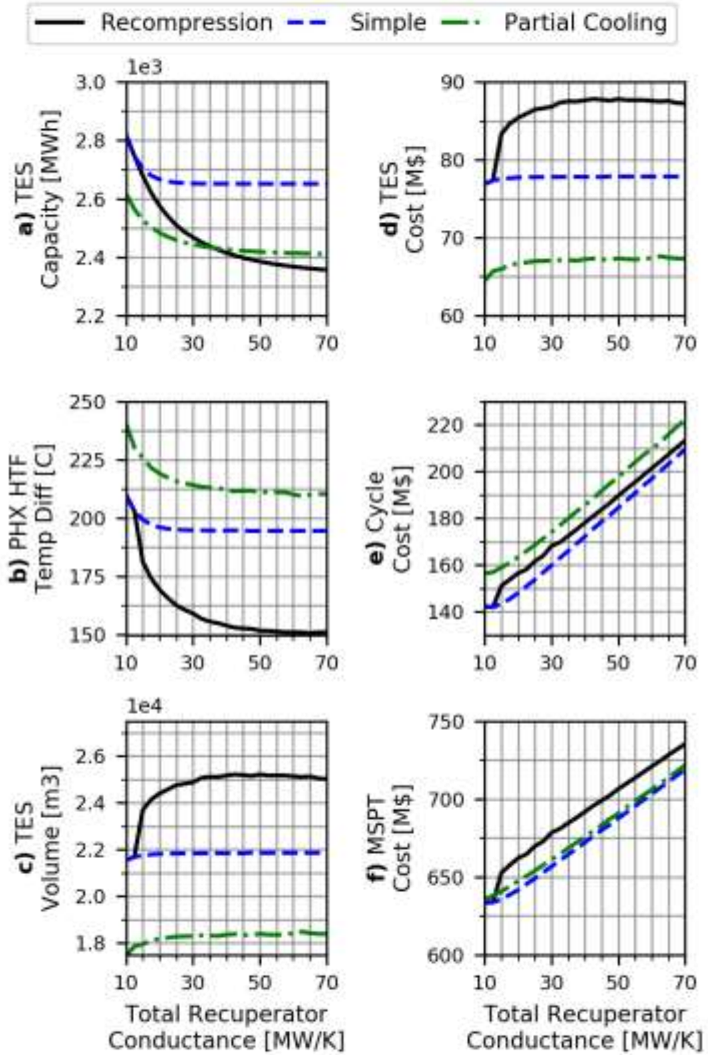


CSP Assumptions

- Use cycle design solution for CSP design
  - Efficiency, Cost, ΔT
- Fixed solar field area and receiver
  - Results in small solar multiple for lower efficiency cycles
- HTF = $MgCl_2$:NaCl:KCl
- 10 hours of storage for each power cycle design heat input
  - Results in more stored energy for lower efficiency cycles
  - Cost from Turchi et al. 2018
- Efficiency constant at off-design

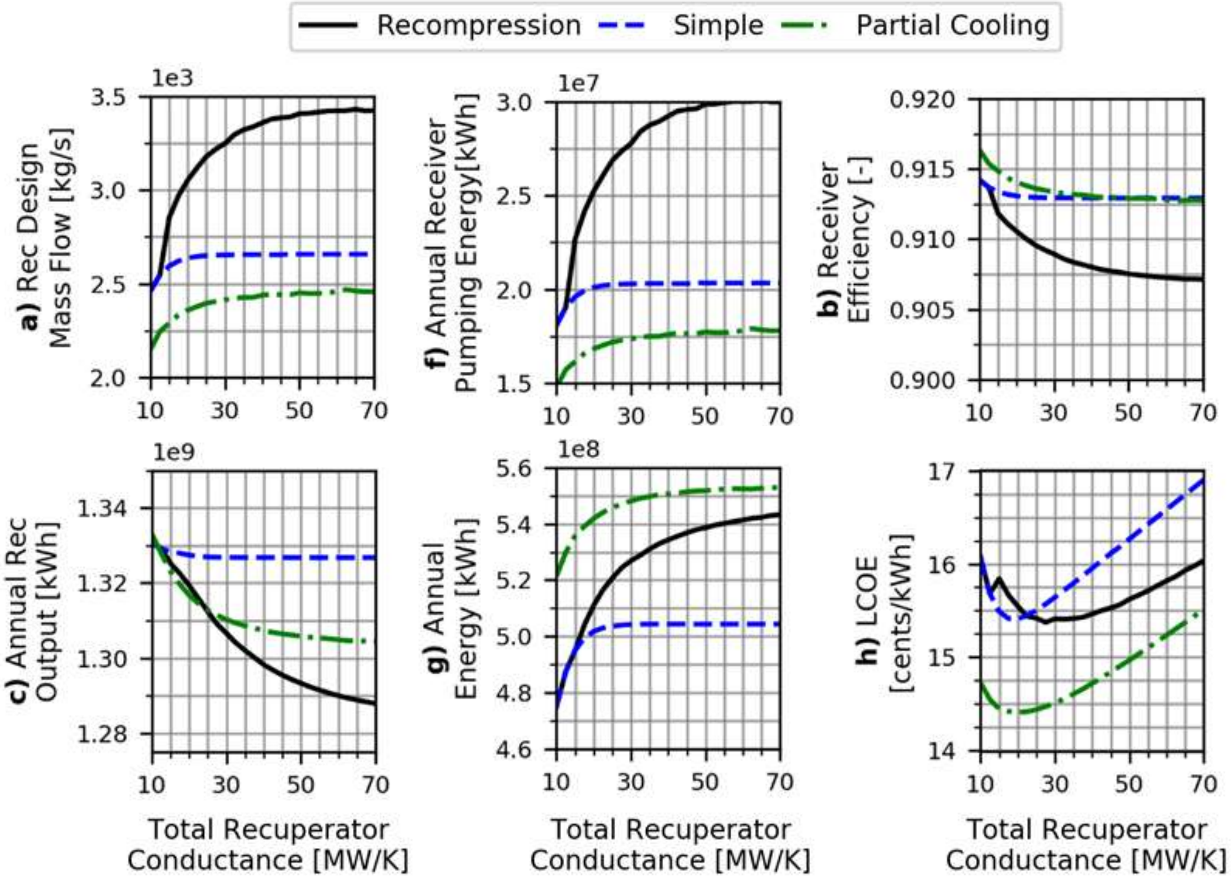
CSP Costs

- PC cycle requires ~27% less storage volume than RC
- PC storage cost is ~20 M$ cheaper than RC storage
  - PC cycle is only ~7 M$ more expensive than RC
- PC *system* cost is ~2.5% less than RC



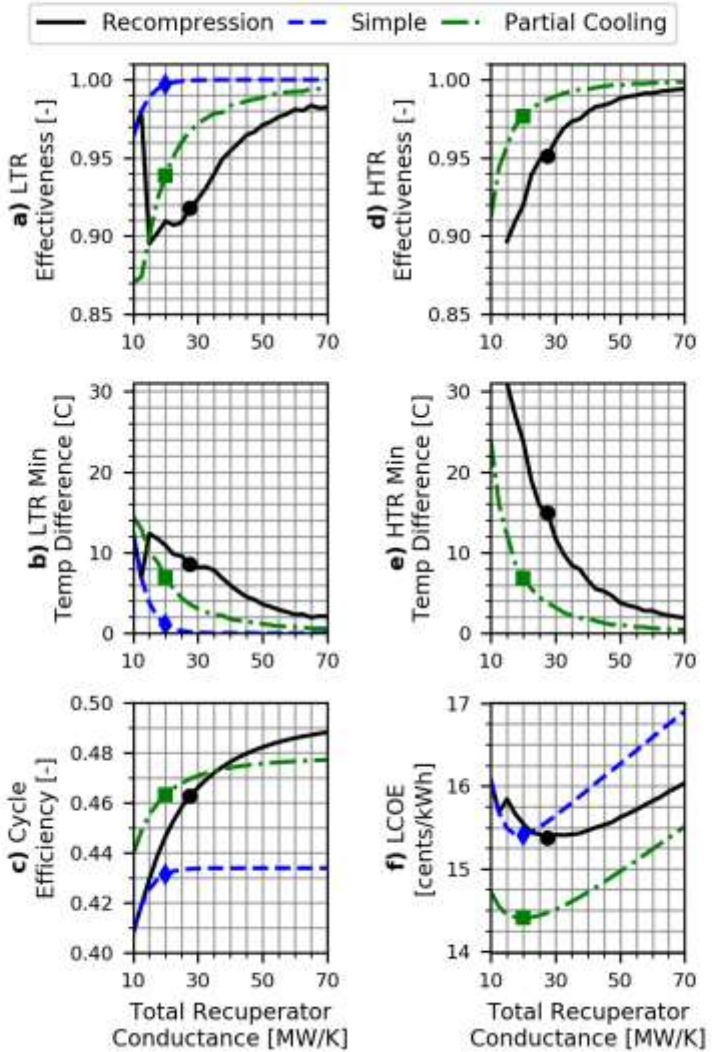
CSP Annual System Performance

- RC higher mass flow rate requires more power to move up tower
- RC smaller ΔT results in more receiver heat loss
- PC system generates more energy
- PC: lower system cost + more energy production = lower LCOE



Min LCOE Cycle Design Parameters

- LTR min temperature difference and effectiveness are different than HTR values
- Simple cycle requires effectiveness approaching 1
- Min LCOE is not at maximum efficiency
  - Difference depends on cycle configuration



Parametrics