Analysis and optimization of the recompression cycle with high temperature recuperator bypass for concentrating solar power applications

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NREL

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Agenda

About Me

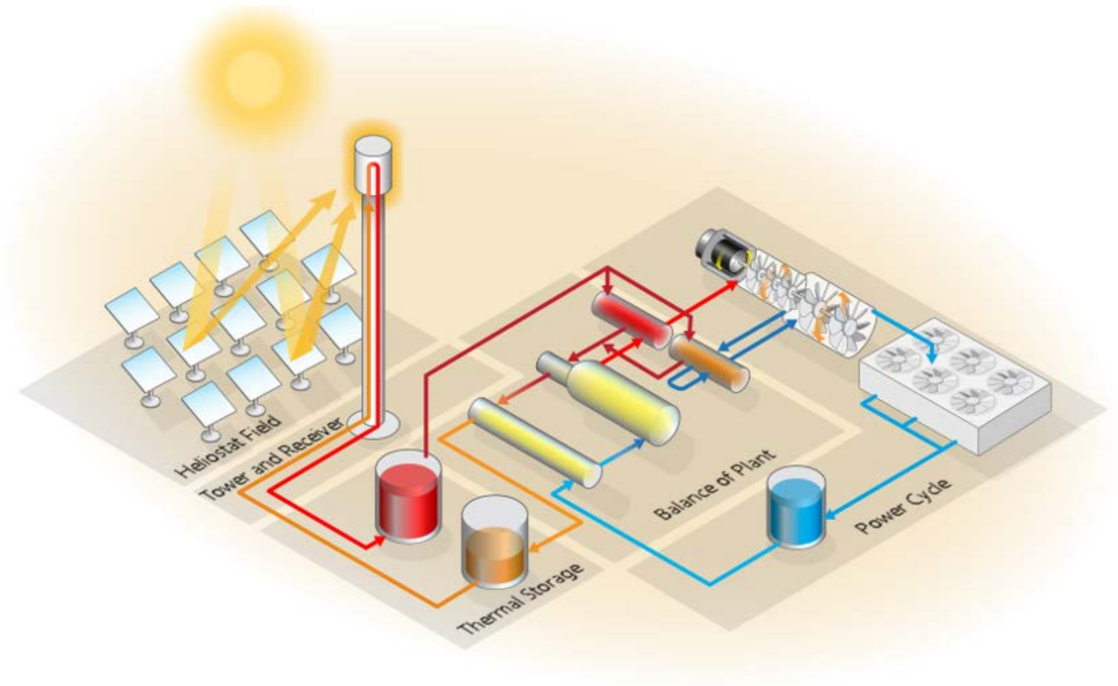
- Thermal energy systems researcher at NREL
- Contributed to models for System Advisor Model (SAM), including:
  - Linear Fresnel
  - Parabolic Trough
  - Pumped Thermal Energy Storage

NREL Transforming ENERGY

System Advisor Model

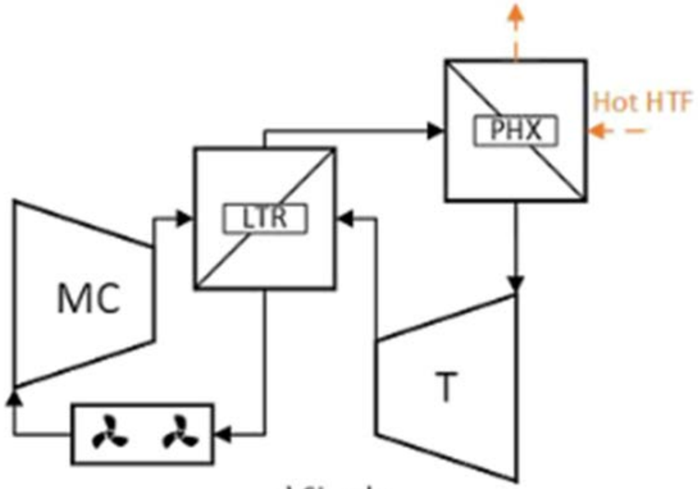
Background

- CSP cycles benefit from large HTF temperature deltas because:
  - Less HTF mass in system
  - Lower storage costs
  - Less pumping power
  - Higher receiver efficiency
- Generally, larger HTF temperature deltas lead to lower efficiency cycles

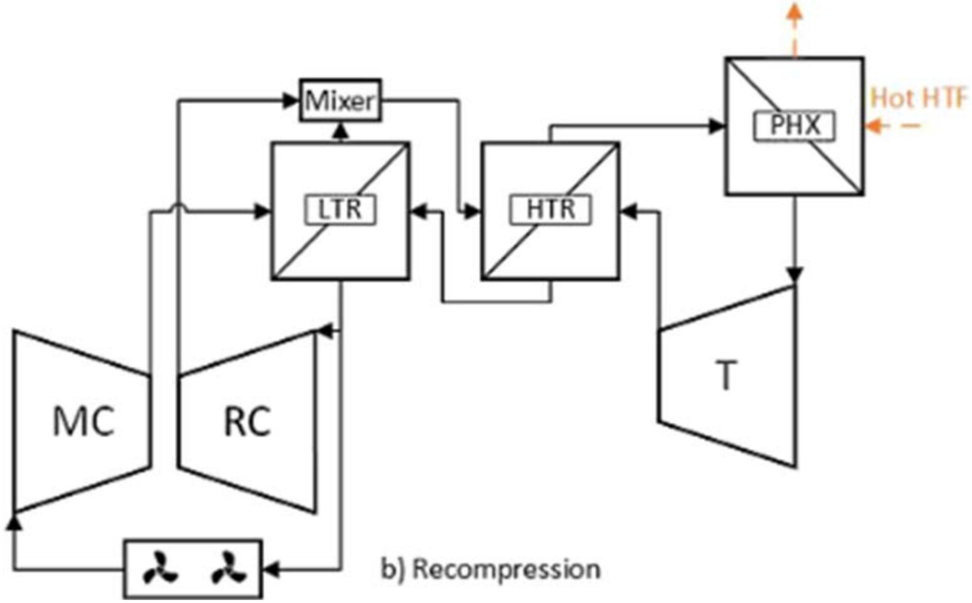


System Advisor Model Version 2022.11.29 (SAM 2022.11.21). National Renewable Energy Laboratory. Golden, CO. Accessed February 28, 2024. https://https://sam.nrel.gov.

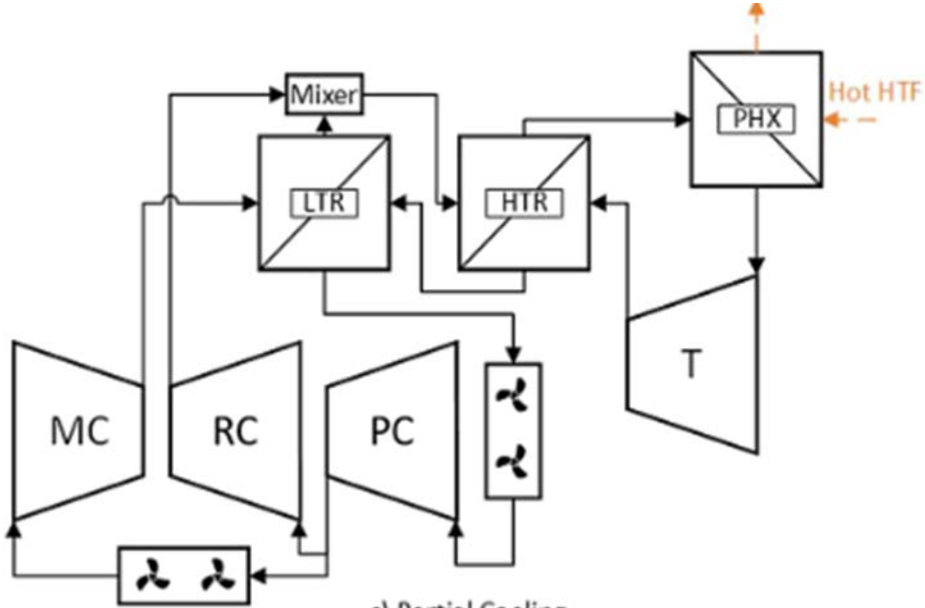
Background Cycles



a) Simple



b) Recompression

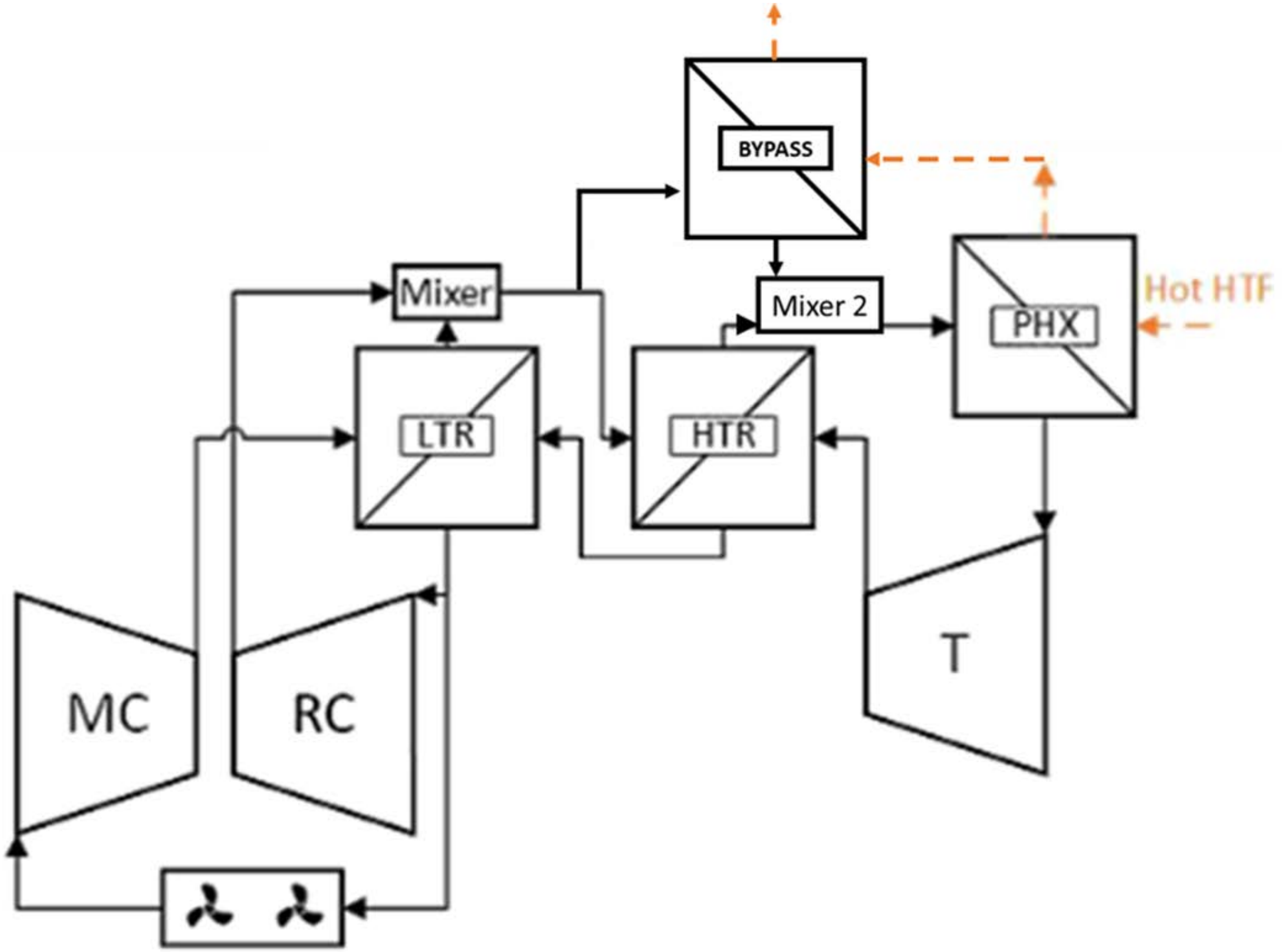


c) Partial Cooling

Neises, Ty, and Craig 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.” *Solar Energy* 181 (March 2019): 27–36. https://doi.org/10.1016/j.solener.2019.01.078.

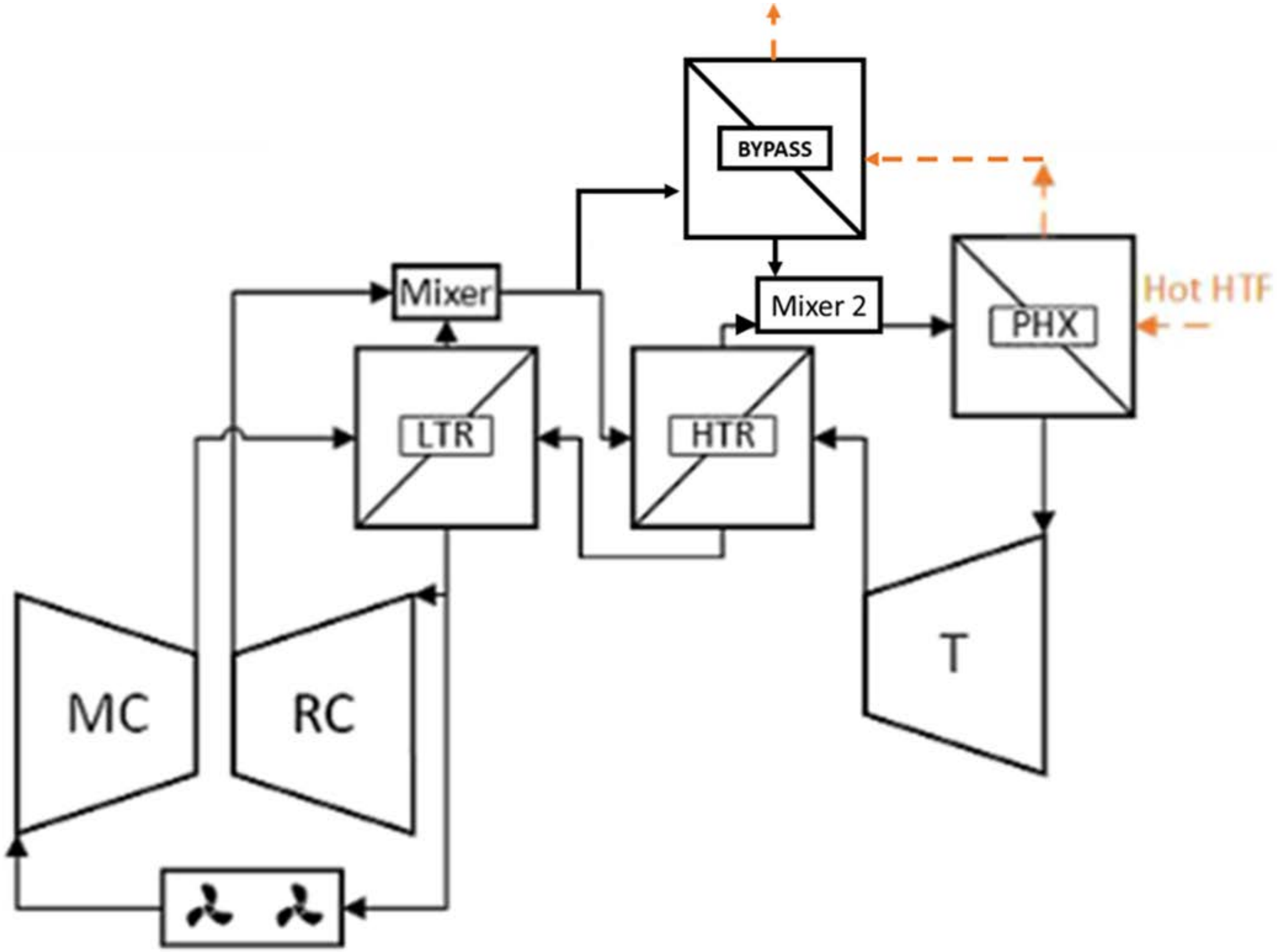
Recompression with HTR Bypass

- Based on the recompression cycle
- Adds second HTF heat exchanger for flow that bypasses the HTR
- Ideally, maintains efficiency of recompression and decreases HTF outlet temperature



Solving the Cycle

- Inputs
  - Design power
  - Component properties
    - Turbomachinary efficiency
    - Heat exchanger conductance, min dT
  - HTF inlet temperature
  - PHX and air cooler approach temperatures
- Assumptions
  - Pressure loss is fraction of total pressure (independent of mass flow rate)
  - No pressure drop in mixers
- Constraints
  - Mixer 2 dT = 0



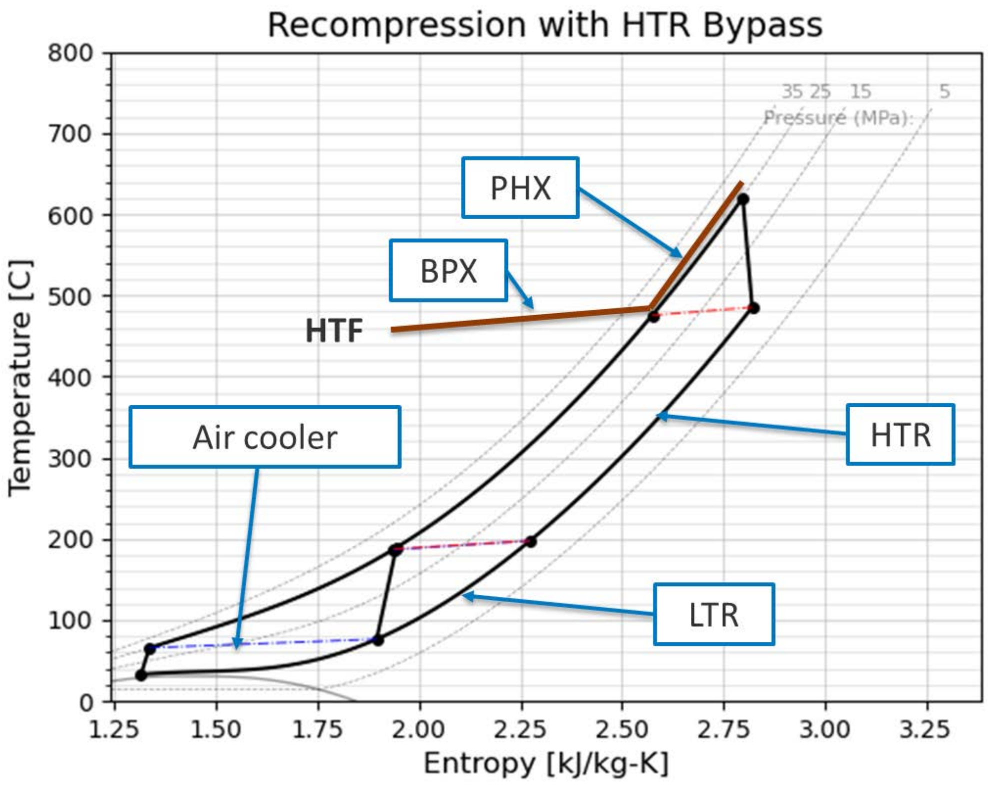
Model Validation

	Alfani 2020 [1] (coal)		Moullec 2019 [2] (CSP)		Alfani 2019 [3] (waste heat)	
	Paper	Model	Paper	Model	Paper	Model
W design (MW)	108.428	108.428	10.01	10.01	5.863	5.863
sCO2 mdot (kg/s)	1041.54	1040.64	162.94	163.02	140.17	138.98
HTF Outlet Temp (C)	-	460.98	290	291.19	214.06	212.31
Thermal Eff. (%)	46.49	46.43	34.4	34.3	30.35	30.41

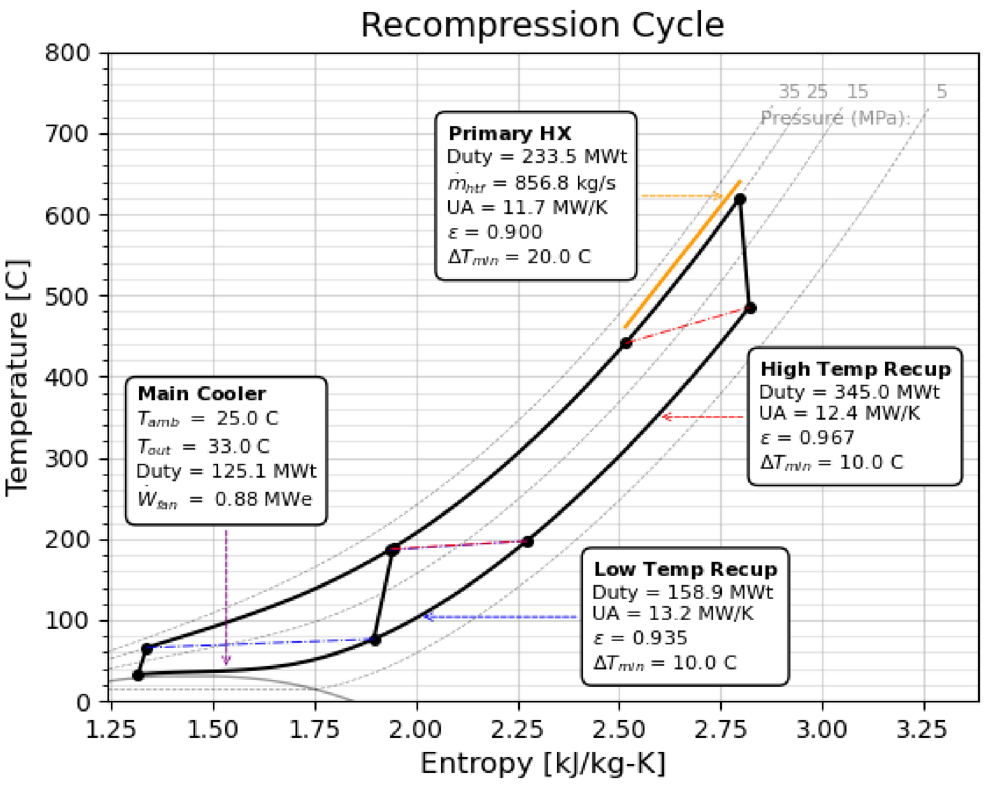
Alfani 2020 Case Parameters [1]

Parameter	Value	Unit
Net Power	100	MWe
HTF Inlet Temperature	640	C
PHX Inlet Approach Temperature	20	C
Ambient Temperature	25	C
Air Cooler Approach Temperature	8	C
Turbine Isentropic Efficiency	89.8	%
Main Compressor Polytropic Efficiency	77.7	%
Recompressor Polytropic Efficiency	76.7	%
Max Pressure	25	MPa
Air Cooler Parasitic Power	0.87805	MWe
Total Recuperator Conductance	36.85	MW/K

Ts Diagram



w/ HTR Bypass

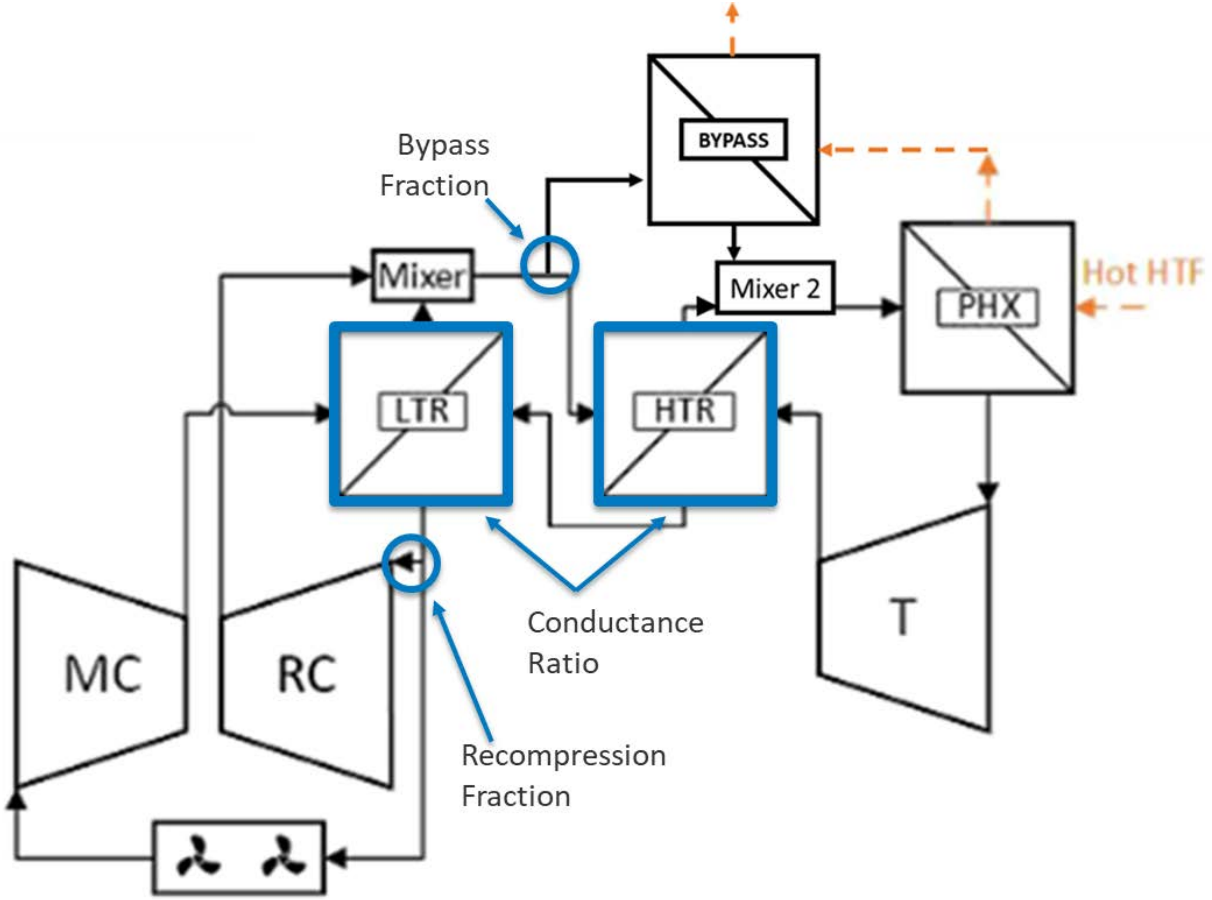


w/o HTR Bypass

Optimization

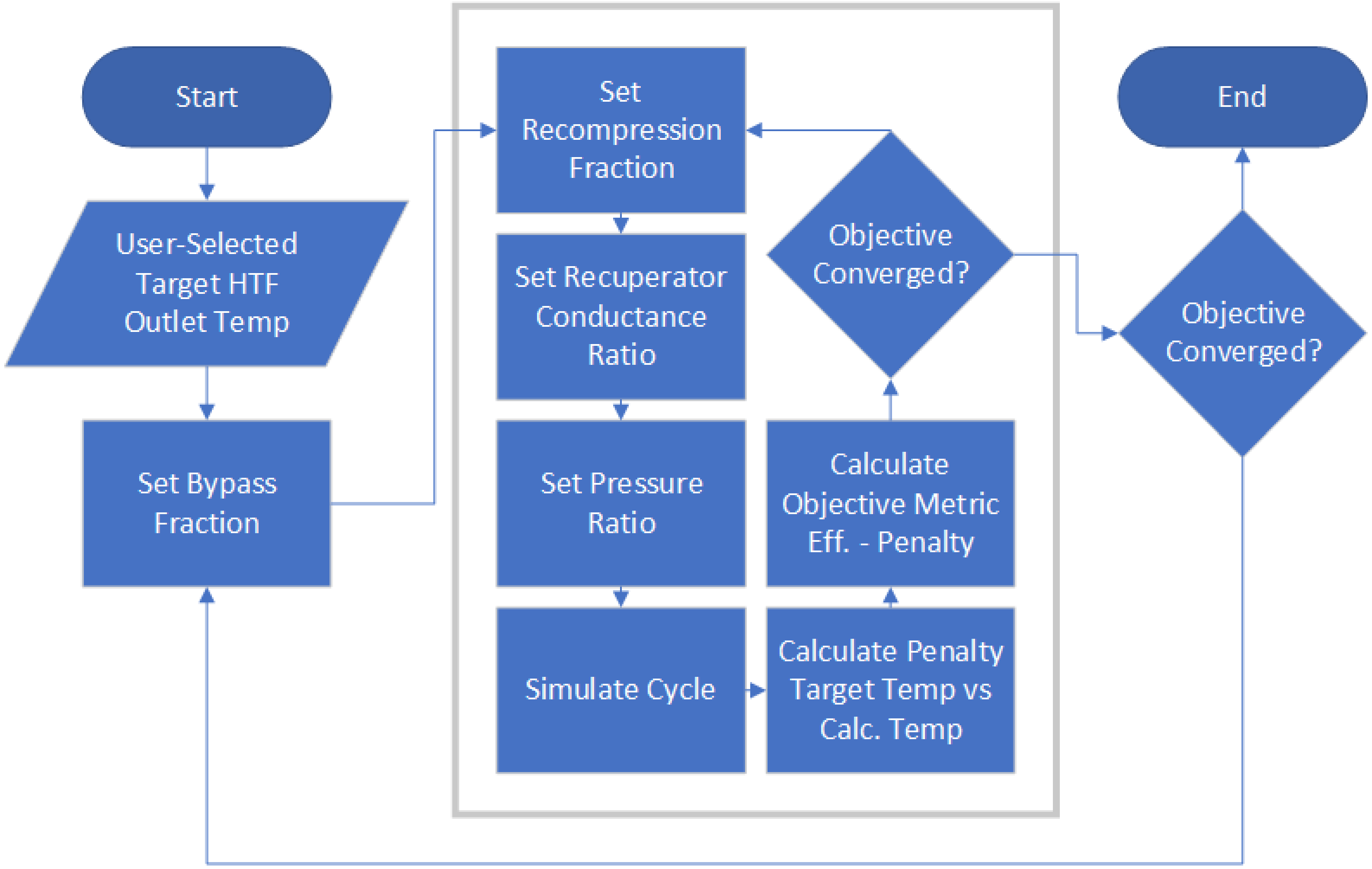
Optimization

- Design Variables:
  - Recompression Fraction
  - Bypass Fraction
  - Minimum Pressure
  - Recuperator Conductance Ratio
- Constraints:
  - Target HTF Outlet Temperature
- Objective Targets:
  - Max Thermal Efficiency



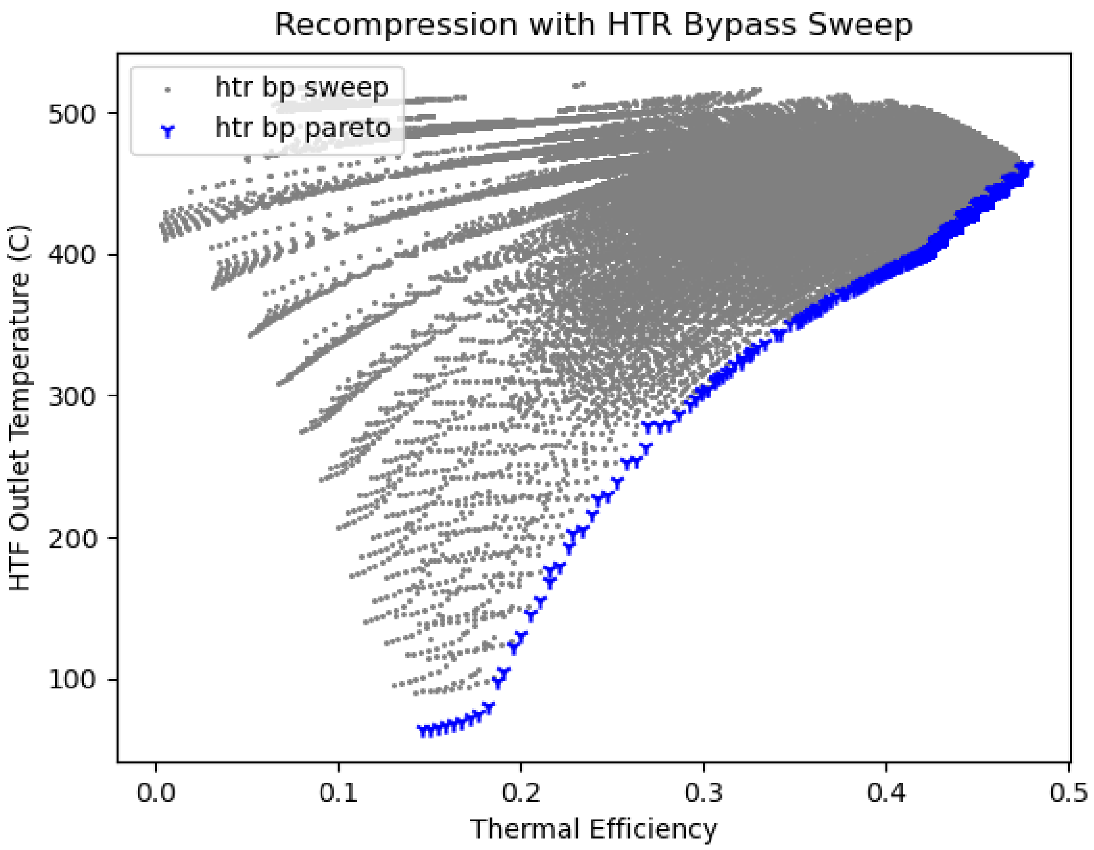
$$obj = \eta_{eff} - penalty$$

Optimization



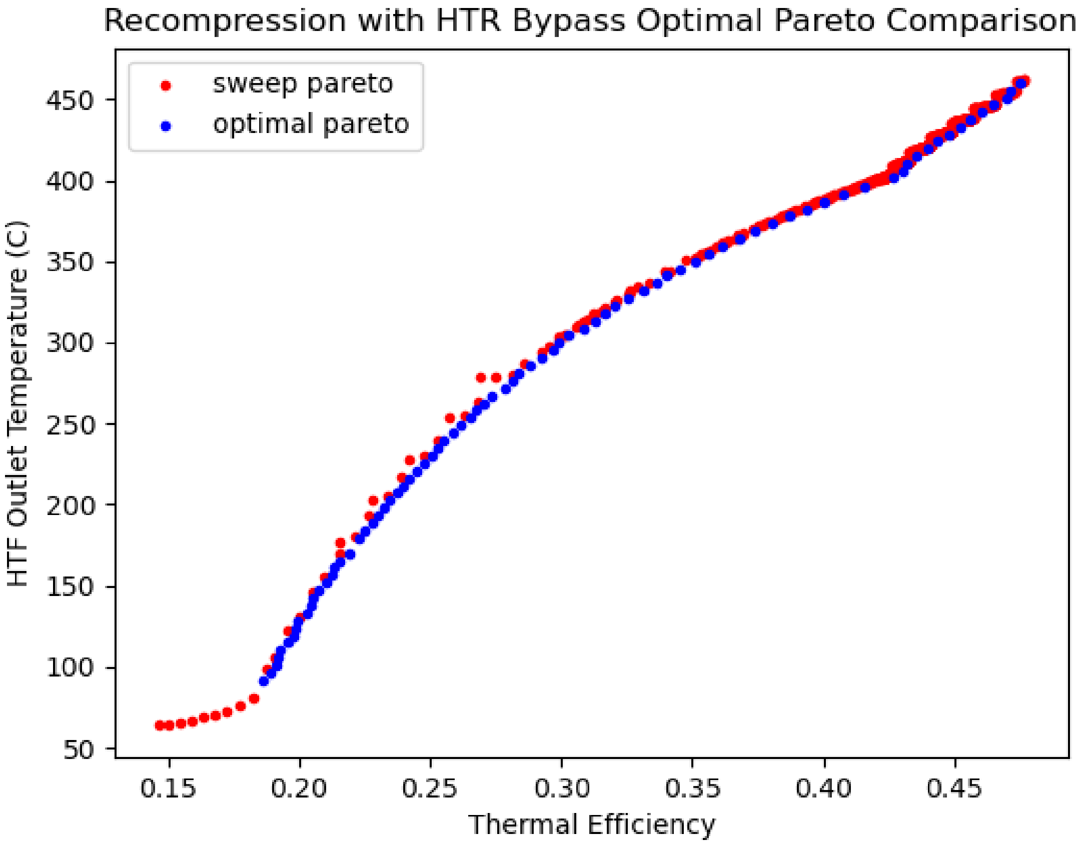
Optimization Validation

- We ran a parametric sweep of design variables to compare optimization results
- Each design variable was divided into 20 values, resulting in 160,000 total runs
- The sweep produced a pareto front maximizing thermal efficiency and minimizing HTF outlet temperature



Optimization Validation

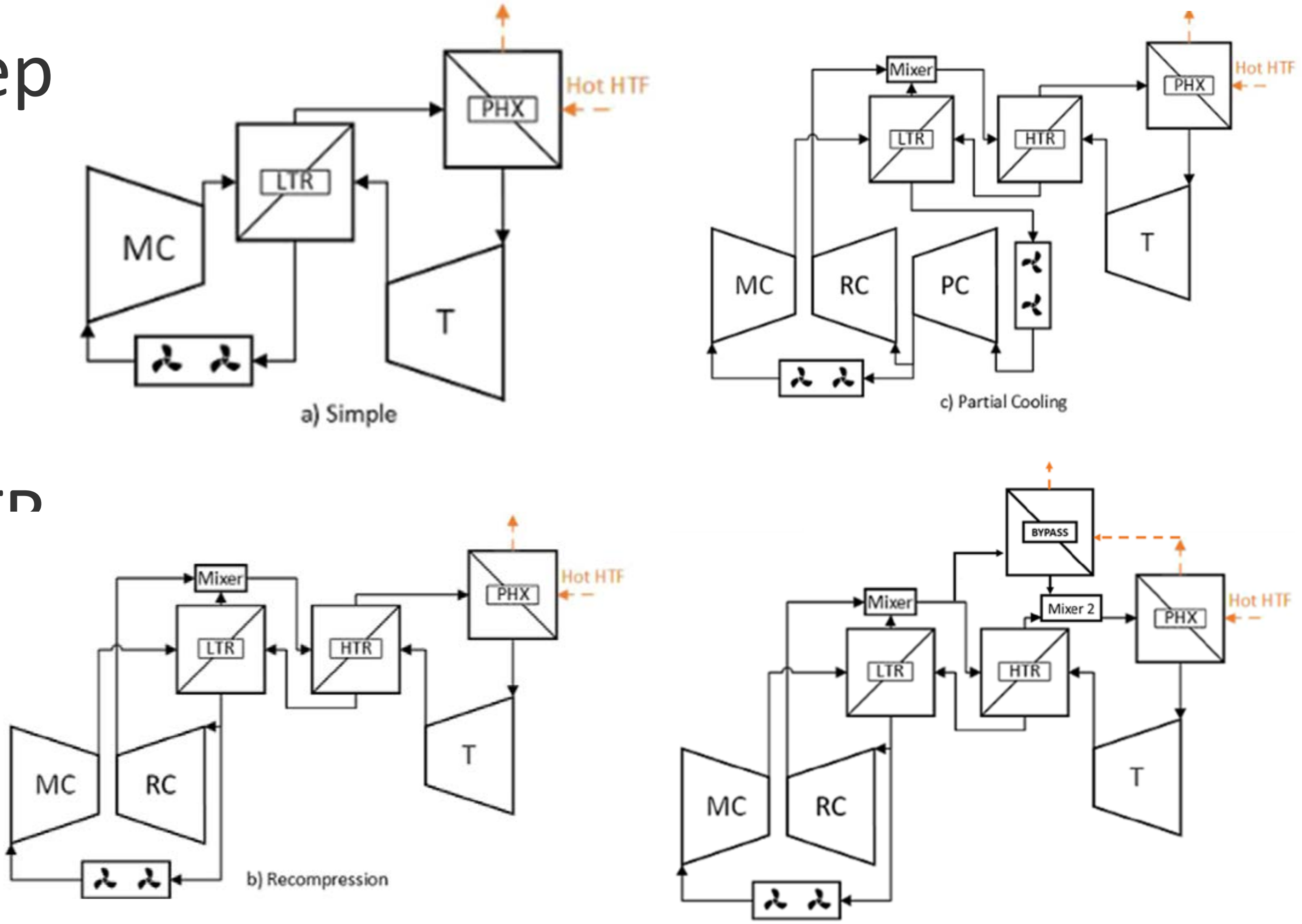
- We validated the optimization against the pareto front from the parametric sweep
- Each optimization data point is targeting its respective HTF outlet temperature



Parametric Sweep – Fixed Conductance

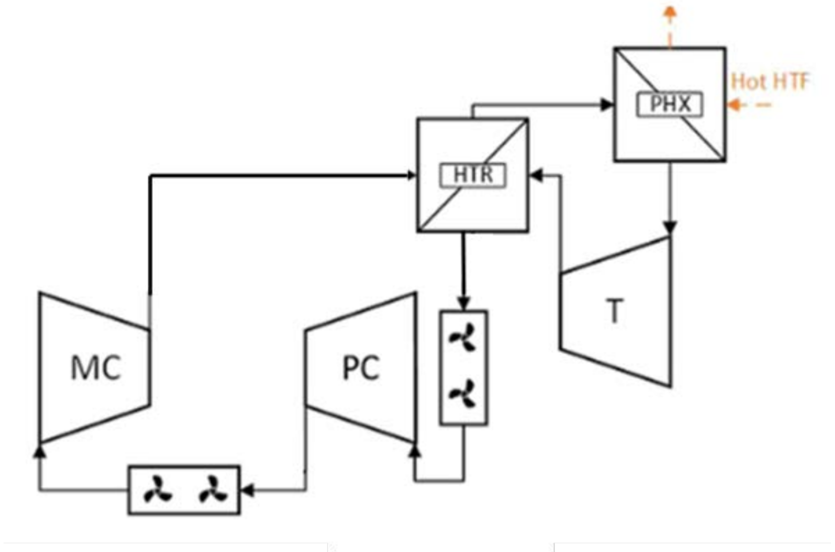
Cycle Comparison – Fixed Conductance

- We ran a parametric sweep for each of the 4 cycles
  - Simple
  - Recompression
  - Recompression with HTR Bypass
  - Partial Cooling

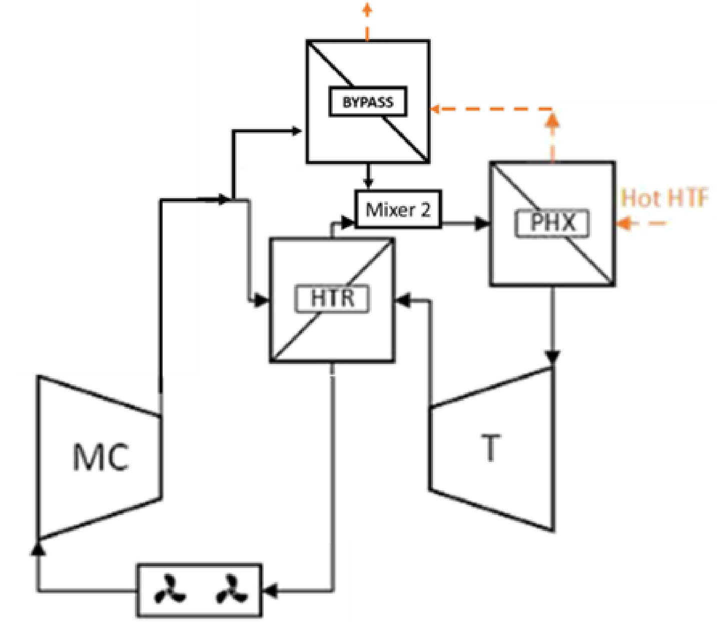


Subset Configurations

- The parametric sweep revealed subset configurations, when the recompressor is removed
- Simple intercooling cycle is formed from the partial cooling cycle with recompression fraction = 0
- Simple split flow bypass cycle is formed from HTR bypass cycle with recompression fraction = 0

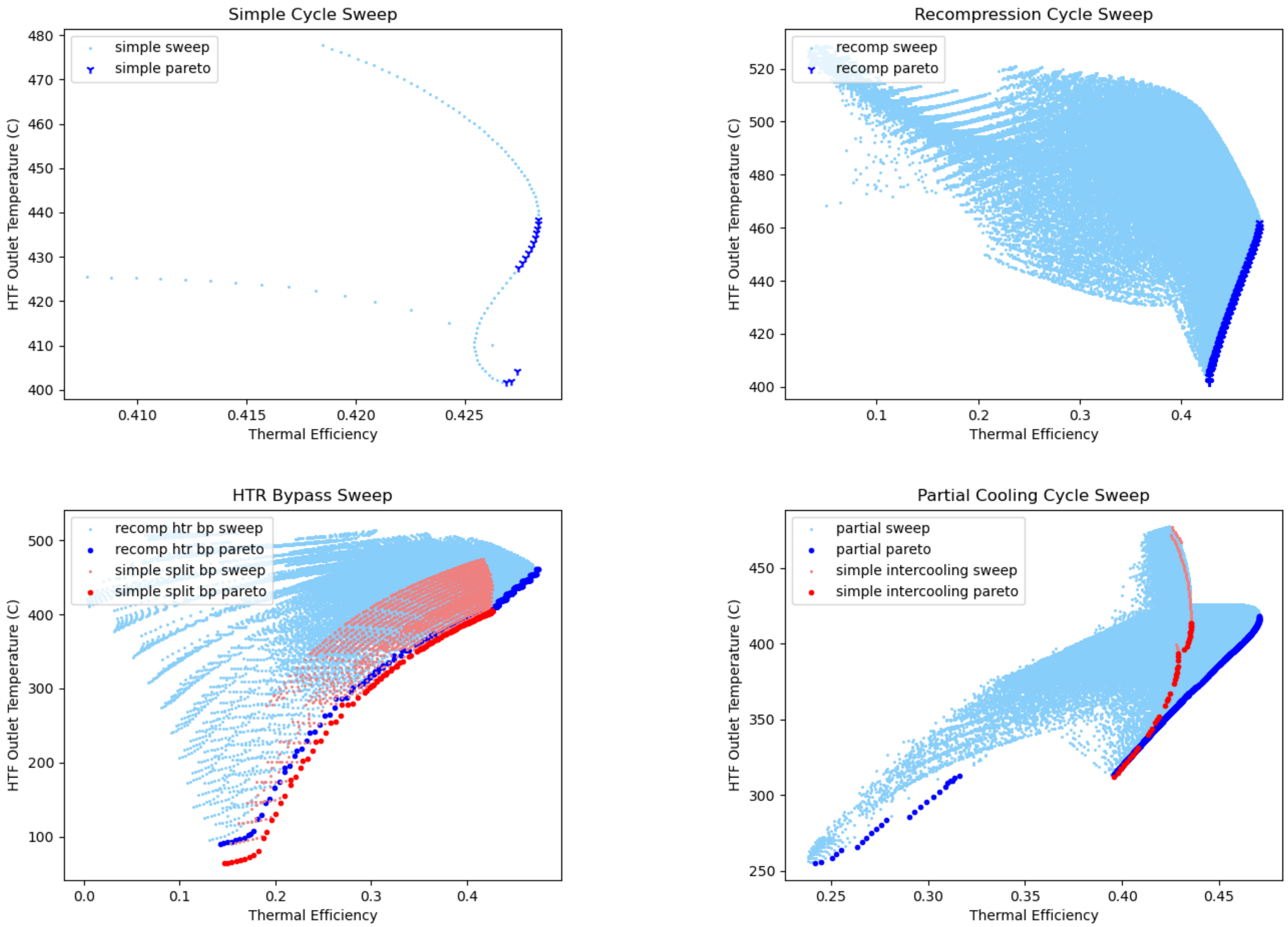


Simple Intercooling

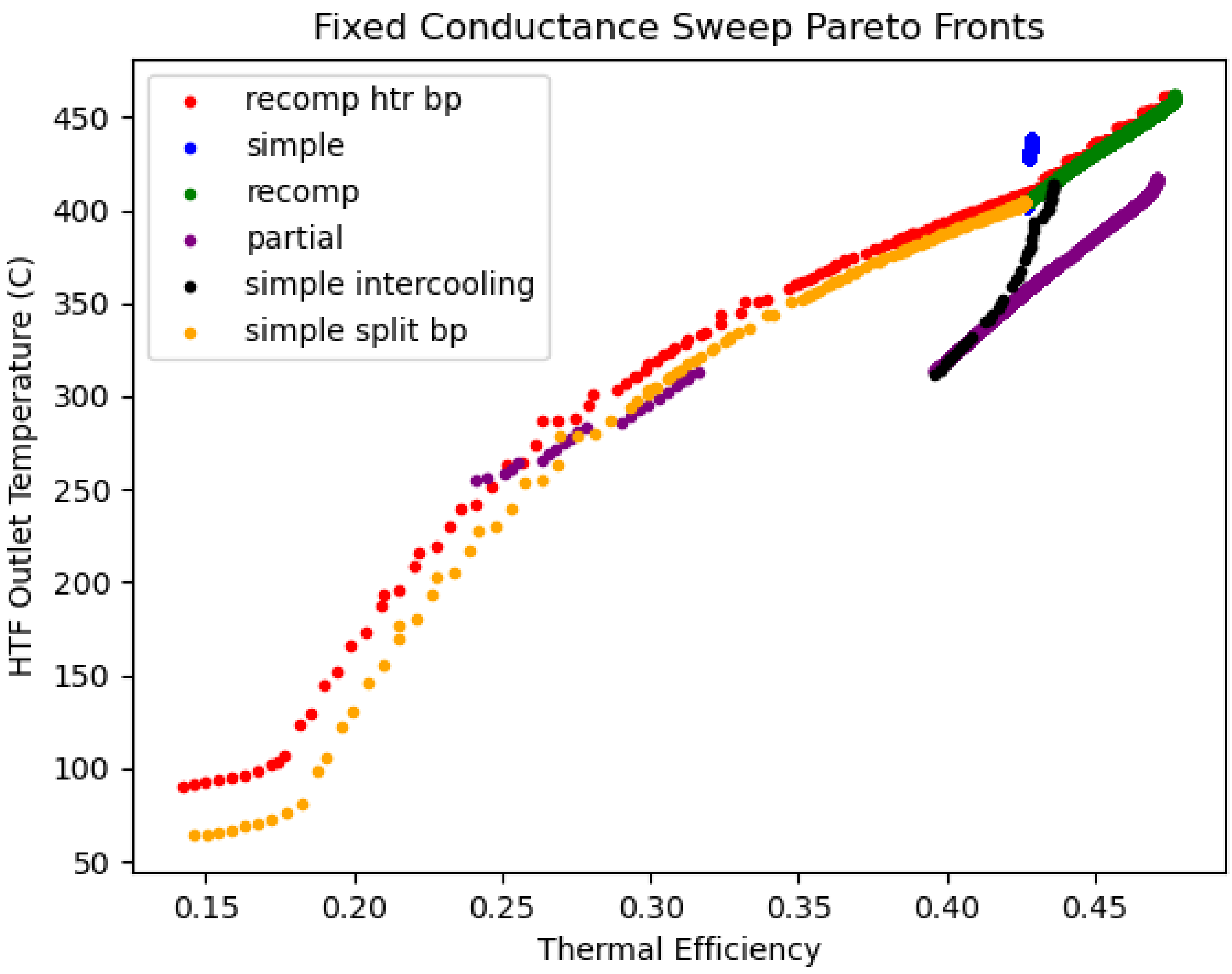


Simple Split Flow Bypass

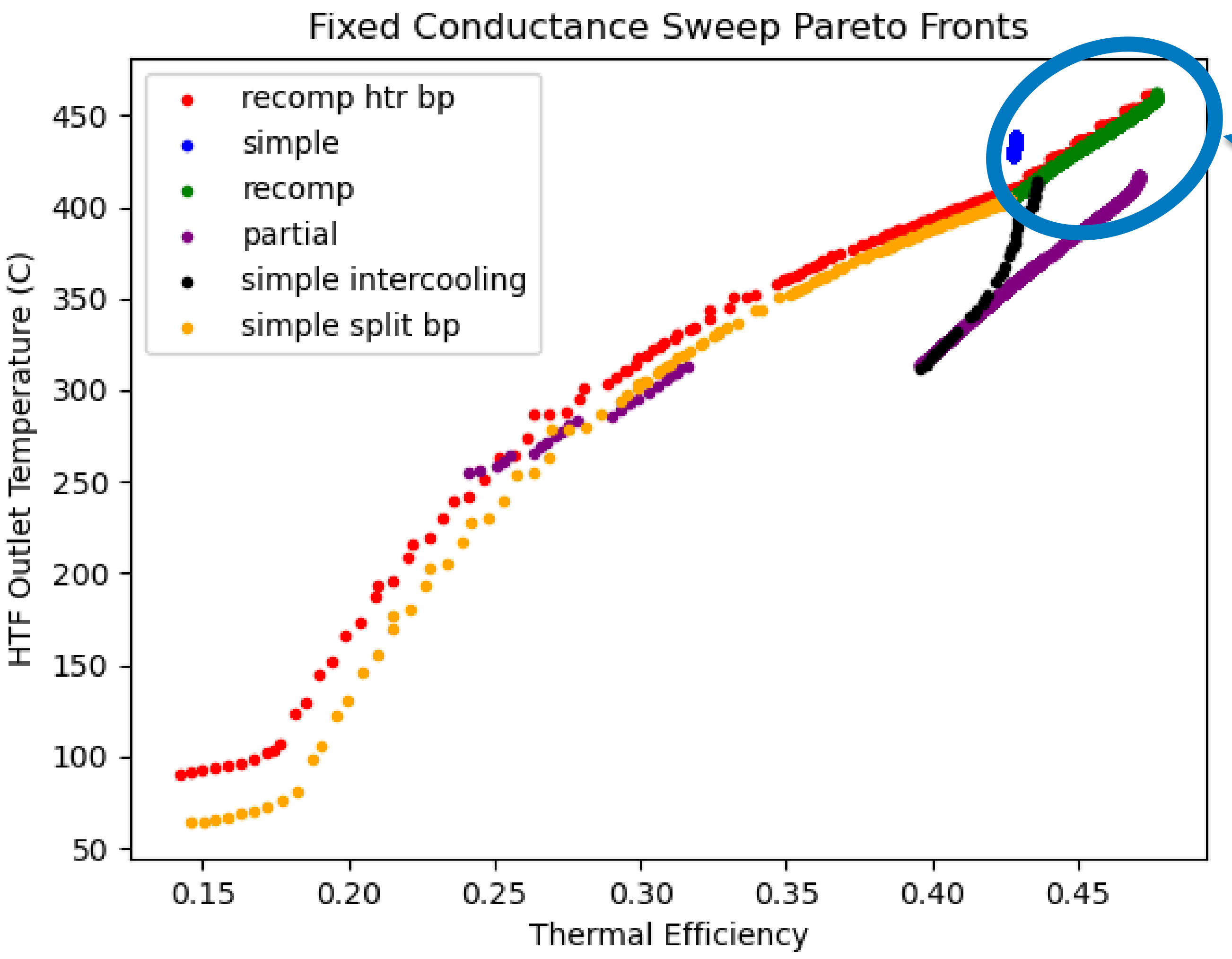
Parametric Sweeps - Fixed Conductance



Pareto Fronts - Fixed Conductance

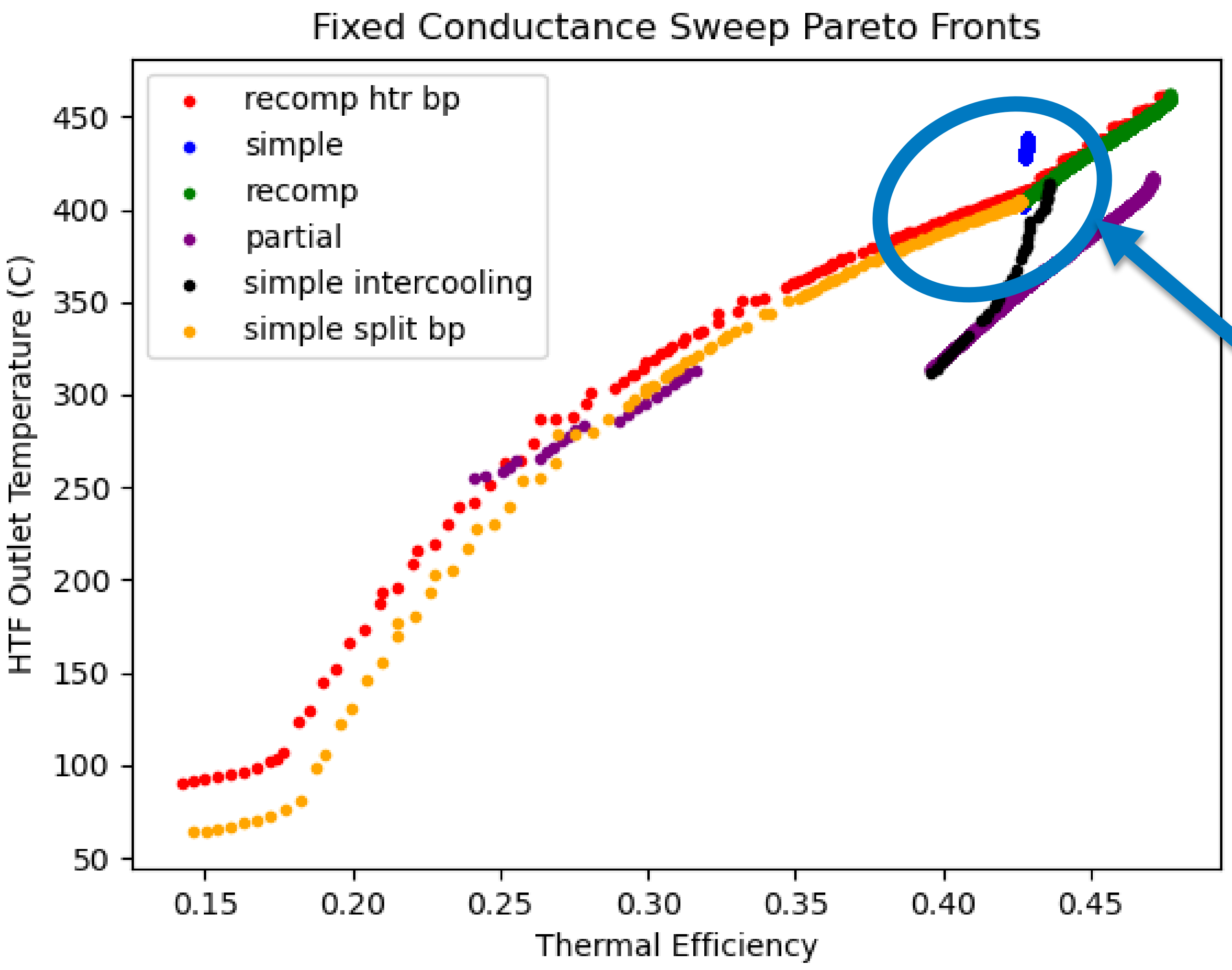


Pareto Fronts - Fixed Conductance



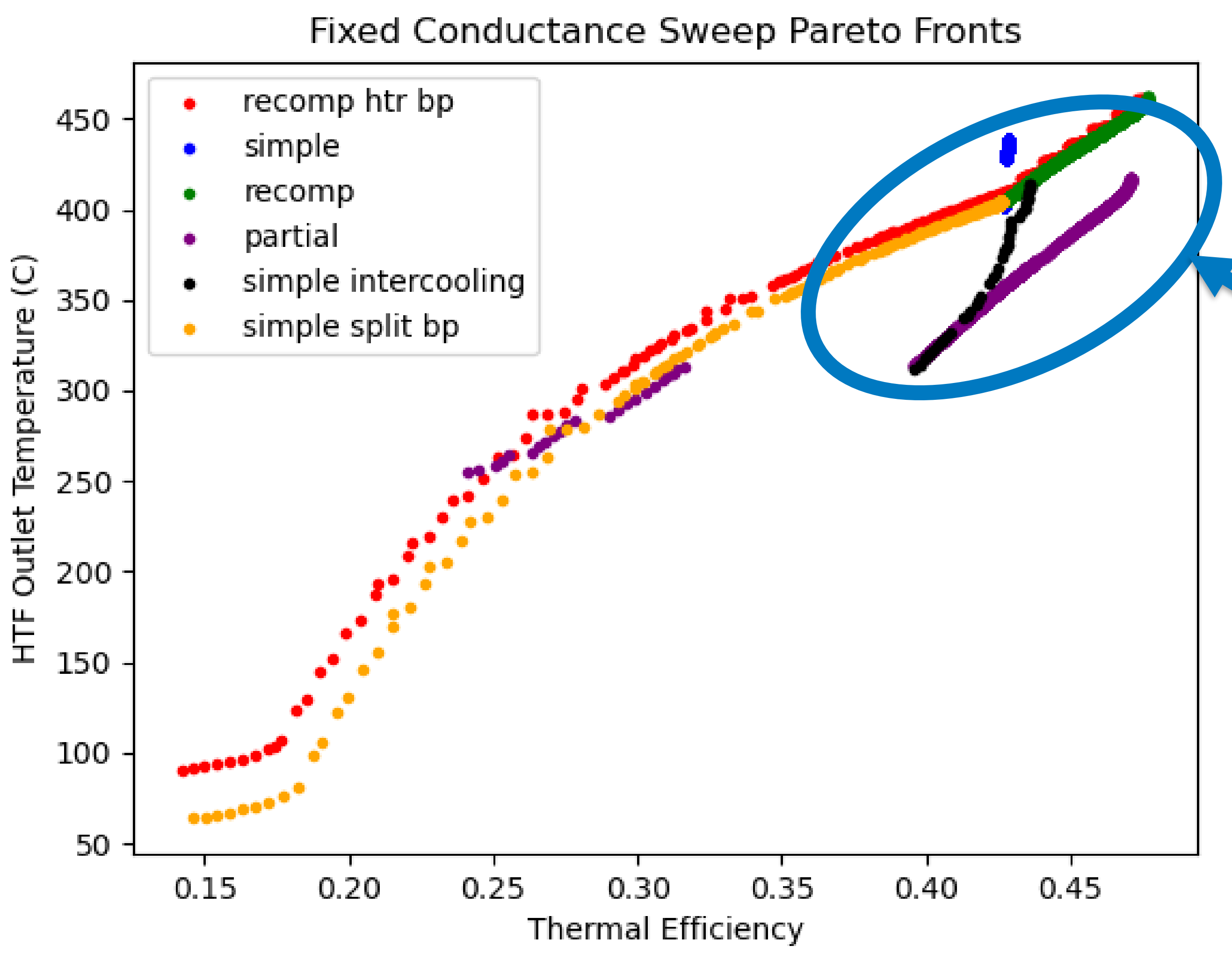
At high HTF outlet temperatures, the bypass fraction = 0 for the recompression with htr bypass cycle

Pareto Fronts - Fixed Conductance



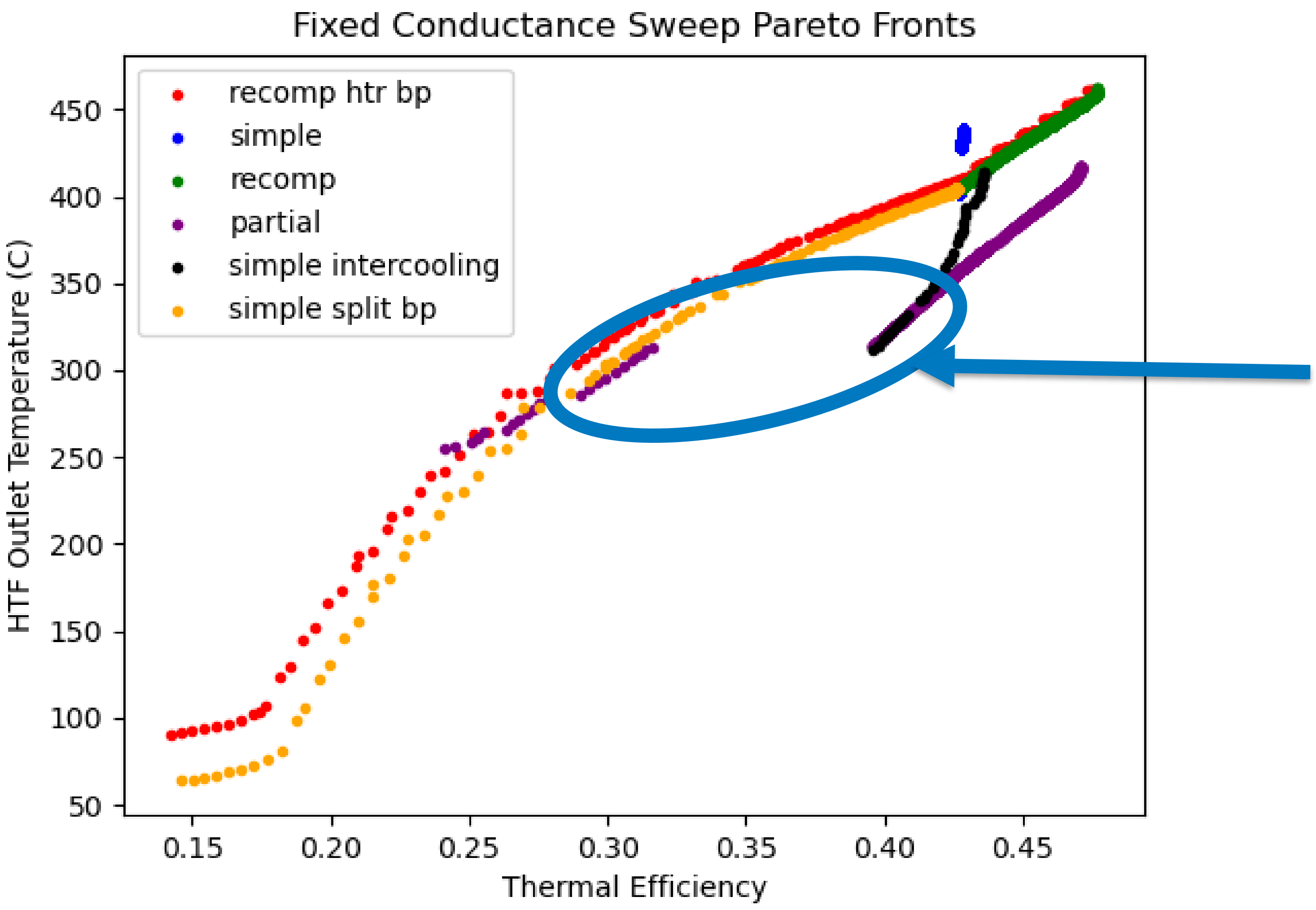
The recompression cycle is unable to reach lower HTF temperatures at this point

Pareto Fronts - Fixed Conductance



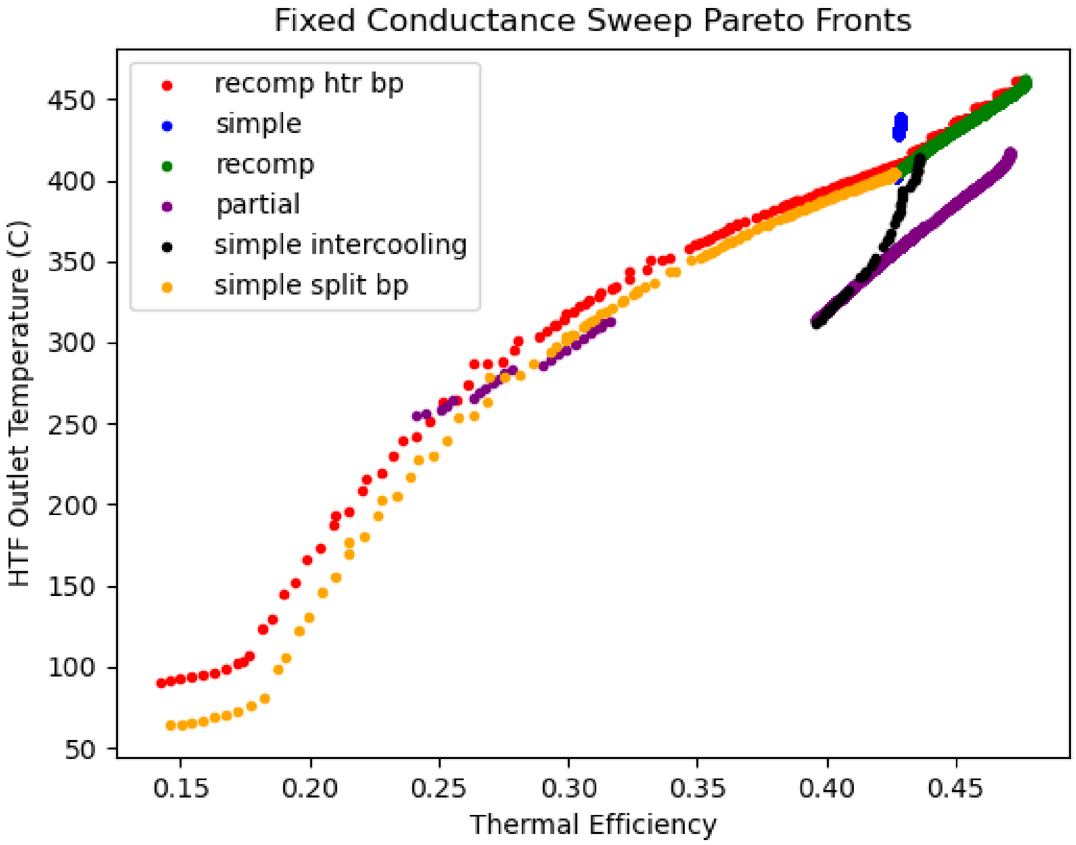
The simple intercooling cycle approaches partial cooling cycle efficiencies as the HTF outlet temperature decreases

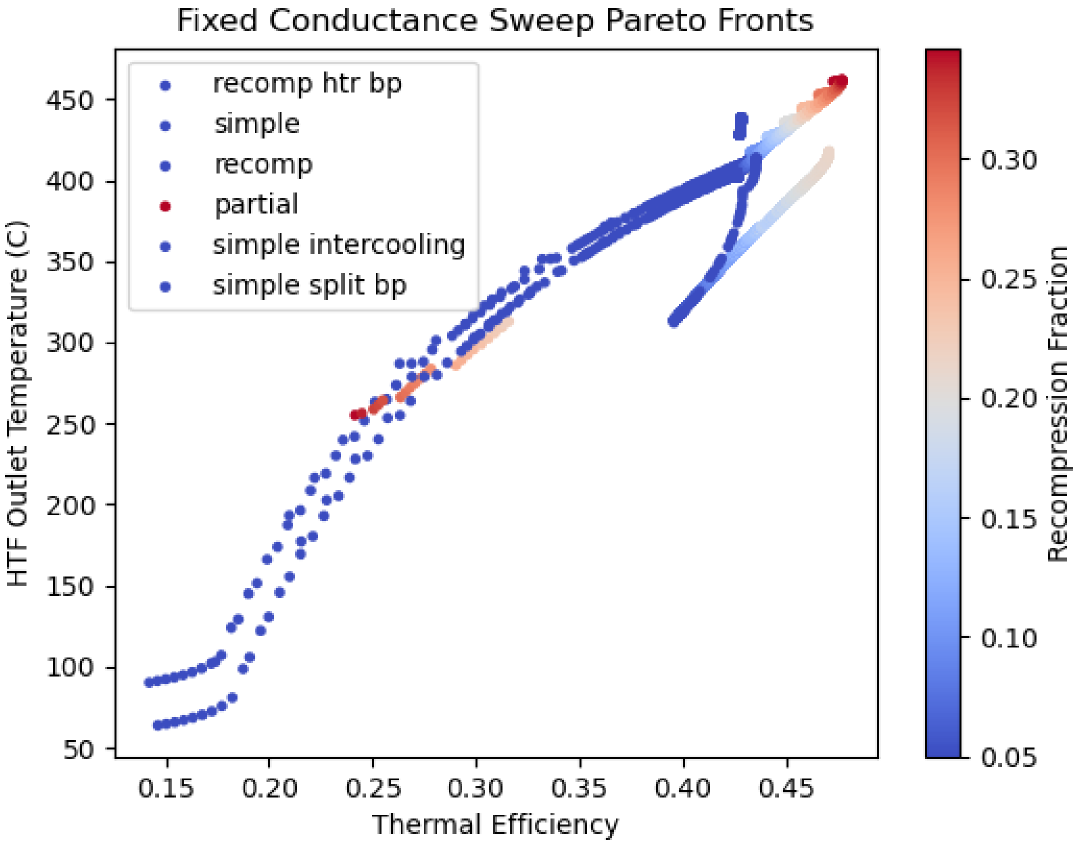
Pareto Fronts - Fixed Conductance



The partial cooling cycle can no longer decrease the recompression fraction and pressure ratio, causing a gap in effciency

Pareto Fronts - Fixed Conductance

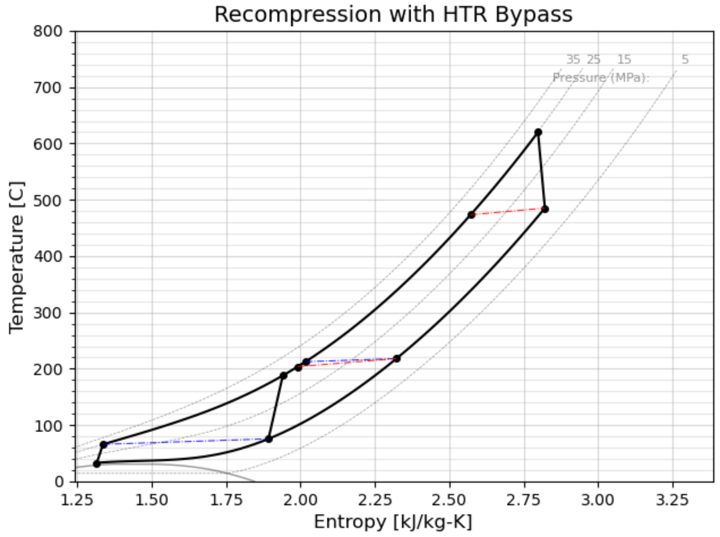




Recuperator Conductance Analysis

Varied Conductance

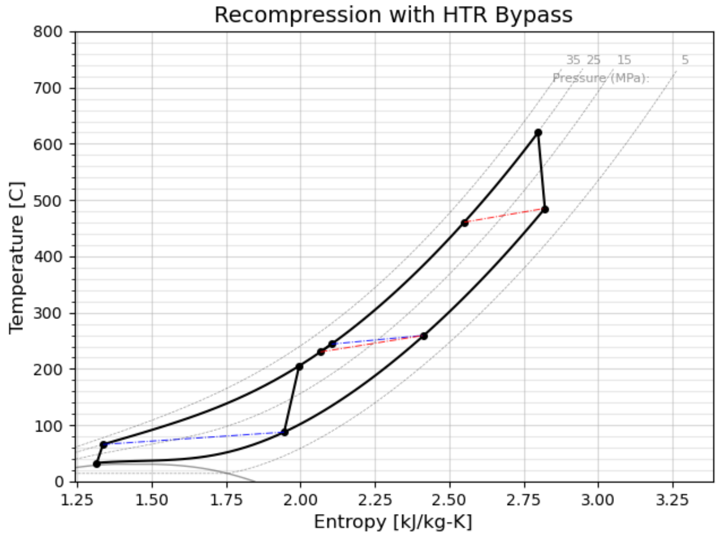
- The previous sweep used a fixed total conductance for the recuperators (36.85 MW/K)
- Decreasing conductance can reduce the HTF outlet temperature (limits recuperated heat)
- We conducted a new sweep for each configuration with varied total conductance
  - UA=0.1-50 MW/K
  - All other design variables optimized for efficiency



UA=36.85 MW/K

HTF delta T: 178.5 °C

η_{eff}: 46.7%

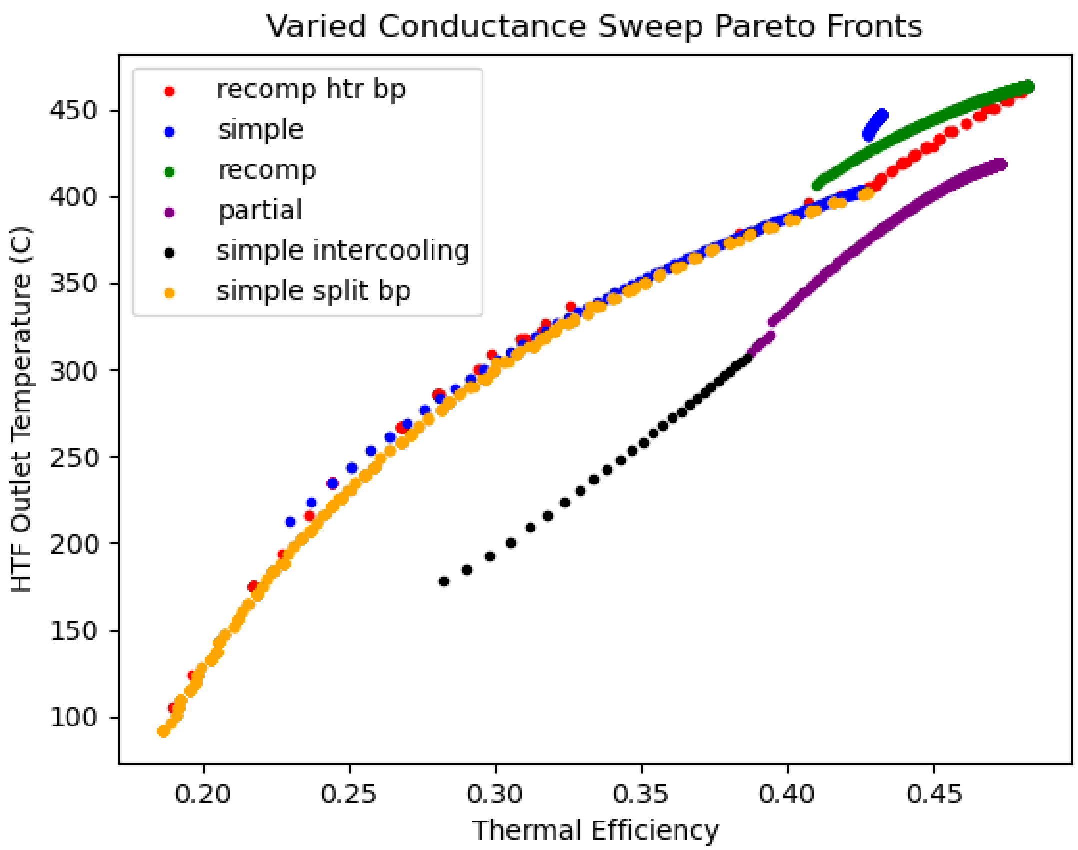


UA=18.43 MW/K

HTF delta T: 186.2 °C

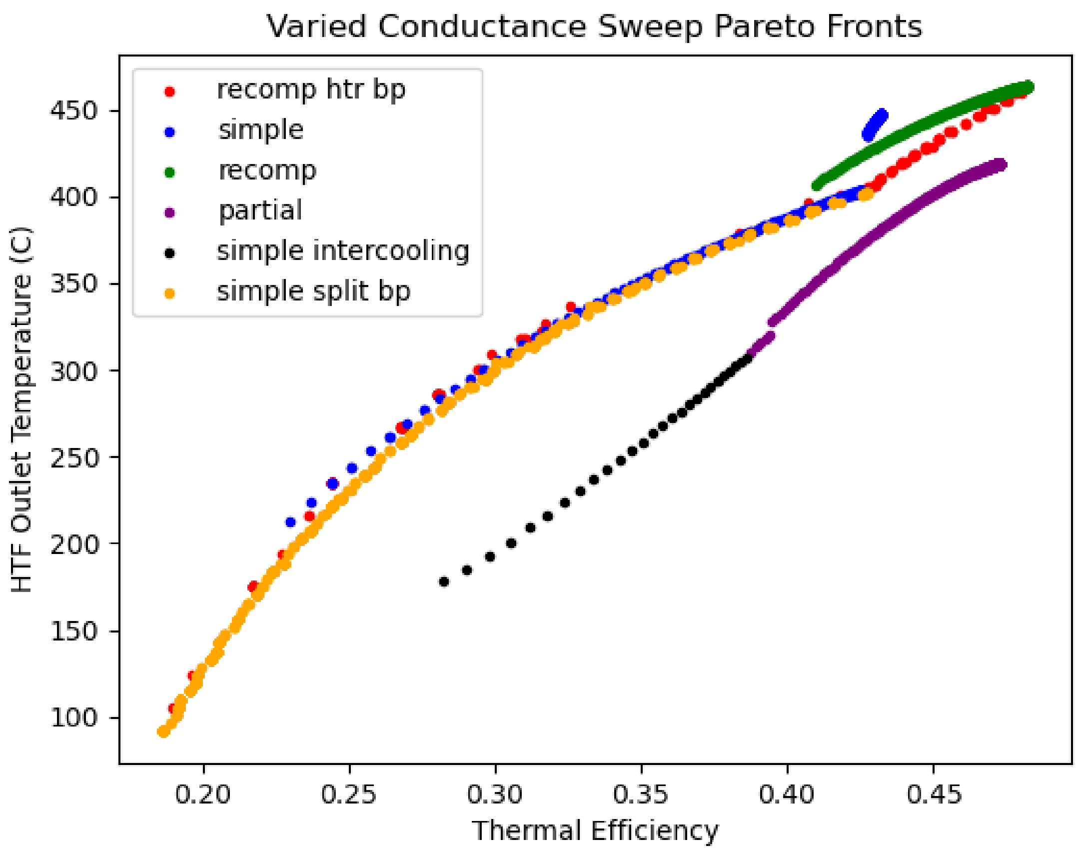
η_{eff}: 43.7%

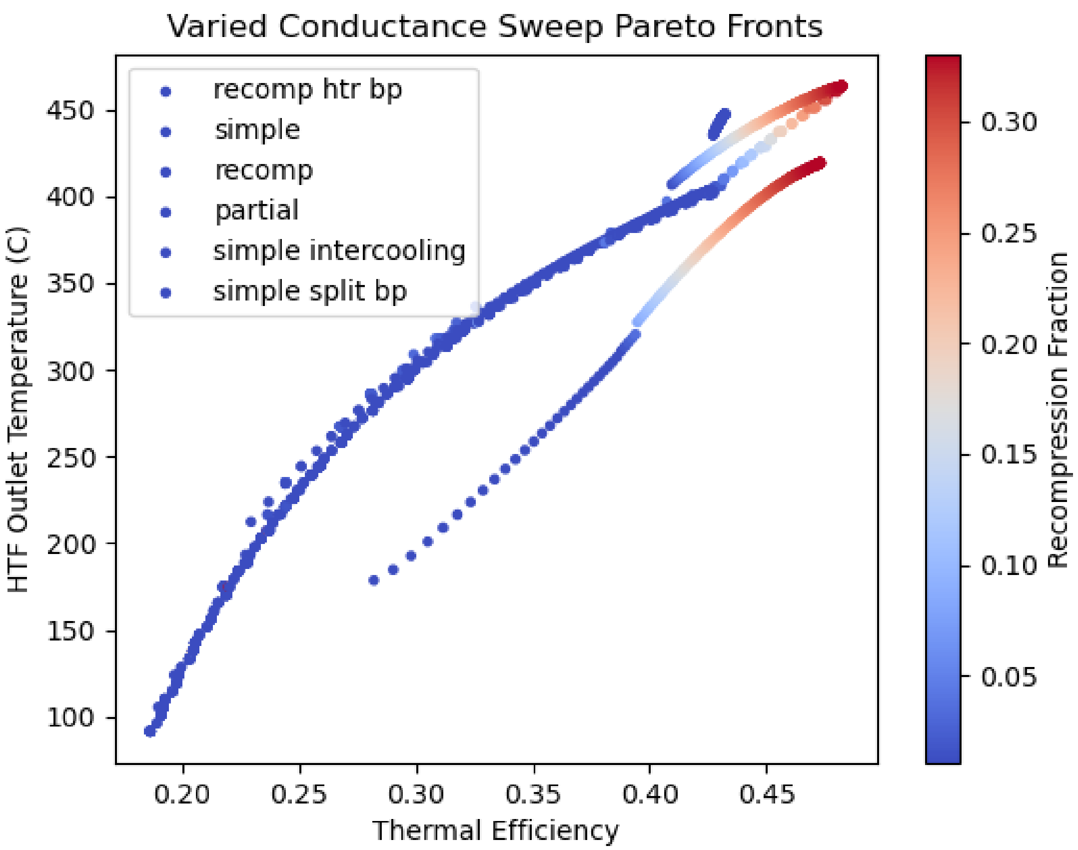
Pareto Fronts – Varied Conductance



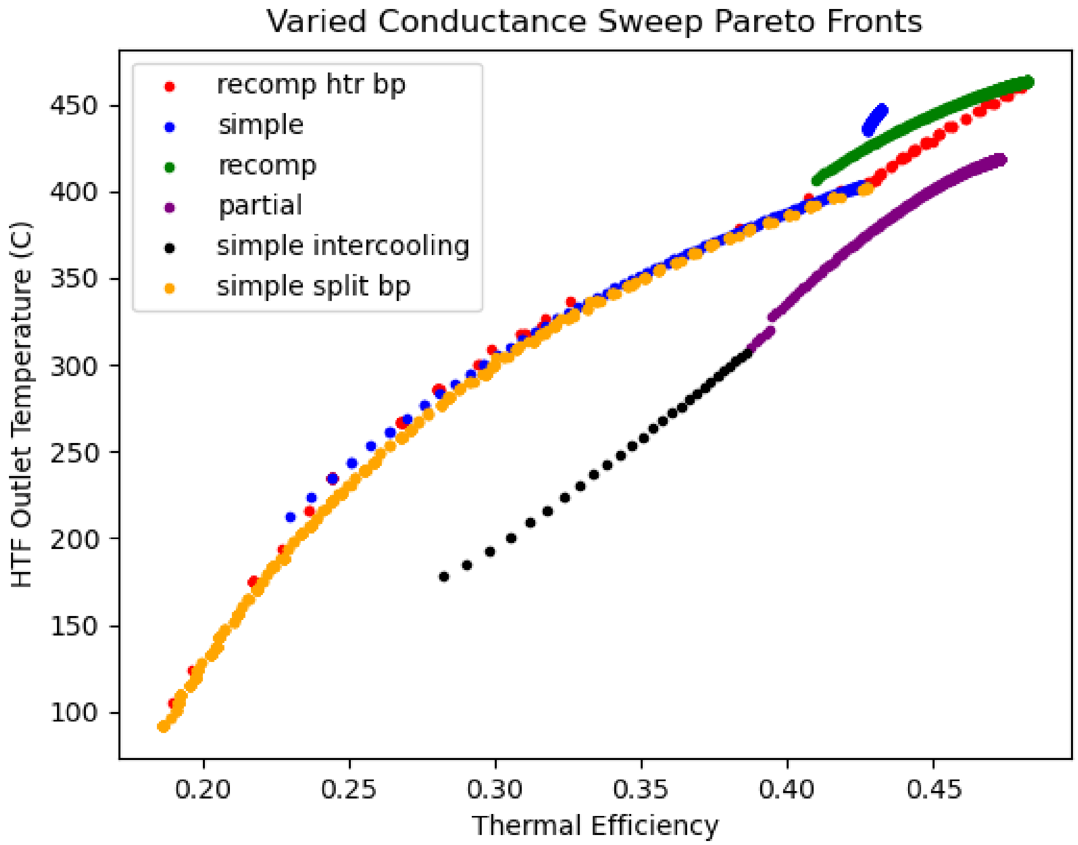
- Each point is one total recuperator conductance, all other variables optimized for efficiency
- Not necessarily most optimal cycles, because multiple ‘optimal’ cycles could use the same total conductance

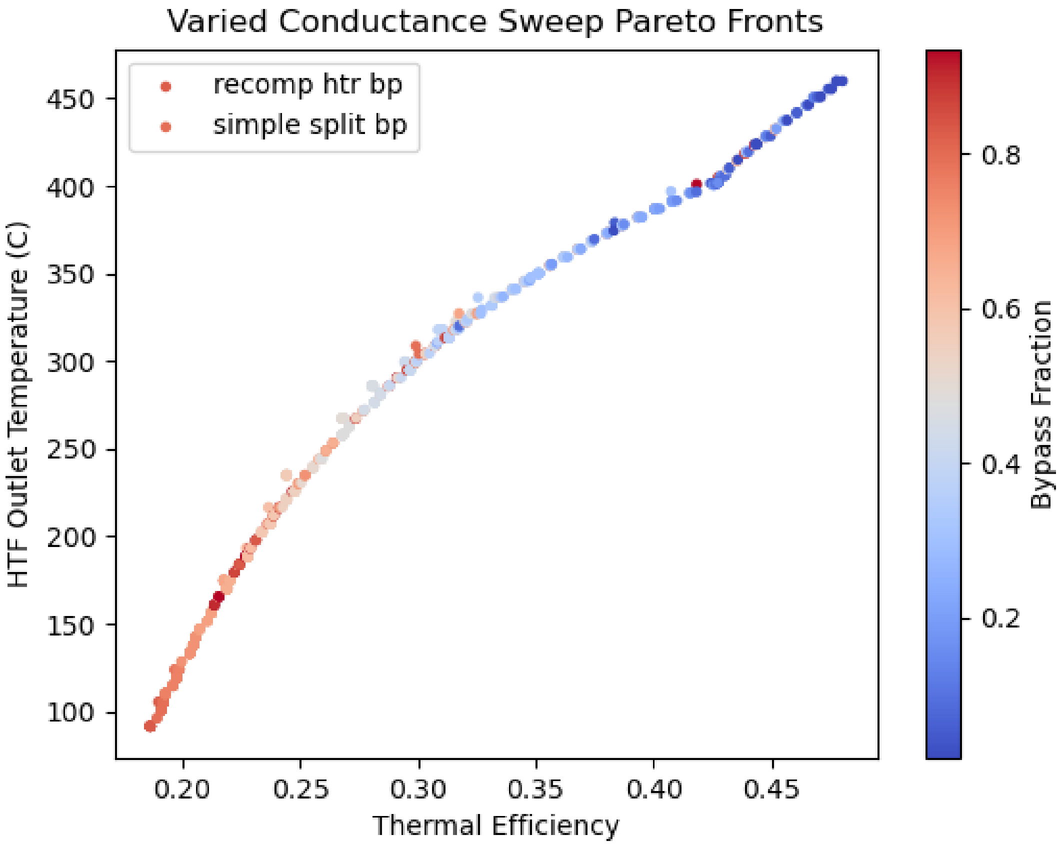
Pareto Fronts – Varied Conductance





Pareto Fronts – Varied Conductance

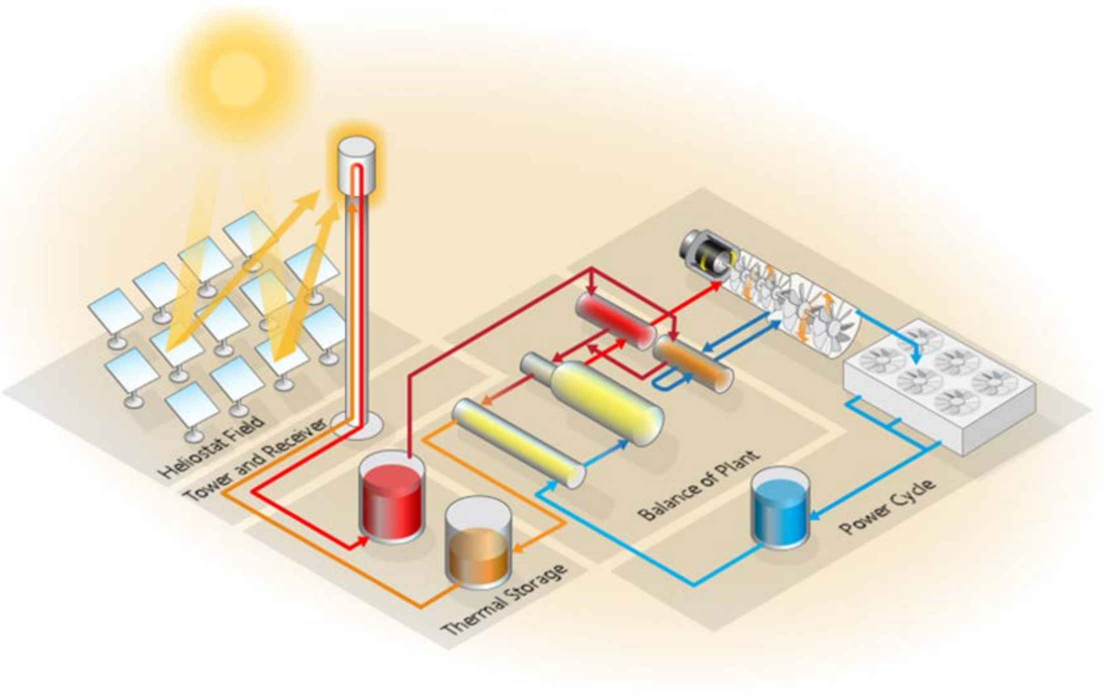




Conclusion

Future Research

- Integrate power cycles into CSP system analysis
- Optimize cycle design using system techno-economics
- Analyze more design conditions (turbo efficiency, inlet temperature, etc)
- Expand HTF temperature range for Gen3 particle applications



System Advisor Model Version 2022.11.29 (SAM 2022.11.21). National Renewable Energy Laboratory. Golden, CO. Accessed February 28, 2024. https://https://sam.nrel.gov.

References

[1] Alfani, Dario, Marco Astolfi, Marco Binotti, and Paolo Silva. "Part Load Strategy Definition and Annual Simulation for Small Size SCO2 Based Pulverized Coal Power Plant," 2020.

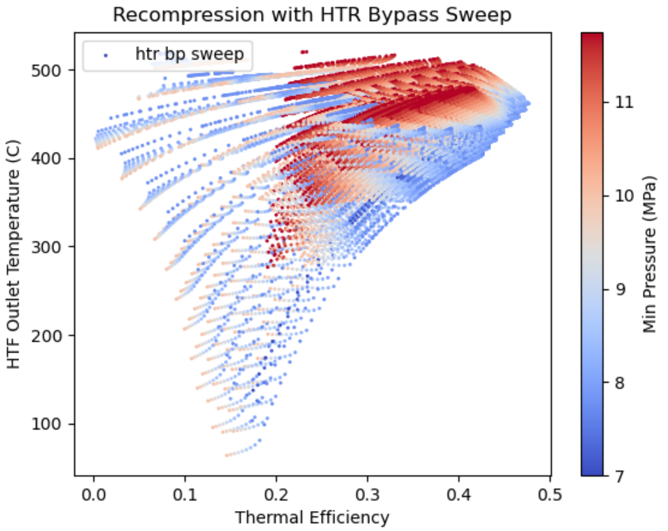
[2] Le Moullec, Yann, Zhipeng Qi, Jinyi Zhang, Pan Zhou, Zijiang Yang, Xihua Wang, Wenlong Chen, and Shuai Wang. "Shouhang-EDF 10MWe Supercritical CO2 Cycle + CSP Demonstration Project." Conference Proceedings of the European SCO2 Conference3rd European Conference on Supercritical CO2 (SCO2) Power Systems 2019: 19th-20th September 2019, October 2, 2019, 138. https://doi.org/10.17185/DUEPUBLICO/48884.

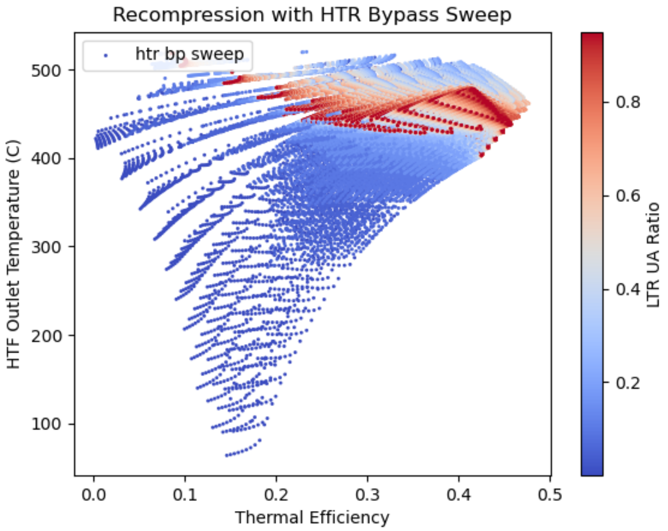
[3] Alfani, Dario, Marco Astolfi, Marco Binotti, Ennio Macchi, and Paolo Silva. "OPTIMIZATION OF THE PART-LOAD OPERATION STRATEGY OF SCO2 POWER PLANTS," 2019.

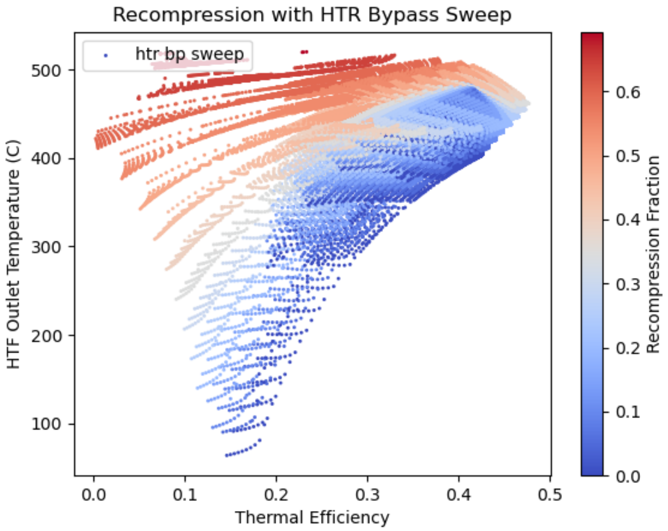
Questions

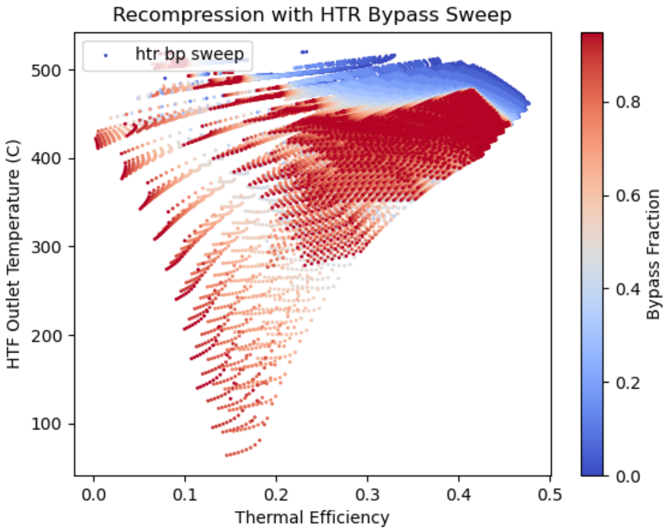
Appendix

HTR BP – Fixed UA

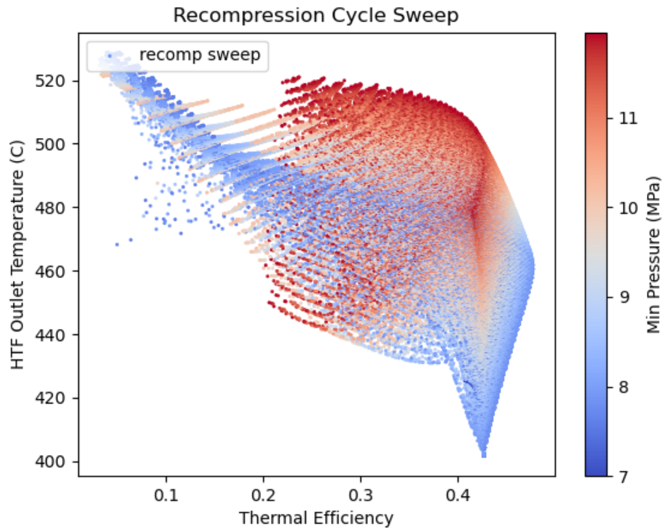


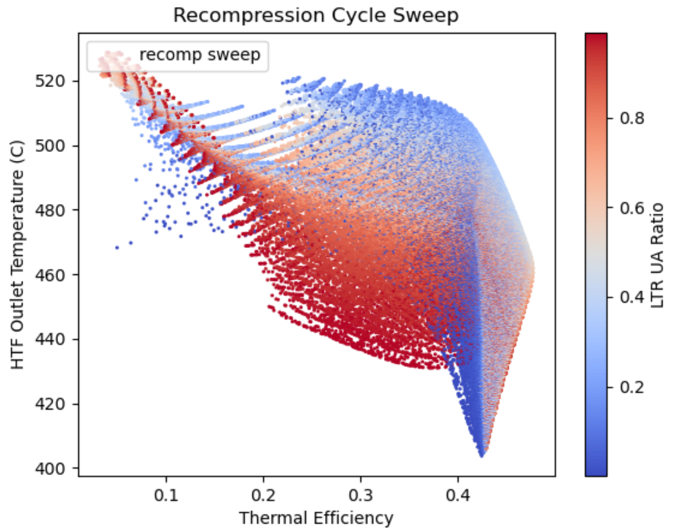


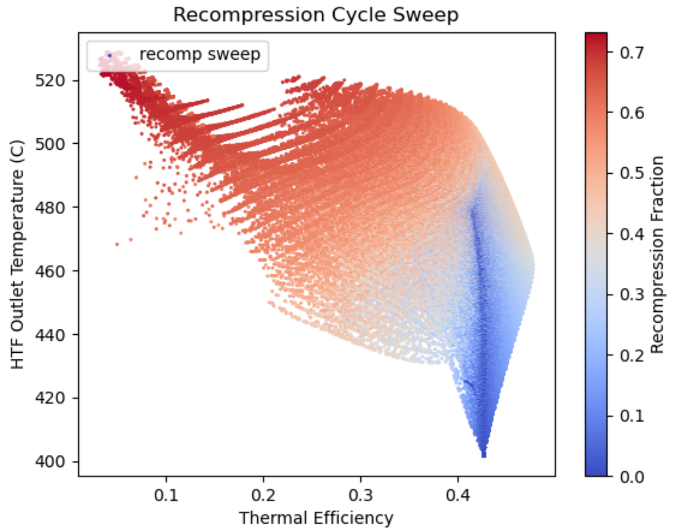




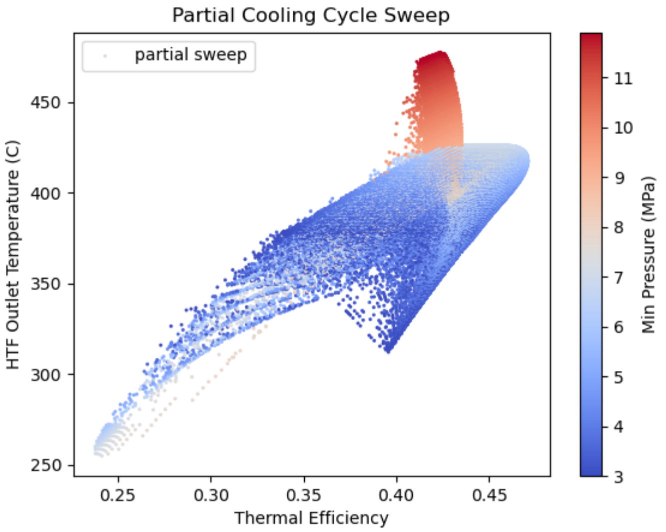
Recomp – Fixed UA

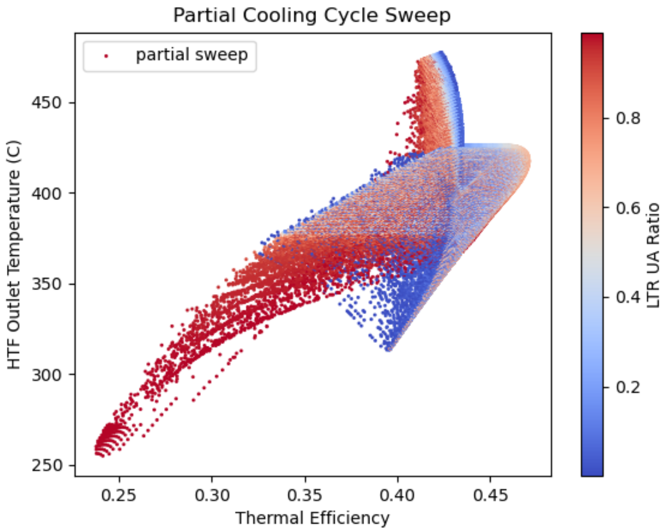


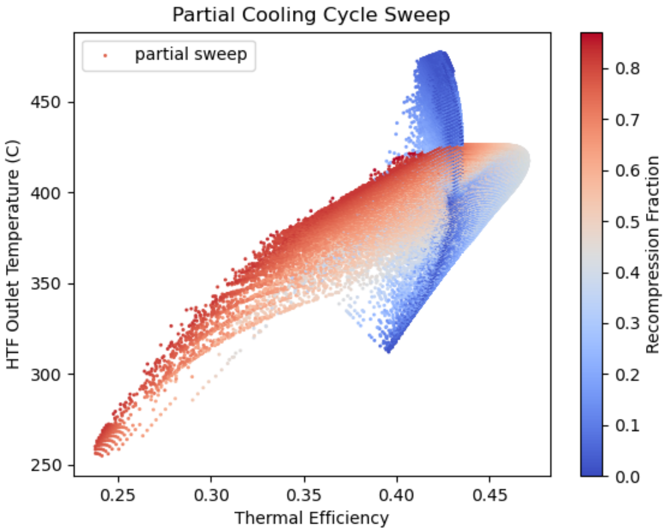




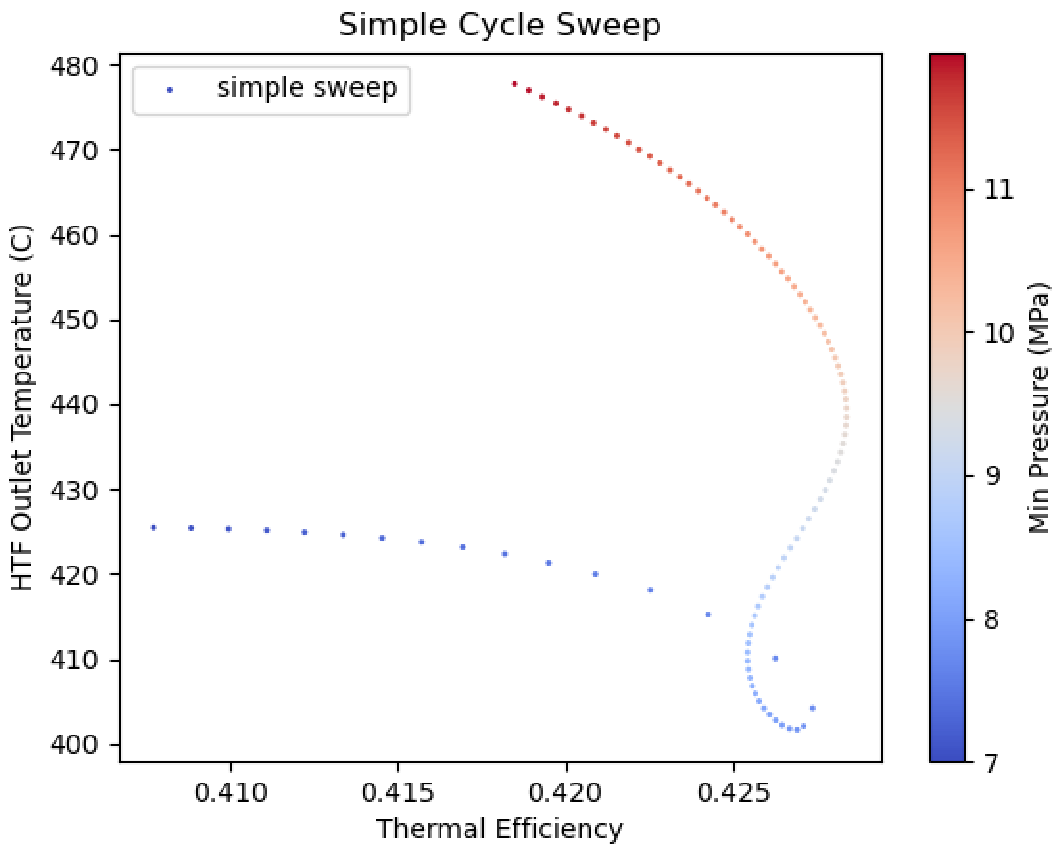
Partial – Fixed UA



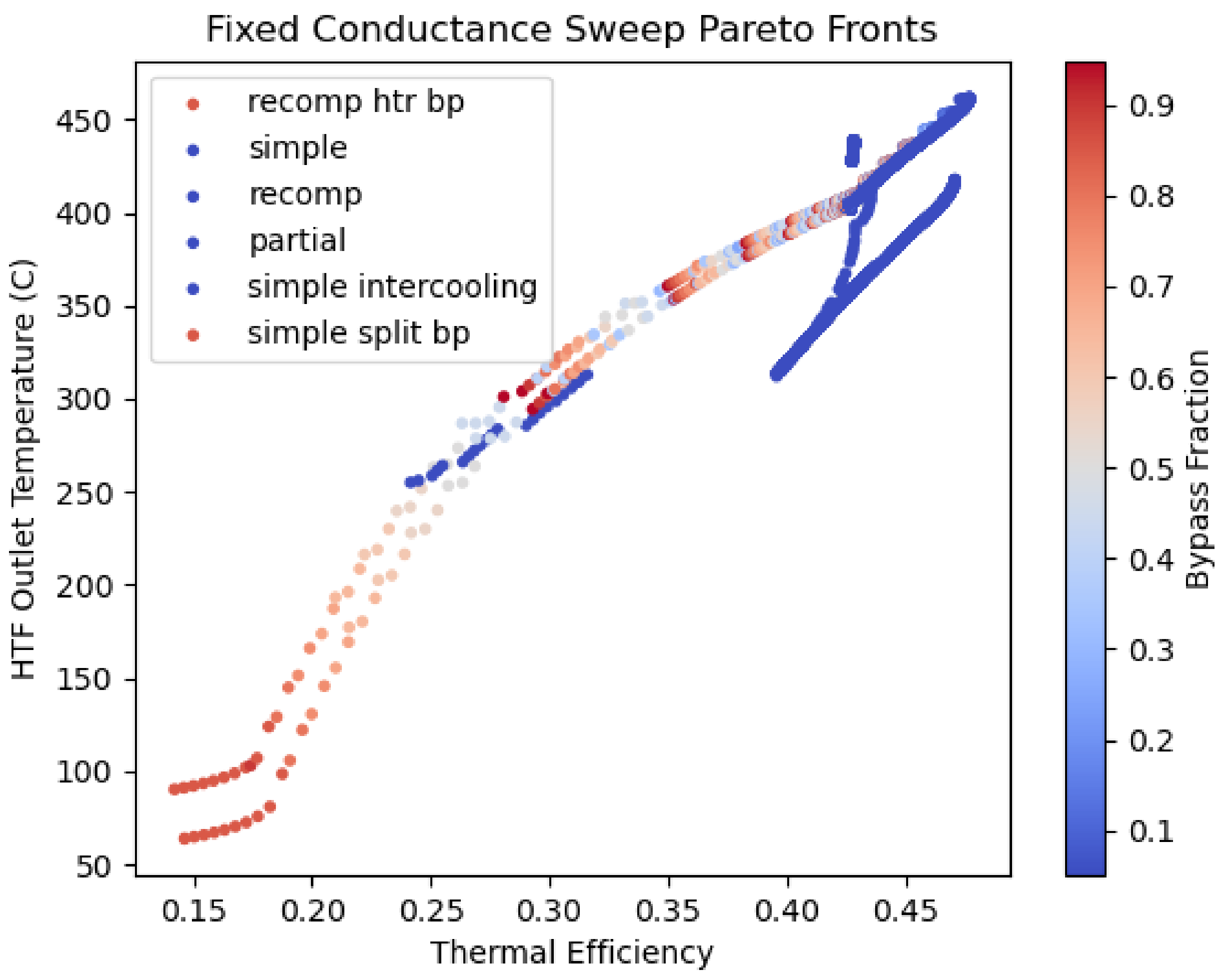




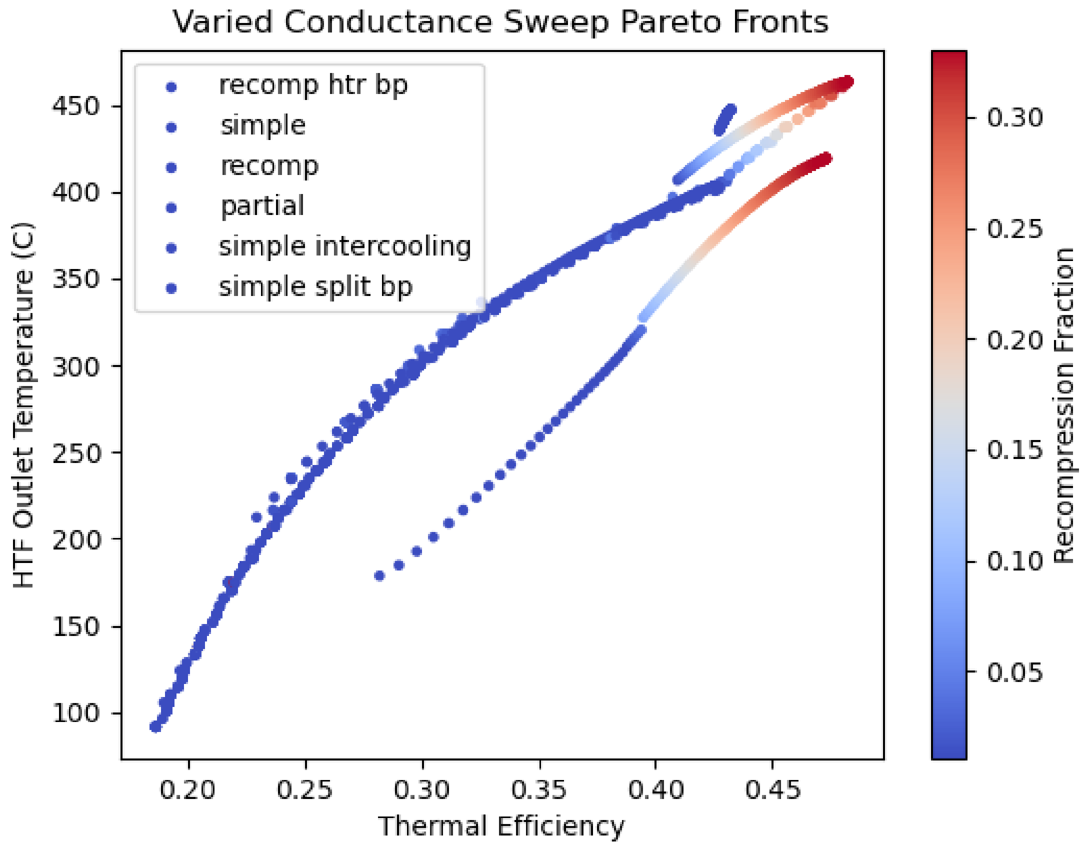
Simple – Fixed UA



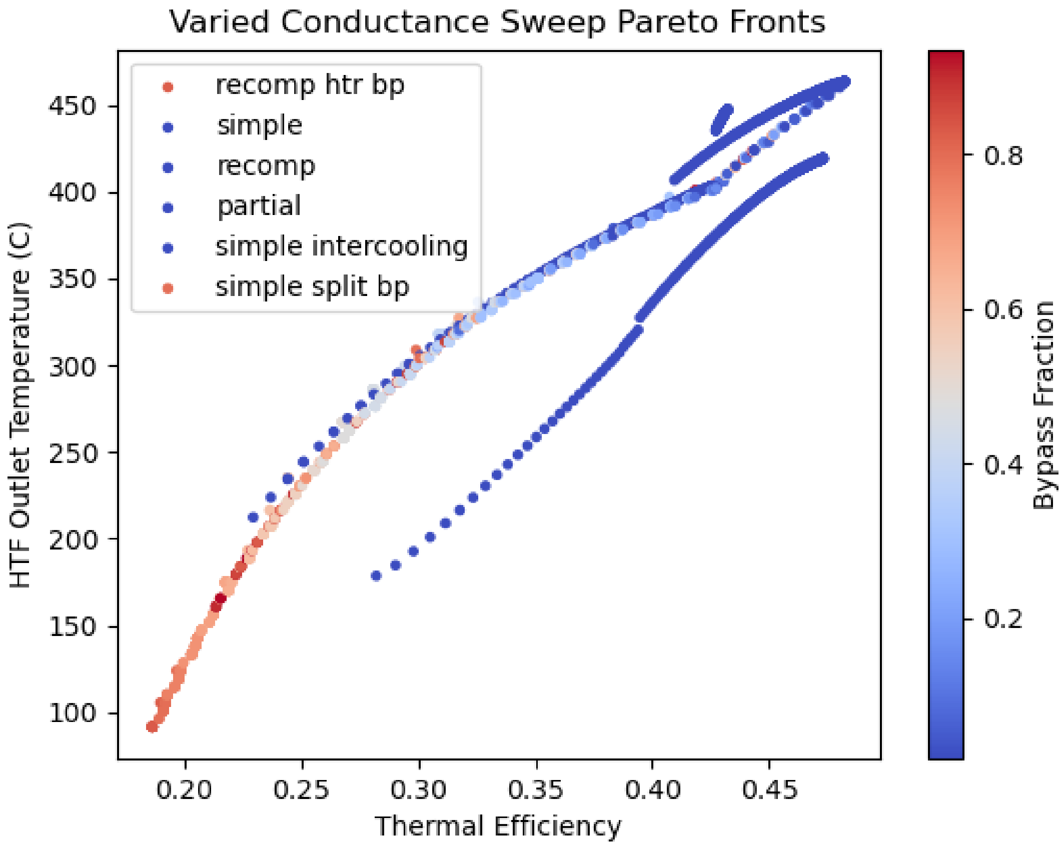
Fixed UA - Bypass



Variable UA

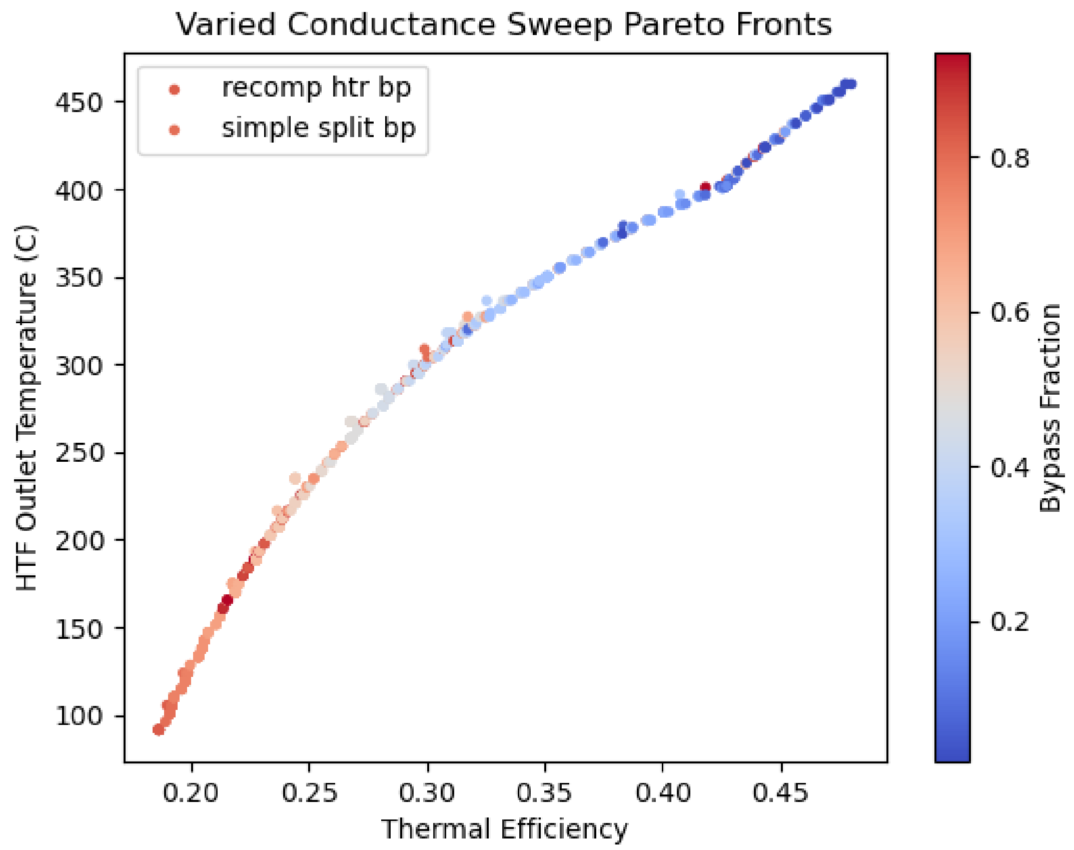


Varied Conductance Sweep Pareto Fronts
recomp htr bp
simple
recomp
partial
simple intercooling
simple split bp
HTF Outlet Temperature (C)
Thermal Efficiency
Recompression Fraction
0.20
0.25
0.30
0.35
0.40
0.45
100
150
200
250
300
350
400
450
0.05
0.10
0.15
0.20
0.25
0.30



Varied Conductance Sweep Pareto Fronts
recomp htr bp
simple
recomp
partial
simple intercooling
simple split bp
HTF Outlet Temperature (C)
Thermal Efficiency
Bypass Fraction
0.20
0.25
0.30
0.35
0.40
0.45
100
150
200
250
300
350
400
450
0.2
0.4
0.6
0.8

Variable UA



Varied Conductance Sweep Pareto Fronts
recomp htr bp
simple split bp
HTF Outlet Temperature (C)
450
400
350
300
250
200
150
100
0.20
0.25
0.30
0.35
0.40
0.45
Thermal Efficiency
Bypass Fraction
0.8
0.6
0.4
0.2