Multi-Objective Cycle Optimization of an Integrally Geared Waste Heat Recovery Unit for a Combined Cycle Power System

Kevin Hoopes, Ball Aerospace

Michael Marshall, Southwest Research Institute

Robert Pelton, Hanwha Power Systems America

Jonathan Bygrave, Hanwha Power Systems America

Overview

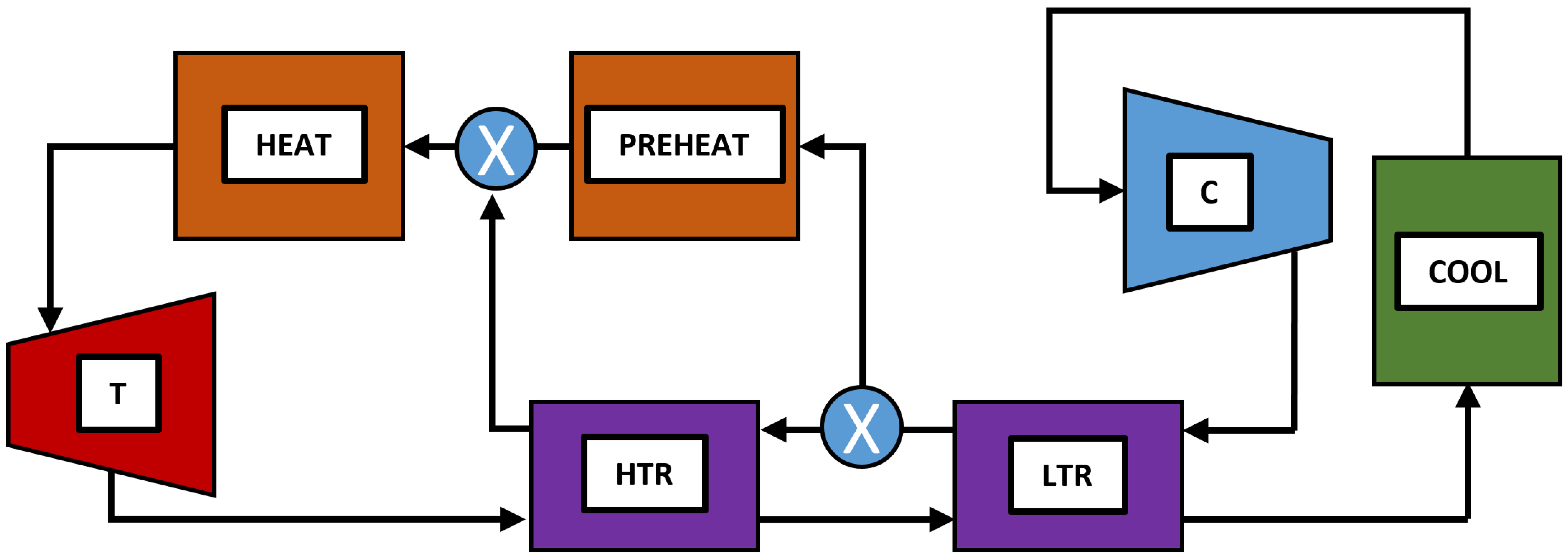
- The goal of the project supported by the DOE and industry partners is to combine a commercially available gas turbine, Solar Turbines Titan 130, with a compact, skidded, sCO_2-based WHRU to form a combined cycle power system.
- An optimization process established the maximum annual energy output attainable for a range of initial capital cost investments for a given installation location.

Background

- Natural gas turbines, installed at compression stations, are not typically coupled with Waste Heat Recover Systems (WHRS) due to:
  - Size
  - Complexity
  - Cost
- A sCO_2 cycle that can improve over traditional ORC in these areas can allow the facility to use the power produced for onsite needs or sell it back to the grid.

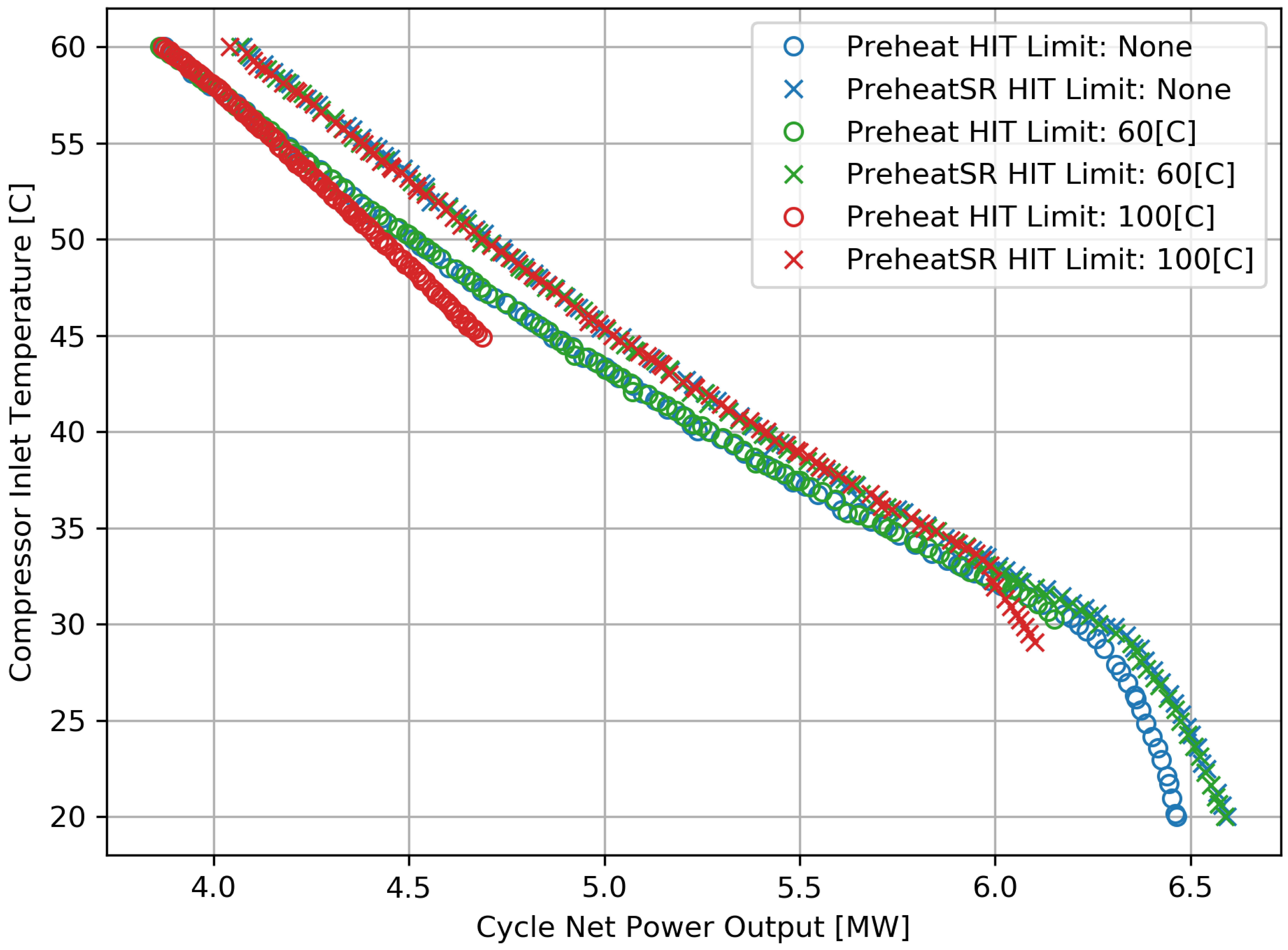
The PreheatSR Cycle

- A preheating cycle is able to maximize extraction of the waste heat from the turbine.
- To prevent acid dew point corrosion in the heater assembly, the recuperator is split so that the preheat inlet temperature is above the lower limit.



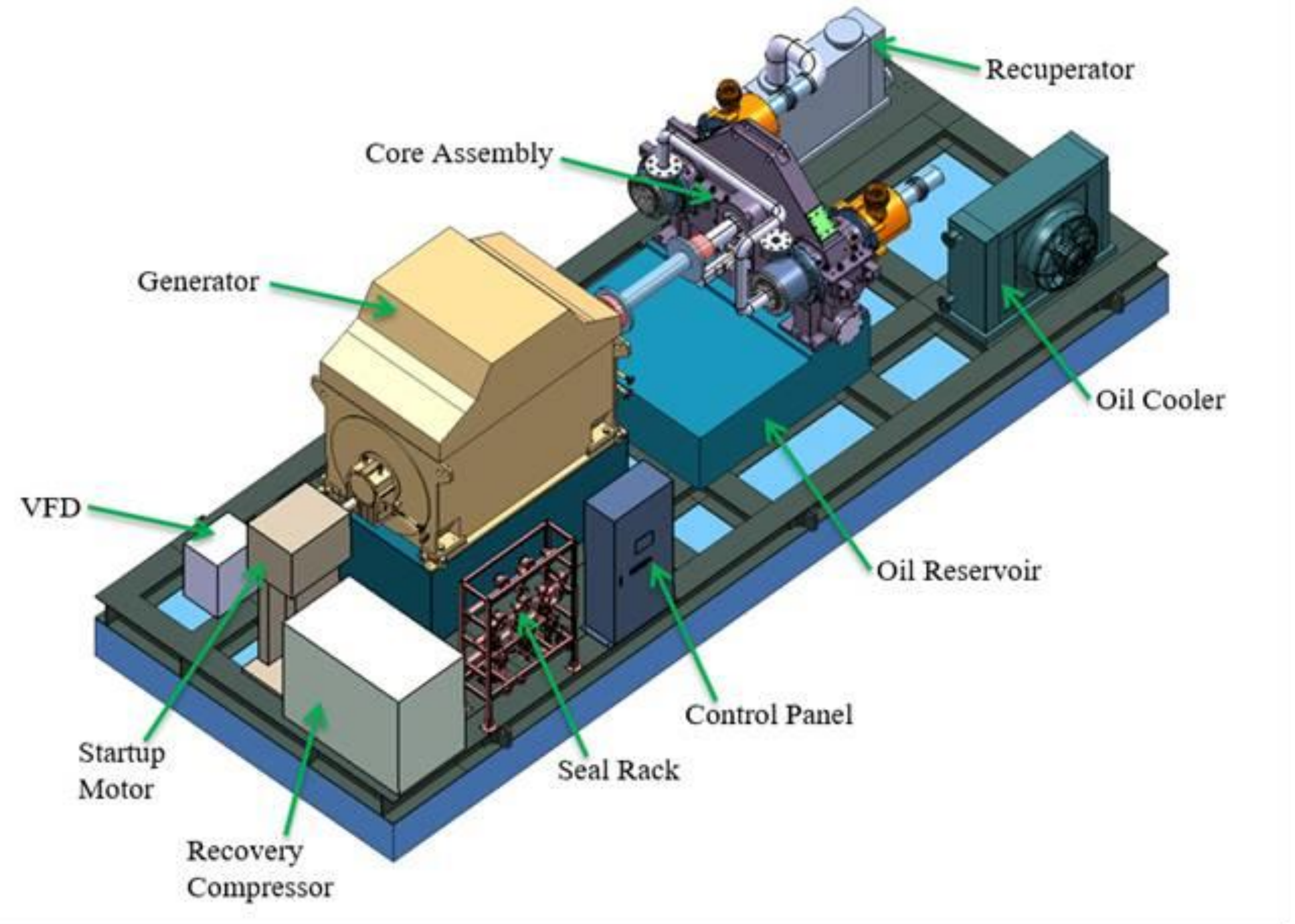
PreheatSR Cycle provides increased performance with acid dew point limits.

- The LTR allows for a low compressor inlet temperature while still meeting heater inlet temperature limits.
- The PreheatSR cycle provides 7% higher power output that the conventional Preheat cycle at the same HIT limit.



The PreheatSR is packaged on a skid featuring an IG machine from Hanwha Power Systems.

- The overall size is conducive to truck shipment.
- The DOE Apollo program has executed successful tests of the integrally geared machine.
- With a low TIT, separate LP and HP pinions can be used. The use of stainless steel can drive down costs.



Additional components include the heater and cooler assembly.

- An air cooler assembly will have multiple bays employing forced convection through a series of fans that include VFD controllers, allowing for optimal net energy output based on ambient condition.
- The heater assembly is similar to a heat recovery steam generator (HRSG), ducting exhaust flow over tubing containing CO_2.
- The main heater section nearest turbine exhaust sees full cycle mass flow, while the downstream preheater section sees partial flow rate.

The optimization process is made up of two layers.

Outer Optimization

Givens: Cycle layout, operating site temp profile

Objectives: Minimize cost, maximize energy out

Constraints: CO_2 > 60 C into Heater

Fitness function input variables:

- Design low pressure
- Design high pressure
- Design heater eff.
- Design ambient air T
- Design cooler eff.
- Design recuperator eff.
- Design cycle massflow
- Design flow split
- Design air massflow

Fitness function output variables:

- Configuration cost
- Yearly energy out

Inner Fitness Function

Optimizes cycle performance for a series of ambient temperatures and integrates that to get overall yearly energy out. Calculates CAPEX from component cost correlations.

Givens: Cycle design variables, GT operating profile, site temp profile

Objectives: Maximize cycle performance for series of ambient temperatures.

Constraints: CO_2 above critical P and T at compressor inlet.

Inner fitness function input variables for each ambient T:

- Cooler air flow rate
- Flow split
- Cycle massflow

Inner fitness function output variables at each ambient T:

- Energy out

Inner Fitness Function Output:

- CAPEX cost from cost correlations
- Integrated yearly performance from series of ambient T optimizations

Off-design evaluations are carried out with NPSS

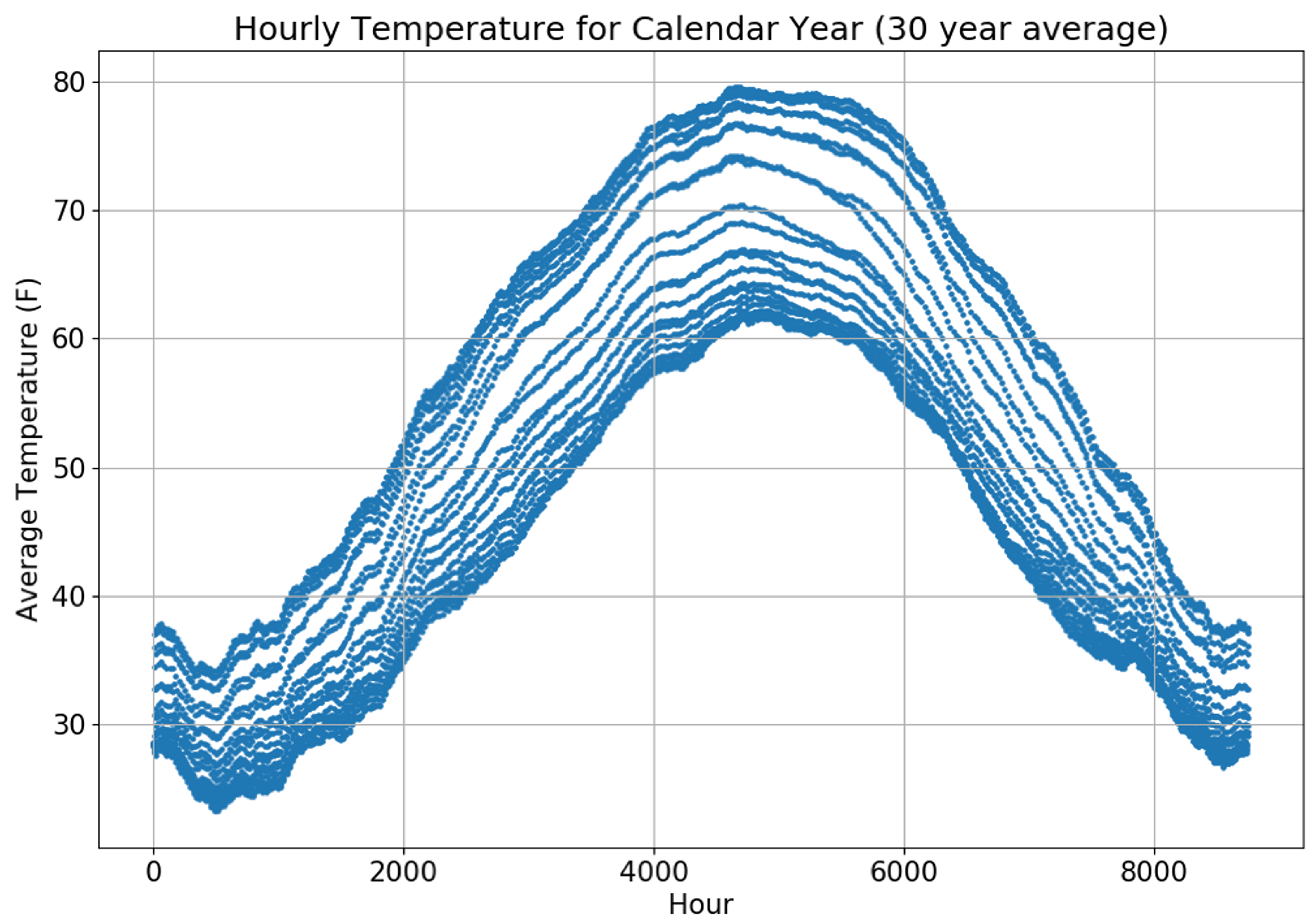
- Numerical Propulsion System Software (NPSS) is a legacy air-breathing engine analysis tool that performs well for closed loop power cycle analysis.
- The heat exchangers use a discretized conductance ratio method to scale performance from design to off-design.

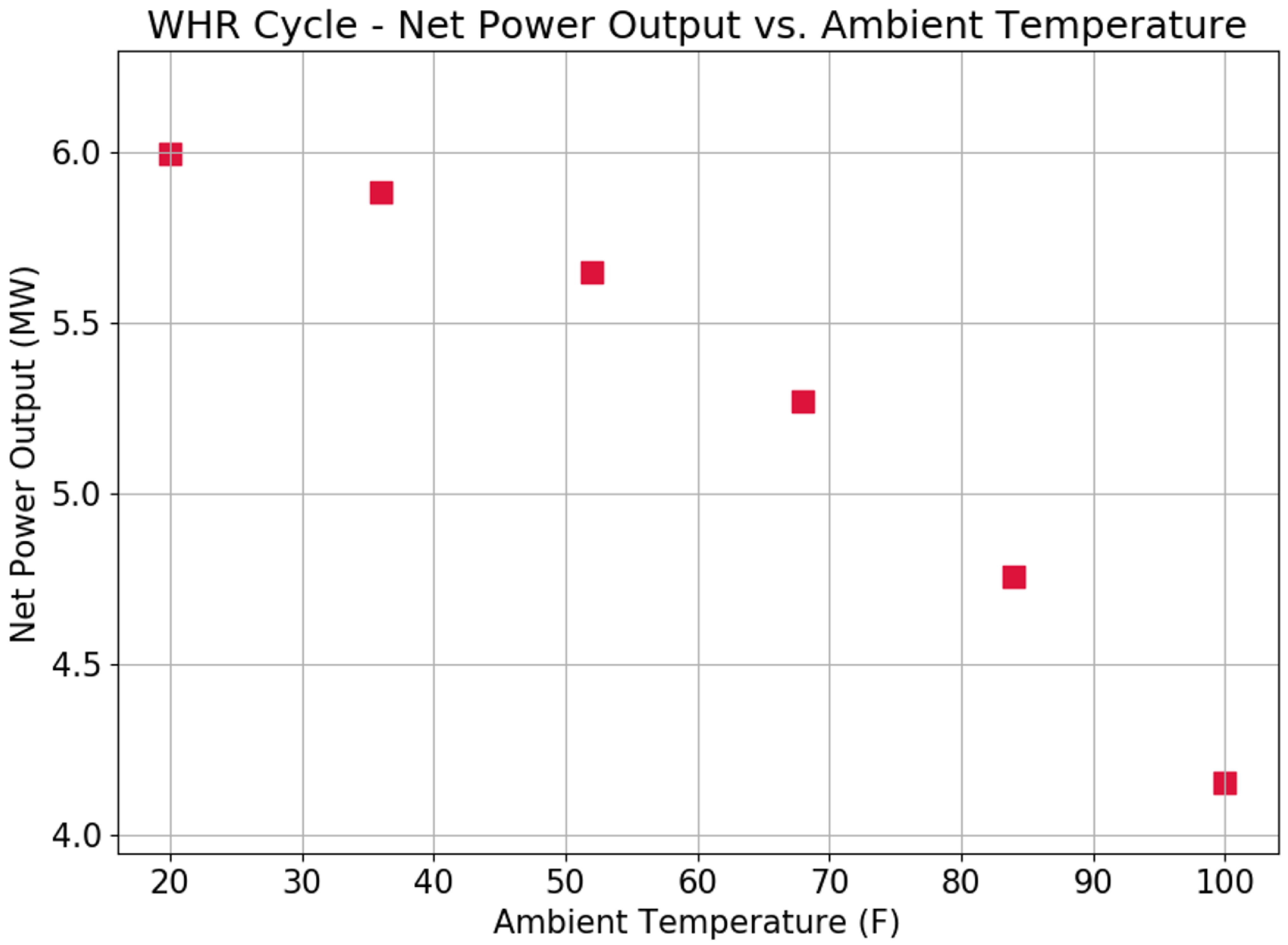
$$U = \frac{hA_1}{hA_2}$$

- HPSA sizing and performance methods allow design conditions to set the sizing of turbomachinery, and scaling performance maps for off-design interpolation.

Calculation of yearly energy output

- The highest net power outputs from off-design case matrix forms a net power output vs. ambient temperature plot.
- This is integrated with over hourly weather data for a gas processing plant in WV using Simpson's rule for interpolation.

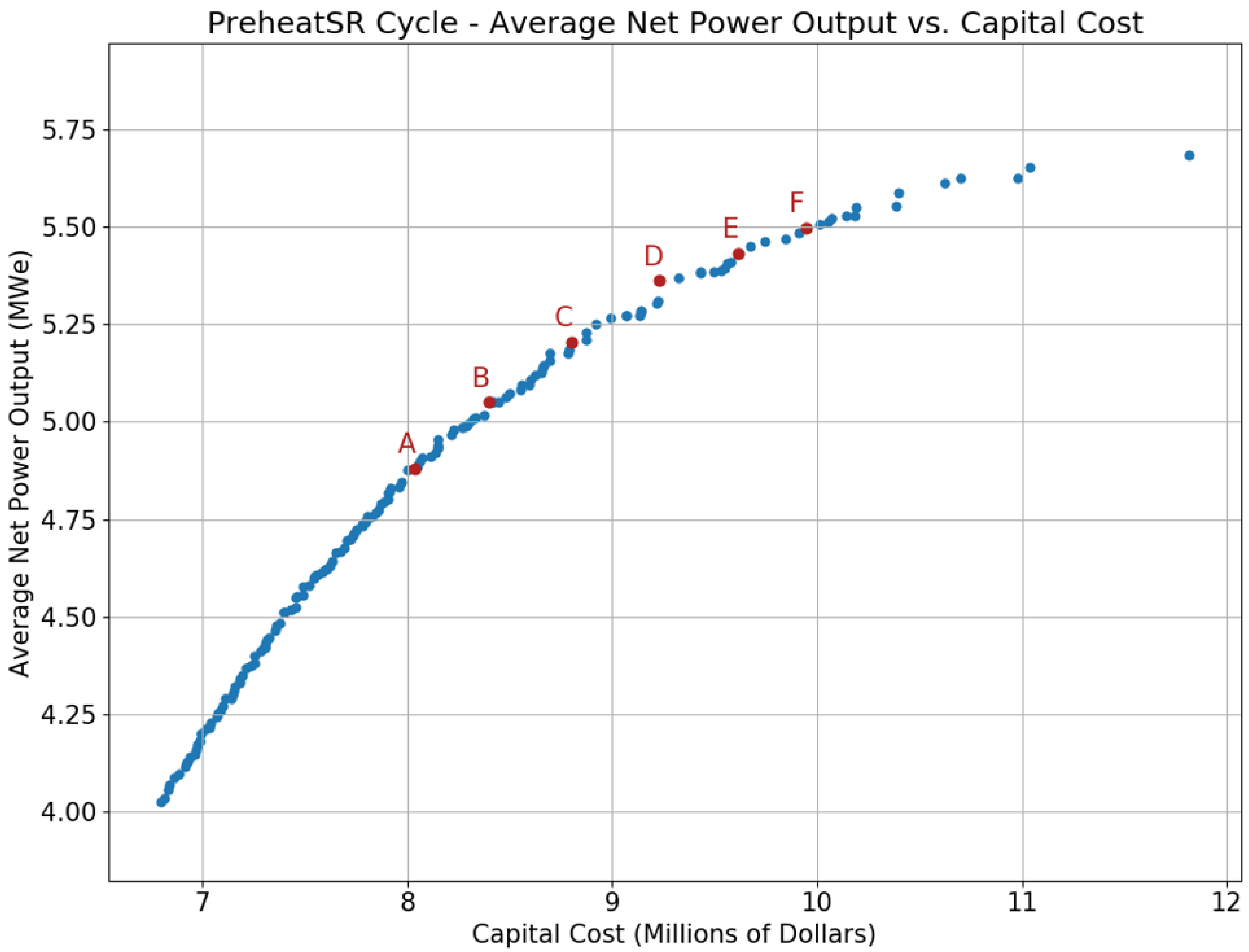


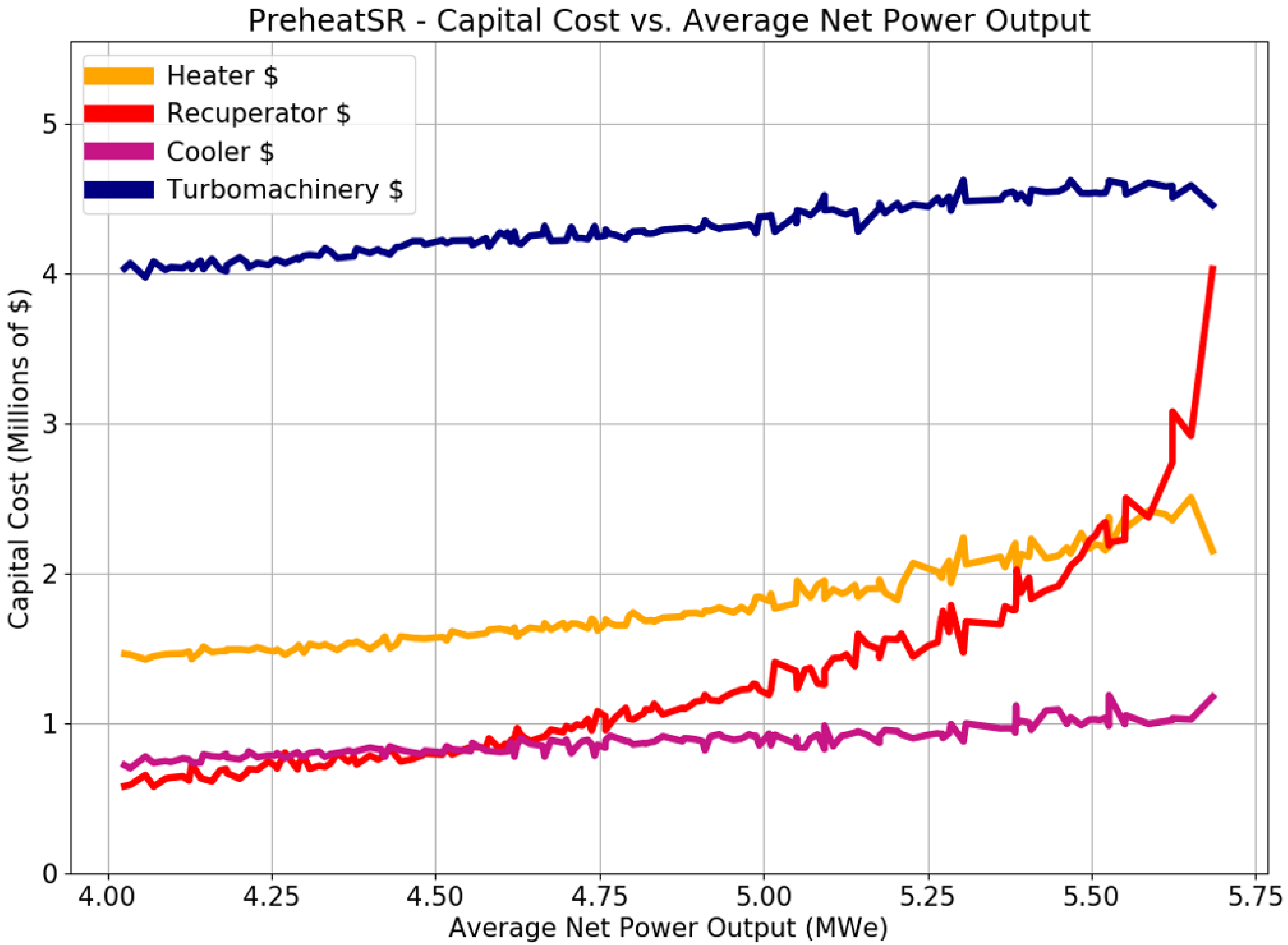


Cost information is derived from multiple sources.

- Turbomachinery and full skid system cost is informed by HPSA production experience and is based on the following variables:
  - Operating temperature and pressure
  - Mass flow
  - Stage count
- Recuperator and cooler cost is based on those functions derived by Weiland et al. (2019), with UA serving as the independent variable.
- Heater quotes received for the multi-stage heat recovery unit at multiple approach temperatures used to form its cost relationship.

A pareto front is formed with 160 unique candidate designs.

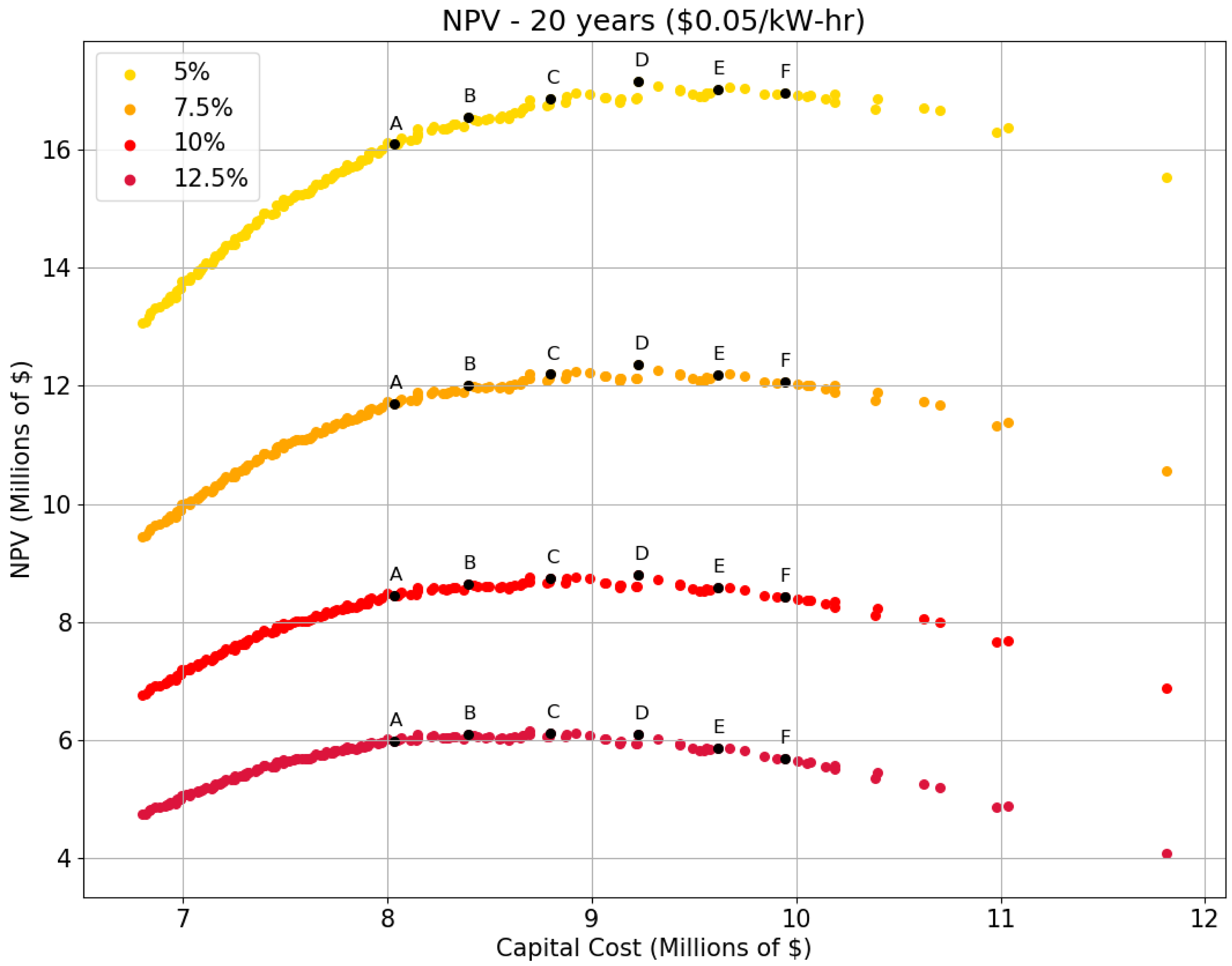




A techno-economic analysis is required to narrow down to a single design.

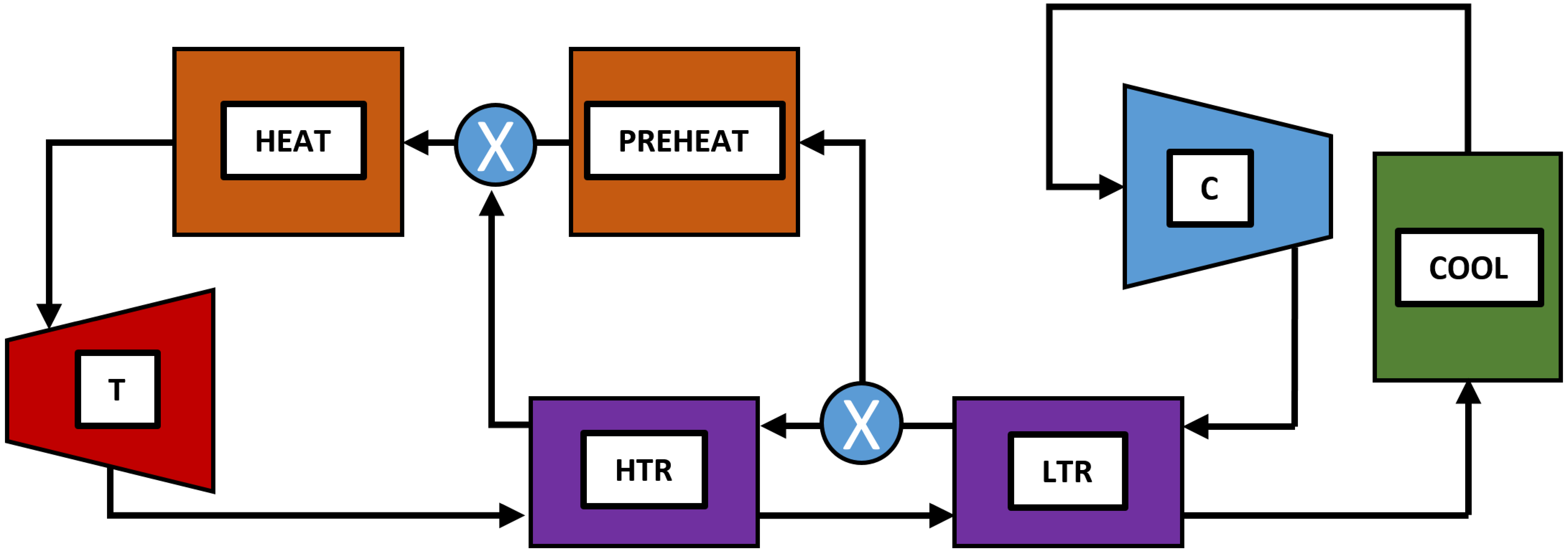
- The calculation of net present value (NPV) evaluates the profitability of investment in a WHRU.
- The following assumptions are made about the operational profile and market conditions:
  - Power can be sold back to the grid at a wholesale rate of $0.05/kW-hr
  - Titan 130 gas turbine load is 70%
  - WHR unit runs 24/7/365
  - Each year includes a maintenance and operation cost of 2.5% of the capital cost

Different discount rates can lead to different designs being selected.



Selected design point parameters for design D.

Compressor Inlet Temperature [C]	32.1
Compressor Inlet Pressure [bar]	89.3
Compressor Discharge Pressure [bar]	252.7
Turbine Inlet Temperature [C]	344.8
Ambient Temperature [C]	17



Conclusions

- The preheatSR cycle allows for high energy recovery while requiring limited complexity and mitigates acid dew point concerns.
- The optimization’s inner process paints a full picture of yearly energy recovery by taking into account the ambient temperature variation and using off-design methods for component performance.
- The optimization’s outer process defines the cost-performance relationship and pinpoints cost drivers.
- The NPV analysis directly pinpoints the cycle design most economical, with test proven components.

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QUESTIONS