Advanced Gas Turbine and sCO2 Combined Cycle Power System

UTSR Meeting

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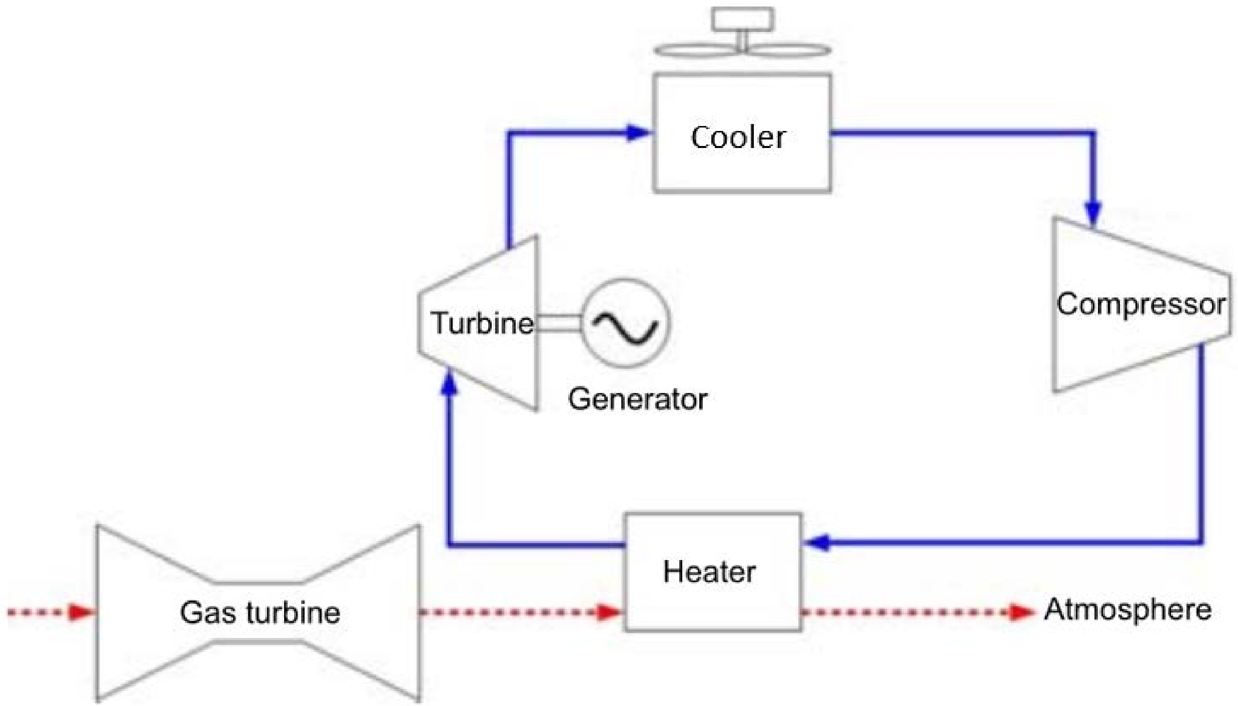
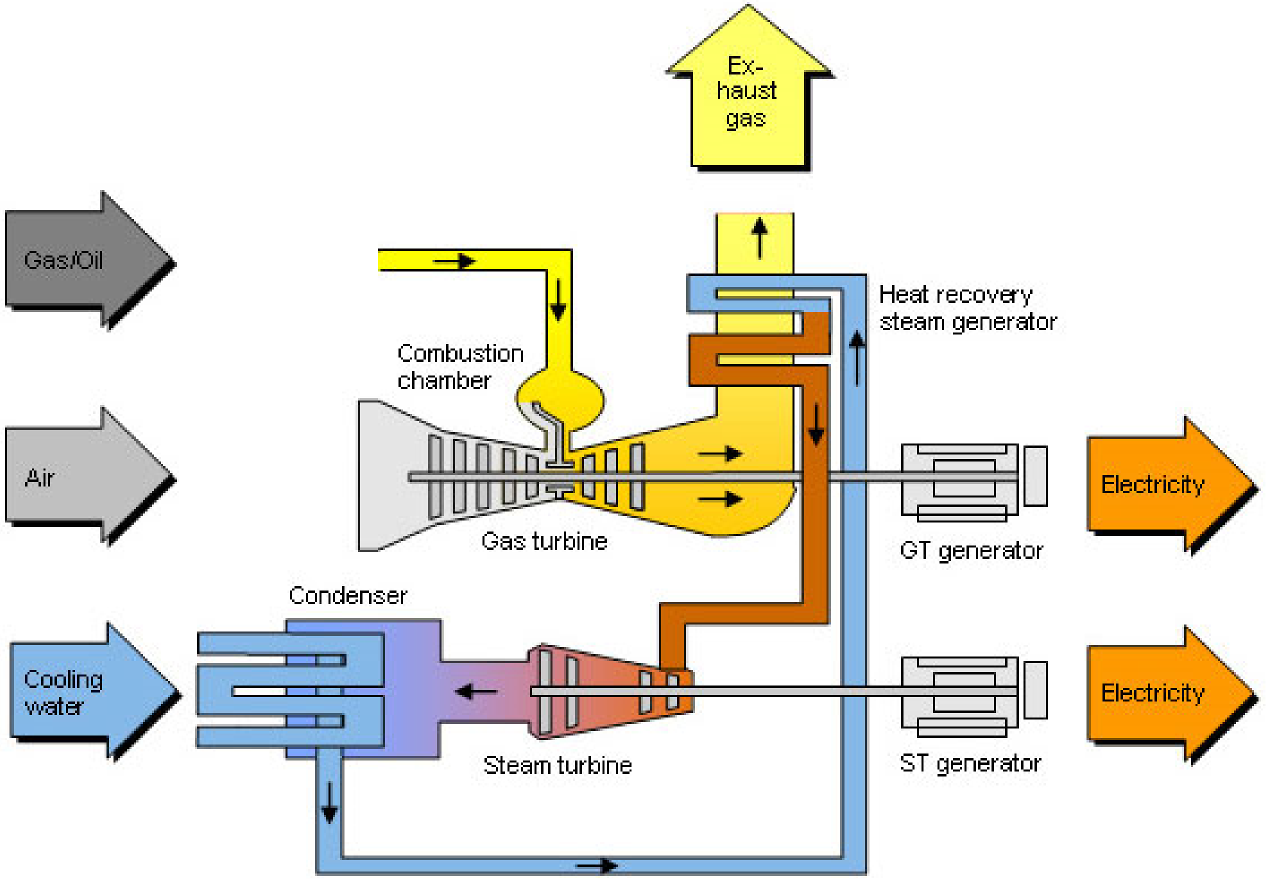


Project background and motivation: Large scale combined cycles



Schematic of large scale Combined Cycle Gas Turbine power plant from Siemens. Large scale plants of this type can be upwards of 300 MWe.

Modern gas turbines are highly efficient with thermal efficiencies between 30 and 45%.

To drive overall efficiency even higher, large gas turbine power plants use a Waste Heat Recovery System (WHRS), also called a bottoming cycle, to extract otherwise wasted heat from the gas turbine exhaust.

This combination of primary and bottoming cycles is called a Combined Cycle Gas Turbine or CCGT.

For large CCGT plants a steam Rankine WHRS is typically used. The addition of this WHRS allows for overall plant thermal efficiency to reach nearly 63% in modern, large, utility scale plants.

Project background and motivation: sCO_2 small scale combined cycle

Solar Turbines gas turbines and gas compressor at a Spectra Energy natural gas compression station.

WHR systems are not typically added to smaller gas turbines due to:

- Size
- Complexity
- Initial capital cost
- On site water requirements

A WHR system based on super critical CO2 (sCO2) as a working fluid could address all of these issues.

This project will develop an advanced WHR cycle using sCO2 as a working fluid and create a conceptual design of a complete WHR system applicable to existing gas turbine installations. This WHRS will be:

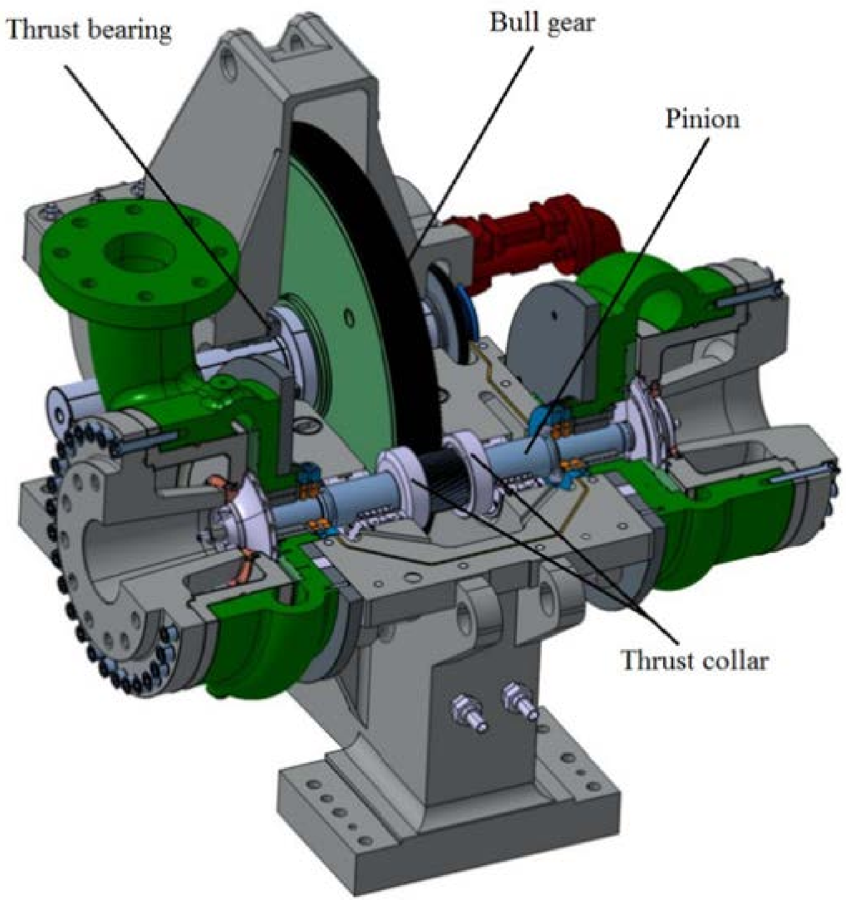
- Highly efficient
- Modular and skidable
- Compatible with air cooling
- Allow for advanced load following

WHRS Development Technical Path

WHR development used the following technical path:

1. Choose target Gas Turbine
2. Choose cycle configuration
3. Optimize cycle component operating points
4. Conceptual cycle component design

Project background: Integrally-Geared turbomachinery



Single pinion integrally-geared compressor from Hanwha Power Systems

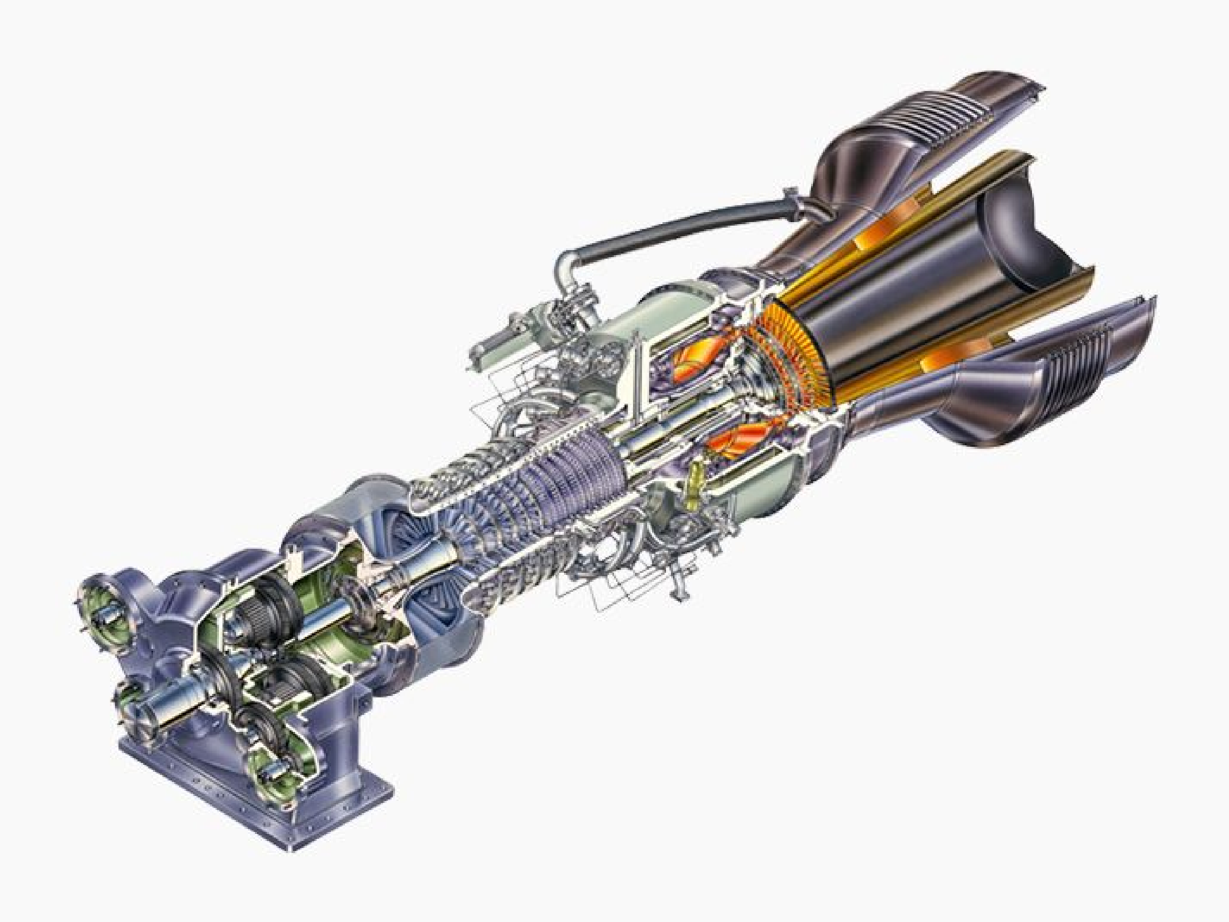
In order to further increase efficiency and compactness, the WHRS will use integrally-geared turbomachinery.

An integrally-geared machine consists of a central bull gear connected to one or more pinion shafts which contain one or two impellers each. These impellers can be radial compressors or radial turbines.

Integrally-geared machines have the following benefits:

- Independent pinion speeds increase overall machine efficiency by allowing optimized aero matching
- Easy access to the process gas between stages for intercooling and or reheating
- Stage access allows for each stage to have variable IGVs for better control
- Compactness

Solar Turbines Titan 130

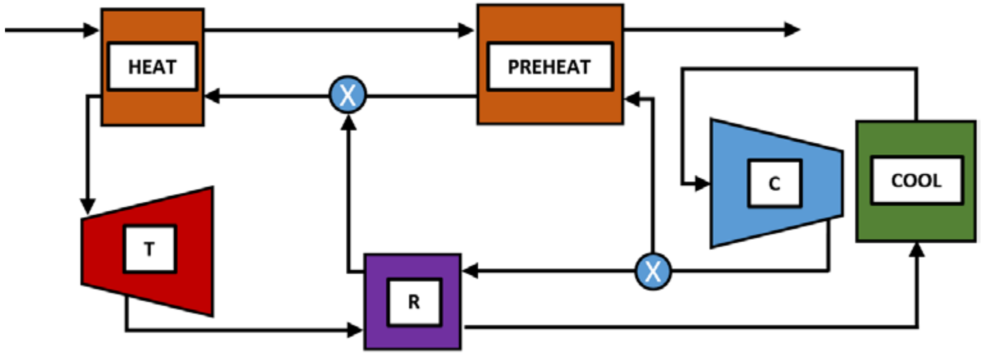


Schematic of a Solar Turbines Titan 130 which produces 16.5 MWe

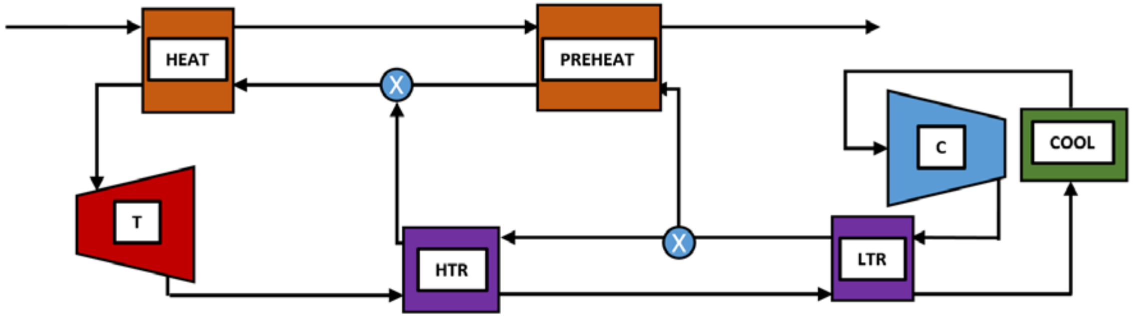
The Solar Turbines Titan 130 was chosen as the target gas turbine because:

1) The size of the Titan 130 is ideal for applying a sCO2 WHRS that uses integrally geared turbomachinery
2) There are over 850 Titan 130s installed around the world.
3) Solar Turbines has confirmed that there is significant demand for this size of gas turbine and this is likely to continue.
4) While larger gas turbines are generally more thermally efficient, there is a smaller installed base and so the numbers of WHRSs required will be less.
5) The Titan 130 has been tested with alternative fuels such as coal derived syngas.

Preheat Cycle



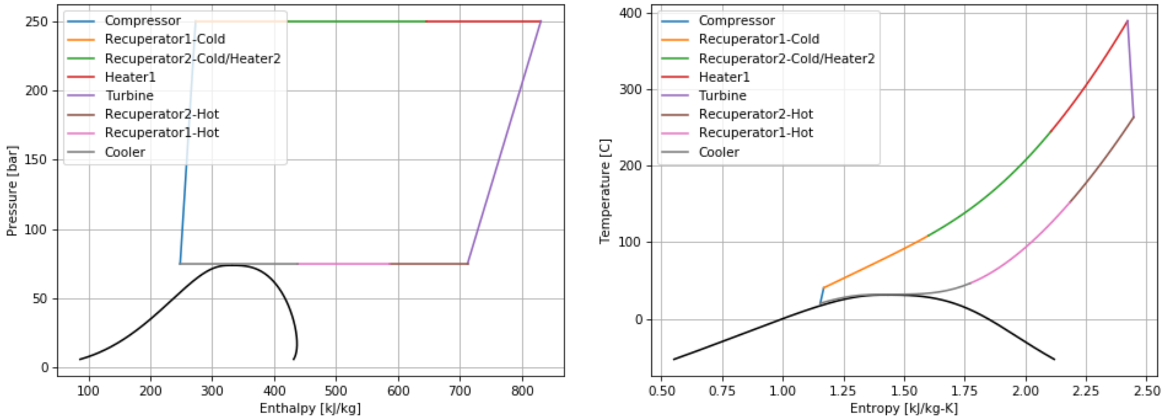
Preheat cycle



Preheat cycle with split recuperator (PreheatSR)

Preliminary analysis showed that the preheat cycle is an excellent choice for Waste Heat Recovery applications as it allows for good recuperation along with high energy extraction from the waste heat stream while minimizing complexity.

If the cycle is modified by splitting the recuperator it is suitable for a wide range of gas turbine fuels (natural gas, coal derived syngas, hydrogen, etc.) which have different acid dew point temperatures. This could take the form of two separate recuperators or a monolithic recuperator with an additional side stream outlet.



Typical PreheatSR cycle Ph/Ts diagram

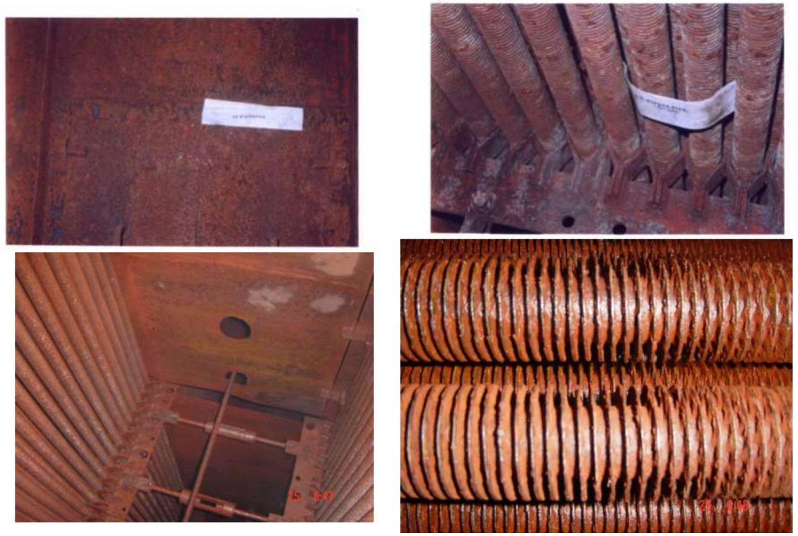
Acid Dew Point Corrosion

Gas turbine exhaust can contain Sulphur and other contaminants, if the temperature of the stream drops too low these can condense into liquid acid droplets and cause corrosion in the coldest end of the flue gas / CO2 heat exchanger (cold CO2 inlet). HRSGs are also susceptible to this.

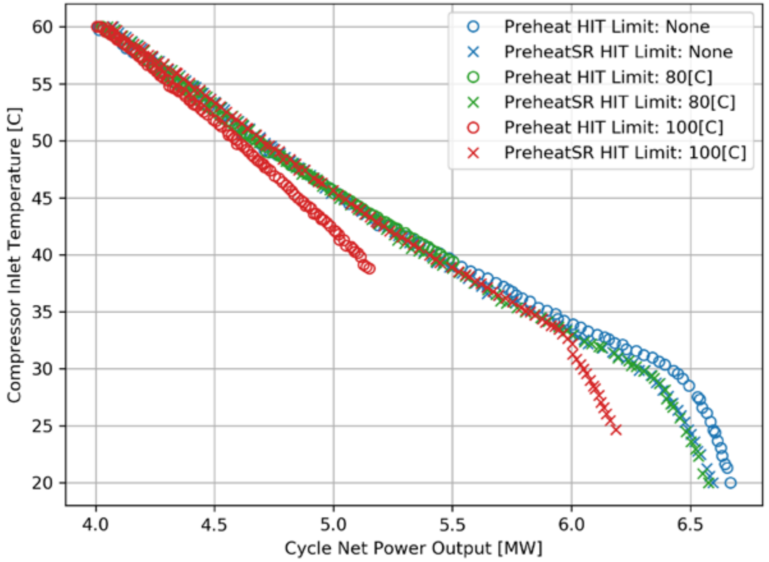
For “clean” pipeline natural gas, 60[C] is a standard industry limit for HRSGs. For coal derived syngas the acid dew point temperature rises to above 100[C] which limits the extractable heat from the waste heat stream.

The preheat cycle with a split recuperator can be configured for any Heater Inlet Temperature (HIT) limit and is therefore adaptable to any gas turbine fuel. There is a loss in performance, but it is small (2.5% for 100[C] limit).

With the split recuperator the cycle outperforms the standard preheat cycle without an HIT and does much better with an HIT imposed



Typical HRSG acid corrosion (from NETRA)



Comparison of standard Preheat and Preheat with split recuperator (PreheatSR)

SwRI Hanwha Power Systems Solar Turbines A Caterpillar Company Williams

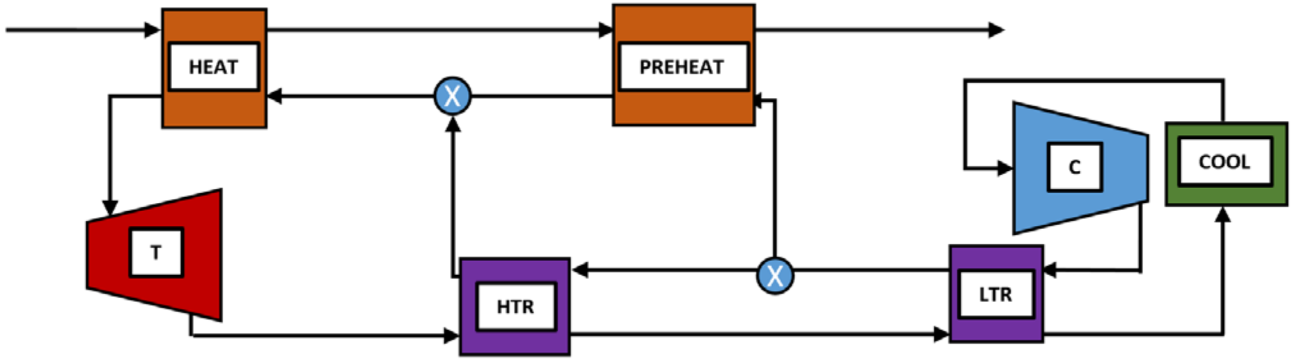
Cycle Optimization

With a cycle selected, the cycle component operating points / design points must be selected.

- What ambient temperature should we use for the cycle design point?
- Where should we place the design point for optimal operation throughout the year?
- What approach temperatures/effectiveness should we choose for the cooler, heater, recuperators?

To address this, we used a multi-objective optimization routine to explore the cycle design space.

The goal of the optimization was to produce a series of designs to maximize cycle performance while minimizing cycle capital cost.



PreheatSR Cycle

Optimization Routine

- The goal is to produce a Pareto front of capital cost vs cycle performance to select a cycle design point.
- Two nested optimization routines are used. The outer optimization works with design parameters while the inner routine optimizes how the machine is run throughout a year at off-design ambient conditions.

Outer Optimization

Givens: Cycle layout, operating site temp profile

Objectives: Minimize cost, maximize energy out

Constraints: CO_2 > 60 C into Heater HX inlet (acid)

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 then integrates that performance to get overall yearly energy out. Also calculates CAPEX from component cost correlations.

Givens: Cycle design variables, GT operating profile, site ambient T 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

Outer fitness function details

The inner fitness function follows the following procedure:

1. Obtain design variables to evaluate from outer optimizer
2. Choose series of ambient temperatures (6)
3. Optimize operating points at each ambient temperature to maximize power output using off-design models for cycle components
   - Vary cycle massflow, cooler air flow, and flow split
   - Find best combination which yields max power at each ambient temperature
4. Create net power out vs ambient temperature curve from optimized points
5. Interpolate net power out vs temperature and site ambient temperature data to create power vs time for the whole year at the target site
6. Integrate power vs time to get net energy produced for the entire year
7. Compute capex cost using cost functions for the set of design variables
8. Return net energy and capex to outer optimizer

For this method, off-design performance models and cost models are needed for each component.

Component Cost/Off-Design Models

Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition
GT2019
June 17-21, 2019, Phoenix, Arizona, USA

GT2019-90493

SCO2 POWER CYCLE COMPONENT COST CORRELATIONS FROM DOE DATA SPANNING MULTIPLE SCALES AND APPLICATIONS

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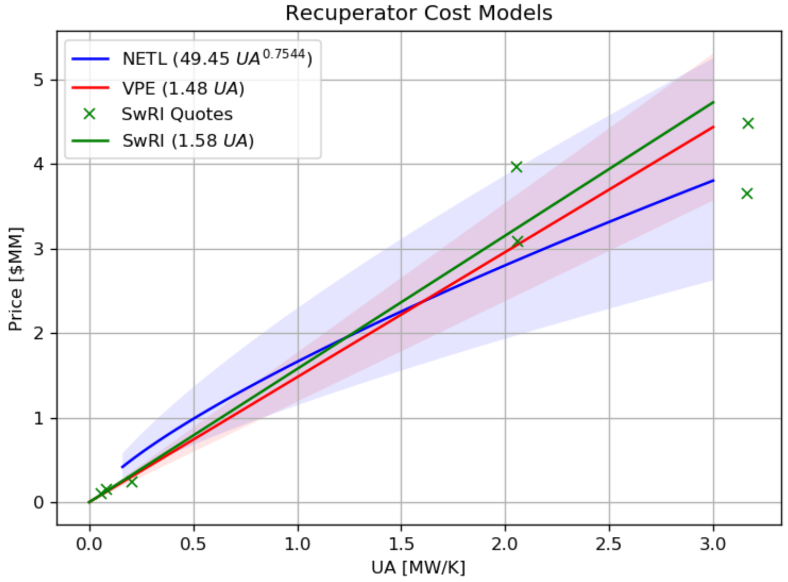
To complete the optimization, cost and off-design models are needed for each component in the cycle.

A recent paper from NETL has cost models for heaters, coolers, recuperators, and turbomachinery. The heater model is not directly applicable as it is for a natural gas fired direct heater. We worked with HRSG vendors to get a more appropriate heater cost model. We also used a custom model from Hanwha for turbomachinery costs.

Component	Cost Model	Off-Design Model
Turbomachinery	Hanwha custom model	Hanwha maps
Heater	SwRI Correlation from Quotes	Conductance Ratio Method: CR from SunShot Heater/Quotes
Recuperator	NETL	Conductance Ratio Method: CR from SunShot Recuperator
Cooler	NETL	Conductance Ratio Method: CR from Quotes
Gas Turbine	N/A	Data from Solar



Recuperator Model Comparison

Conductance Ratio Method

Recuperator, heater, and cooler use the conductance ratio method for off-design performance.

This method has been validated against multiple experimental data sets (3 published) including several sCO2 heat exchangers (GT2017-64908).

Essentially the method scales on design performance using the off-design flow conditions.

On-Design

$$Q = UA \cdot f(\Delta T) \qquad \frac{1}{UA} = \left.\frac{1}{hA}\right|_{hot} + R_{wall} + \left.\frac{1}{hA}\right|_{cold} \qquad (hA)^* = \frac{hA_{hot}}{hA_{cold}}$$

Calculate overall resistance required

Use $(hA)^*$ to divide UA into constituent terms

Scale with off-design conditions

Off-Design

Combine scaled hA terms to form new UA

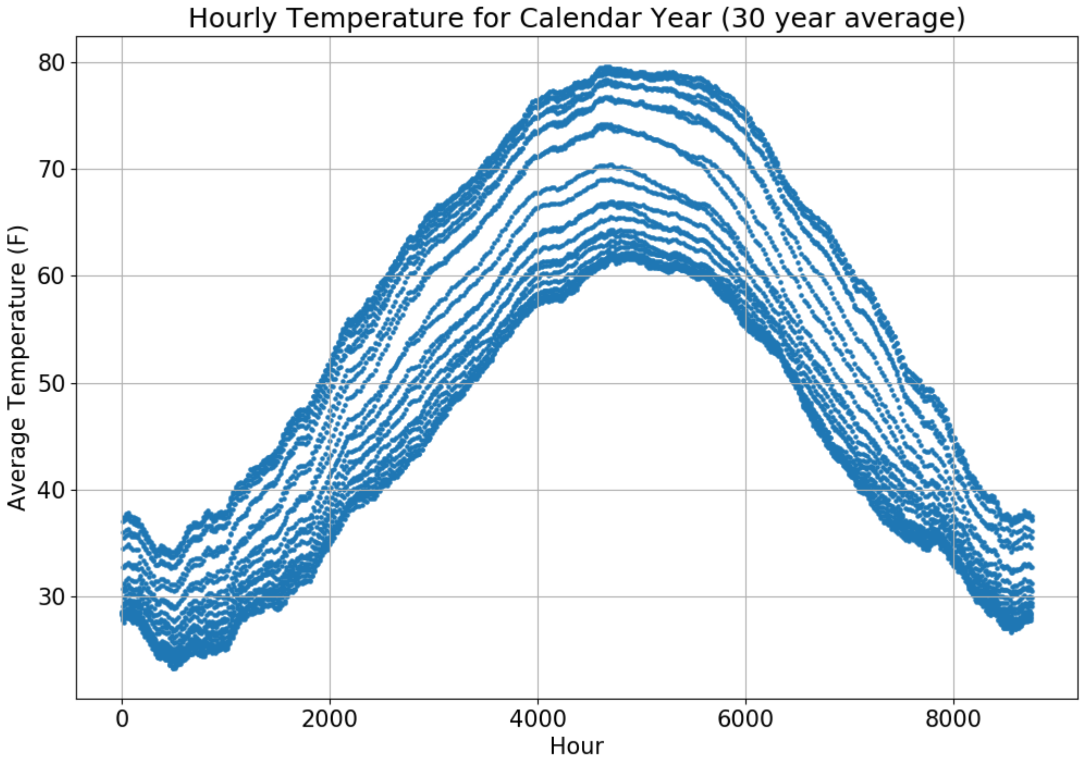
$$\frac{1}{UA} = \left.\frac{1}{hA}\right|_{hot} + R_{wall} + \left.\frac{1}{hA}\right|_{cold}$$

$$Q = UA \cdot f(\Delta T) = \dot{m}\,\Delta h_{hot} = \dot{m}\,\Delta h_{cold}$$

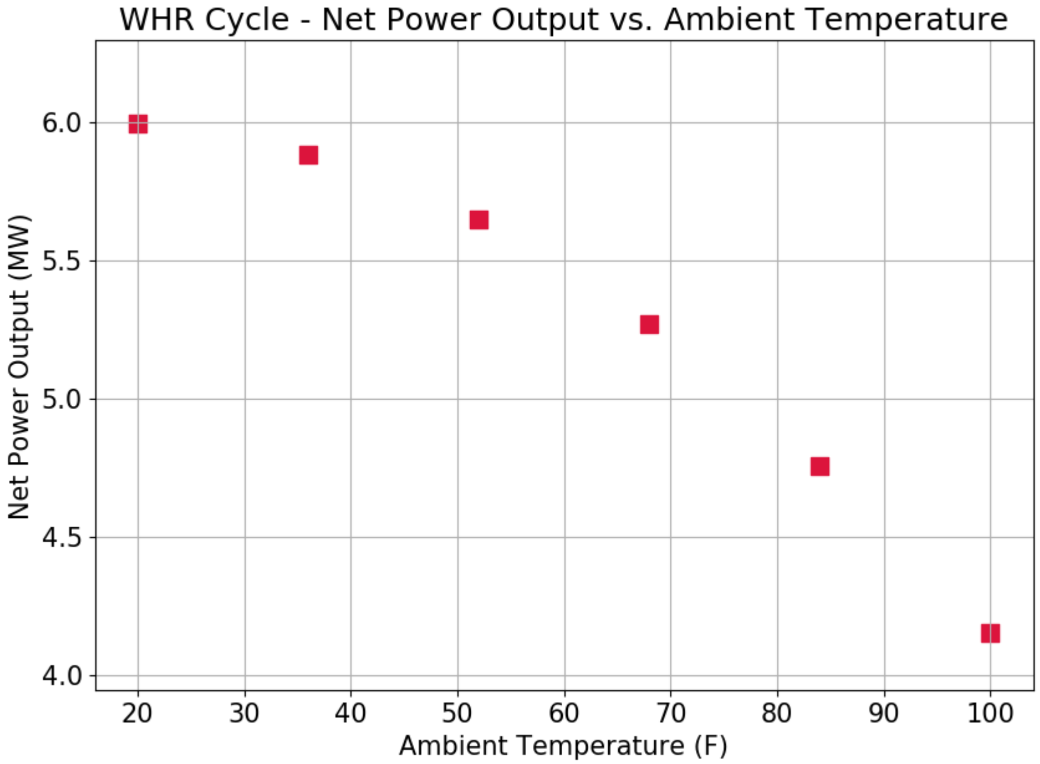
Use UA term and energy conservation to predict outlet temperatures

Calculation of Yearly Energy Output

- Calculation of a yearly energy output for a specific design uses two components: the hourly temperature variation for a calendar year, and the net output power vs temperature relationship.
- The net power output at each ambient data point uses cubic interpolation from the power vs temperature curve, and Simpson's rule is used to integrate the net power output over a year's time.



Yearly ambient temperature plot for weather station in WV (Site of prospective WHRU at gas processing plant)



Power vs Ambient temperature curve

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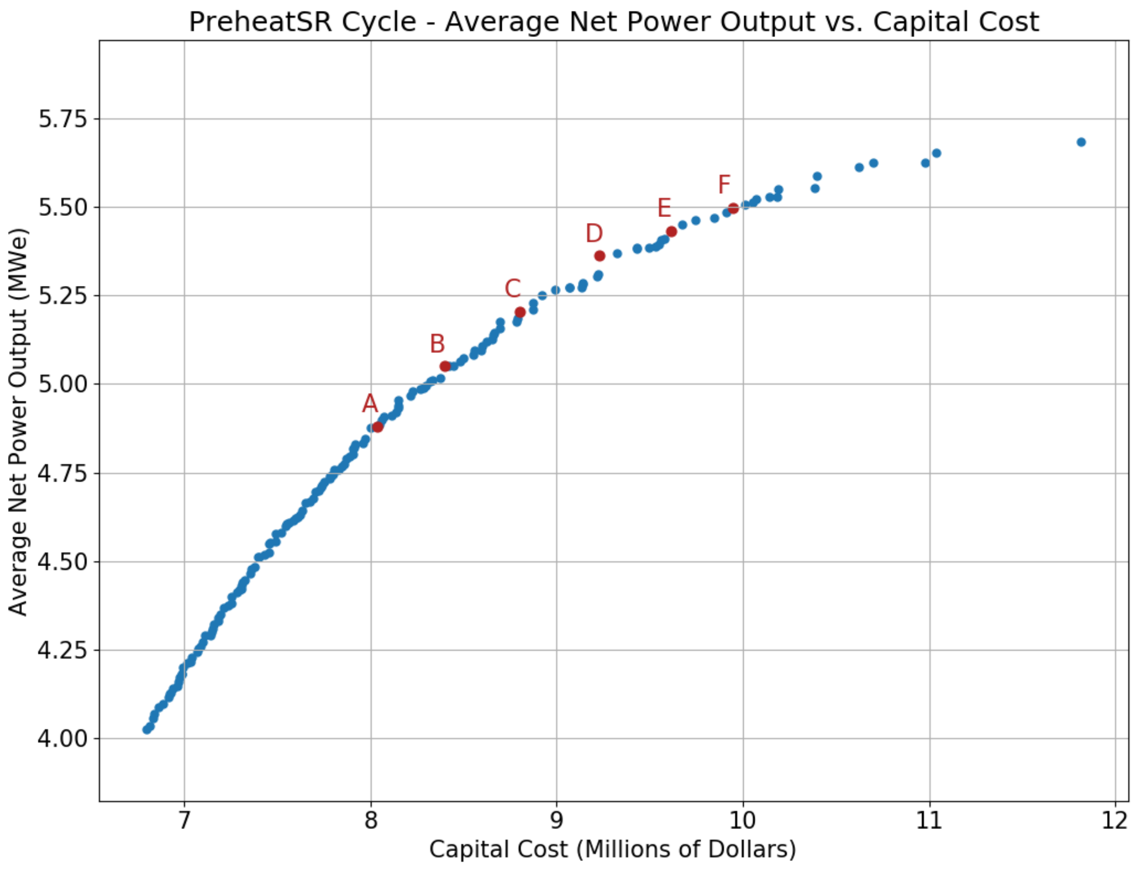
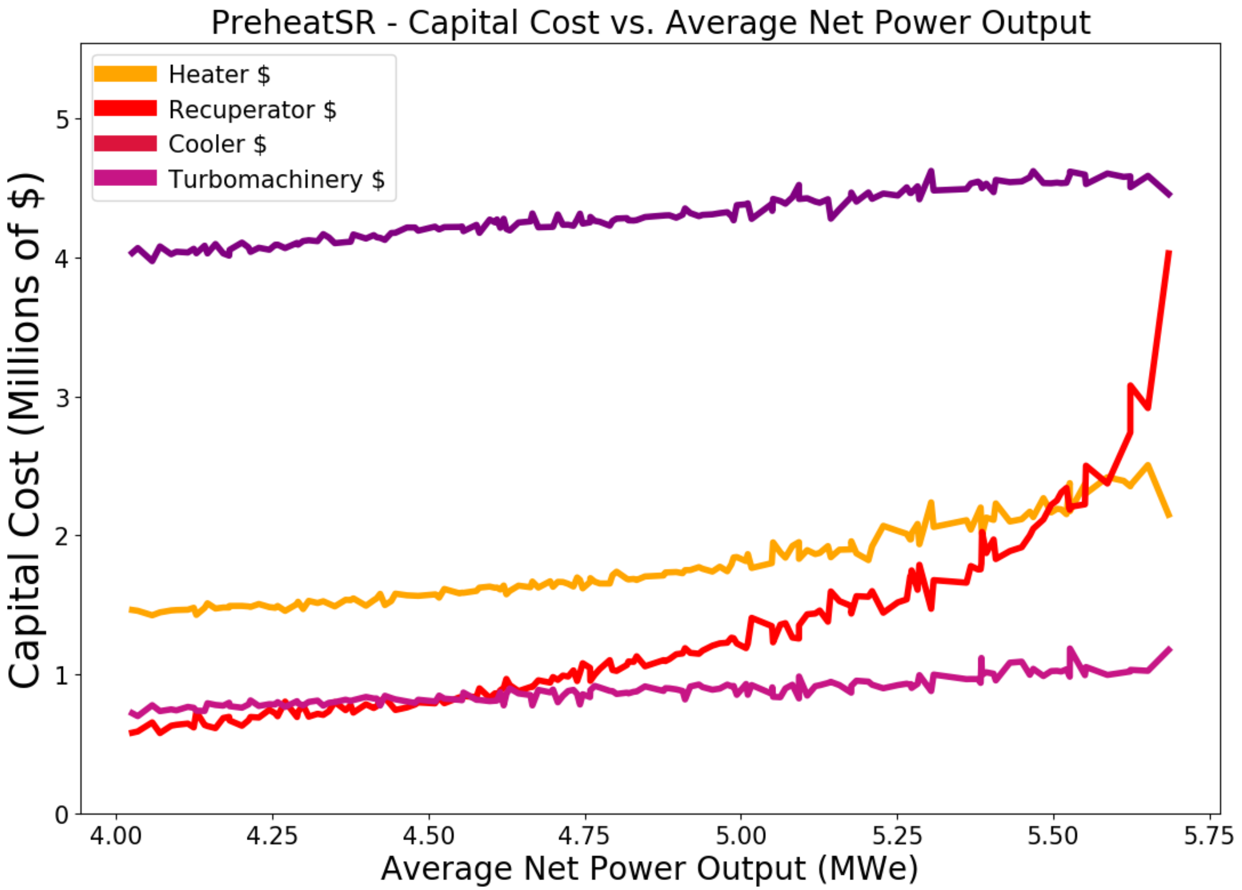
Optimization Results

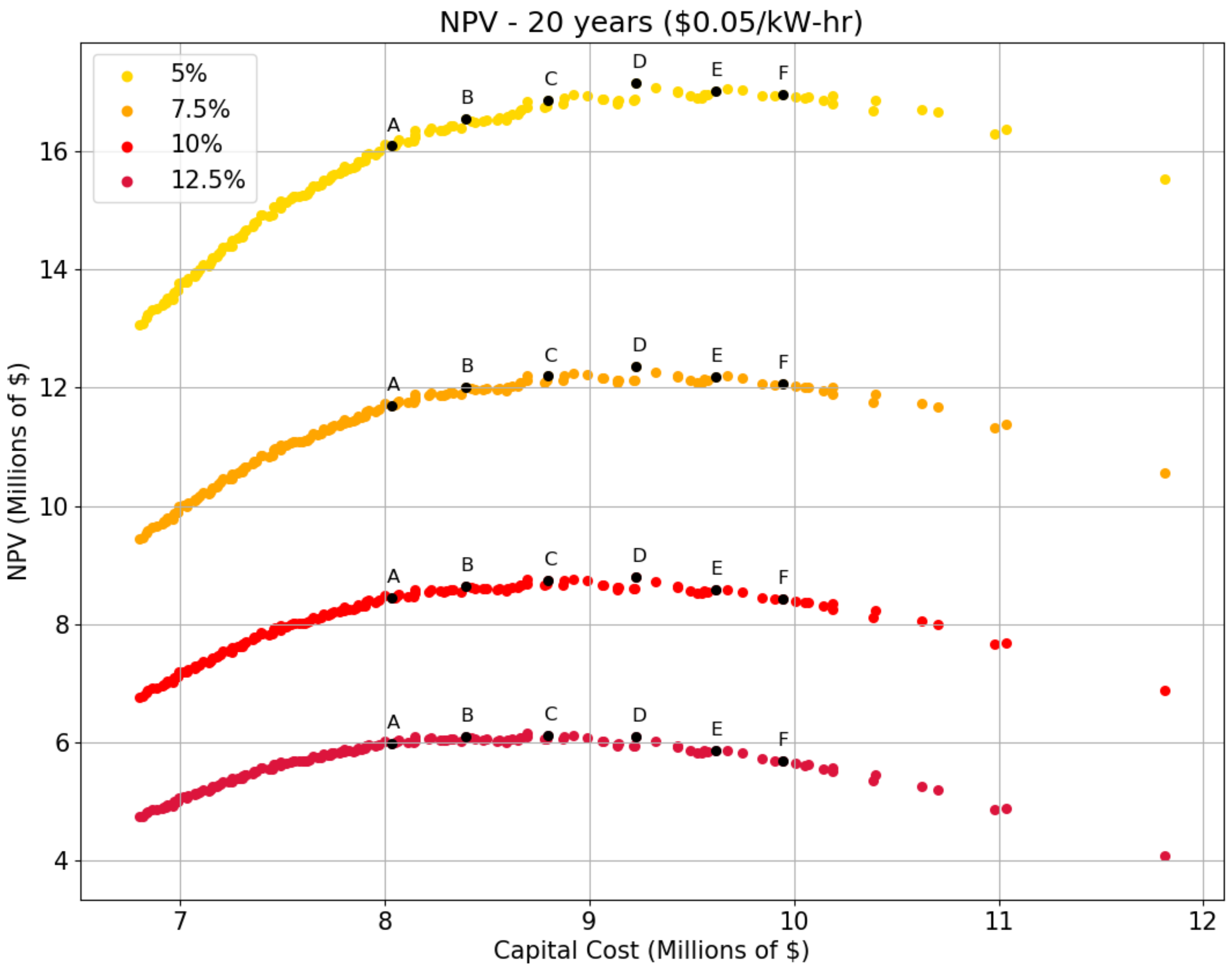


Multi-objective optimization result



Breakout of component costs

Optimization Results



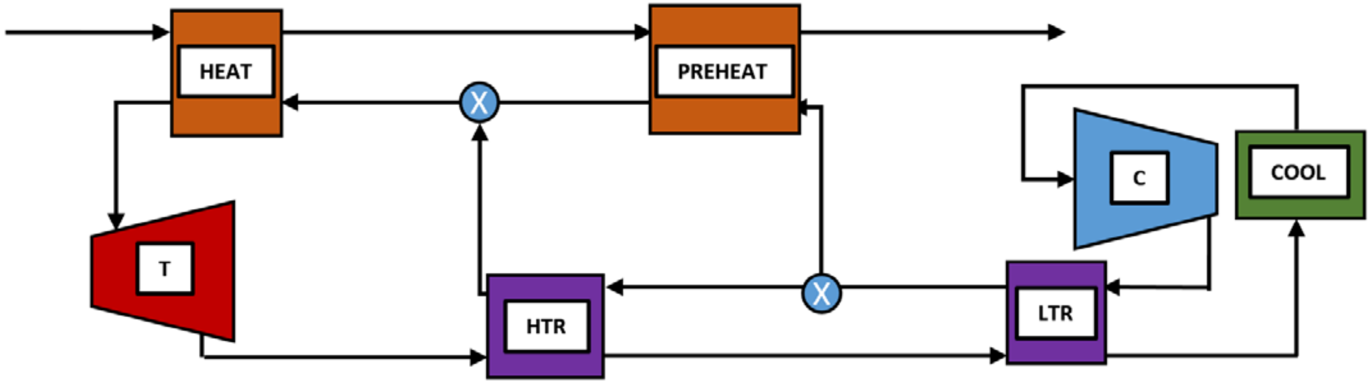
Net Present Value for a series of discount rates

After the application of a discount rate, net present value allows for the selection of the overall most profitable cycle.

Adjustments need to be added for:

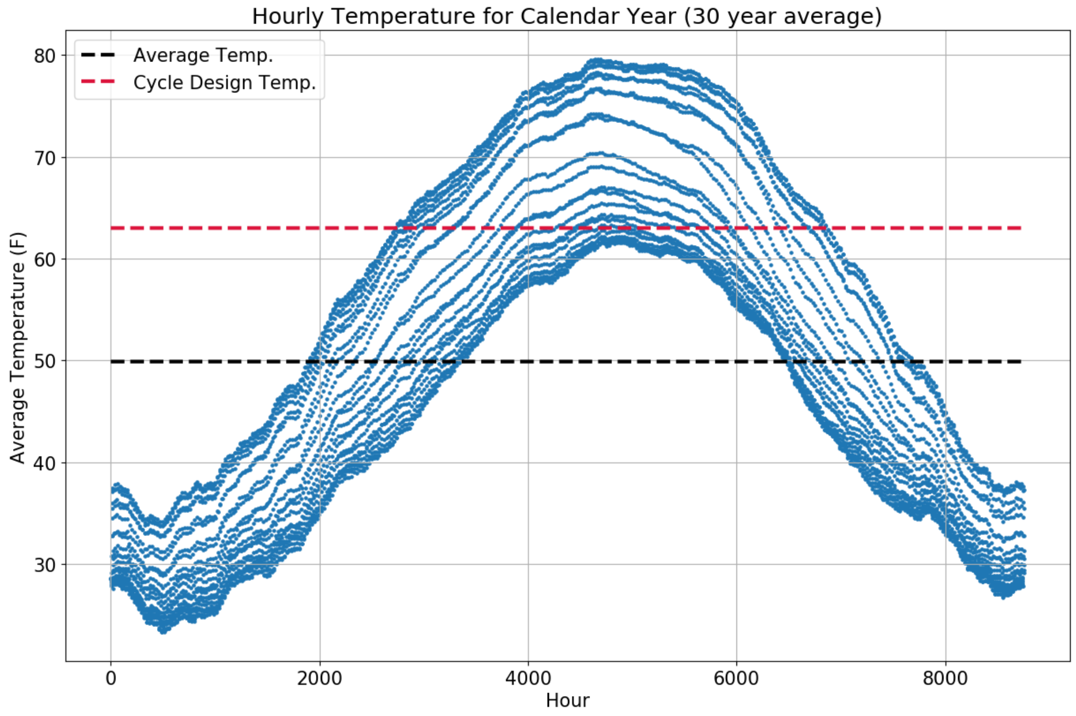
- electricity price variation
- Gas turbine load variation

Cycle Details



PreheatSR Cycle

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



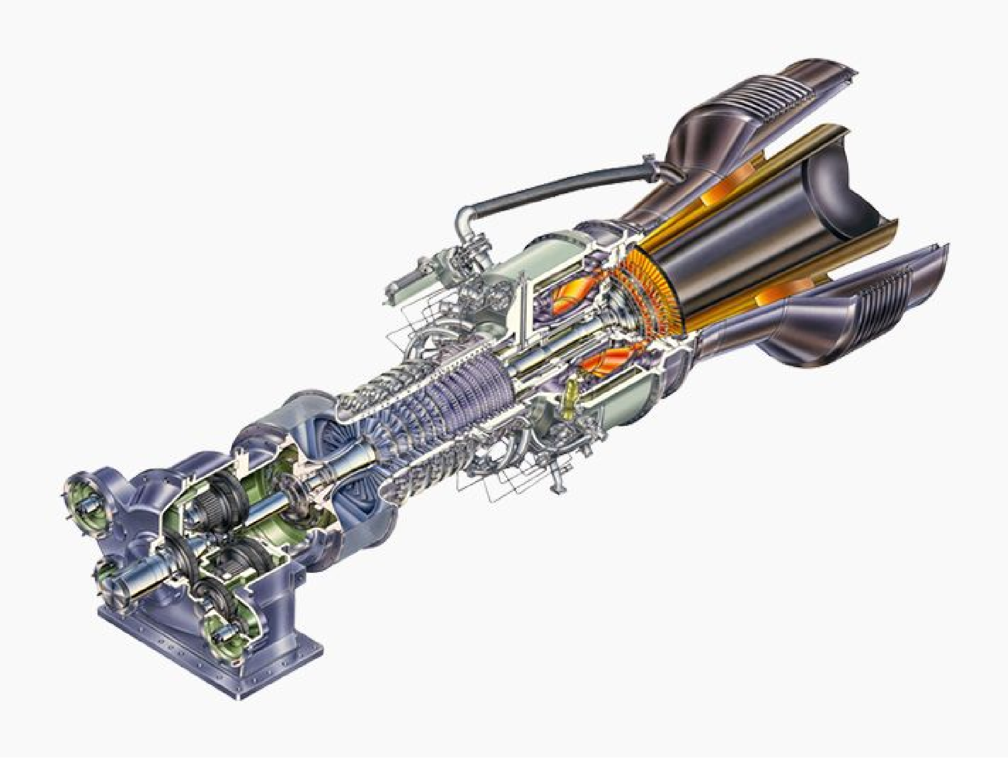
Cycle D design point temperature vs yearly ambient temperature variation

Titan 130 Combined Cycle Efficiency

At ISO conditions in an electrical generation configuration, the Titan 130 generates 16.530 [MWe] at a thermal efficiency of 35.4%

At ISO conditions and 100% load, the WHRU cycle adds an additional 5.743 [MWe] which creates an overall combined cycle efficiency of 47.7%

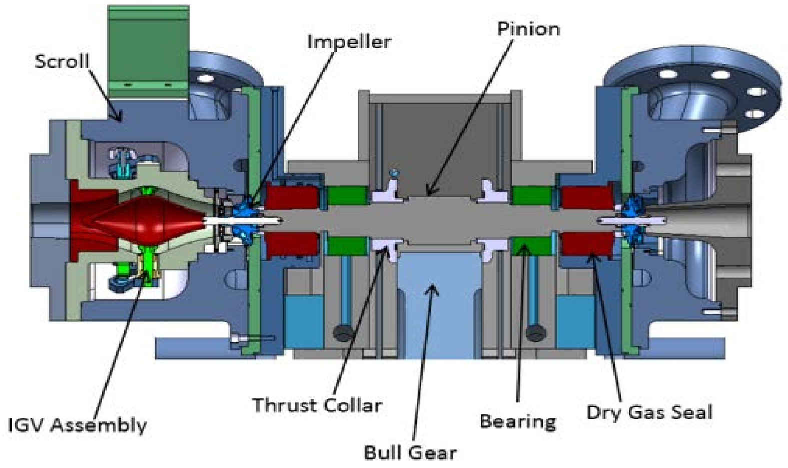
Traditional HRSGs can add up to 3.4 [MWe]. The developed sCO2 WHRU provides a 68% improvement over traditional HRSGs.



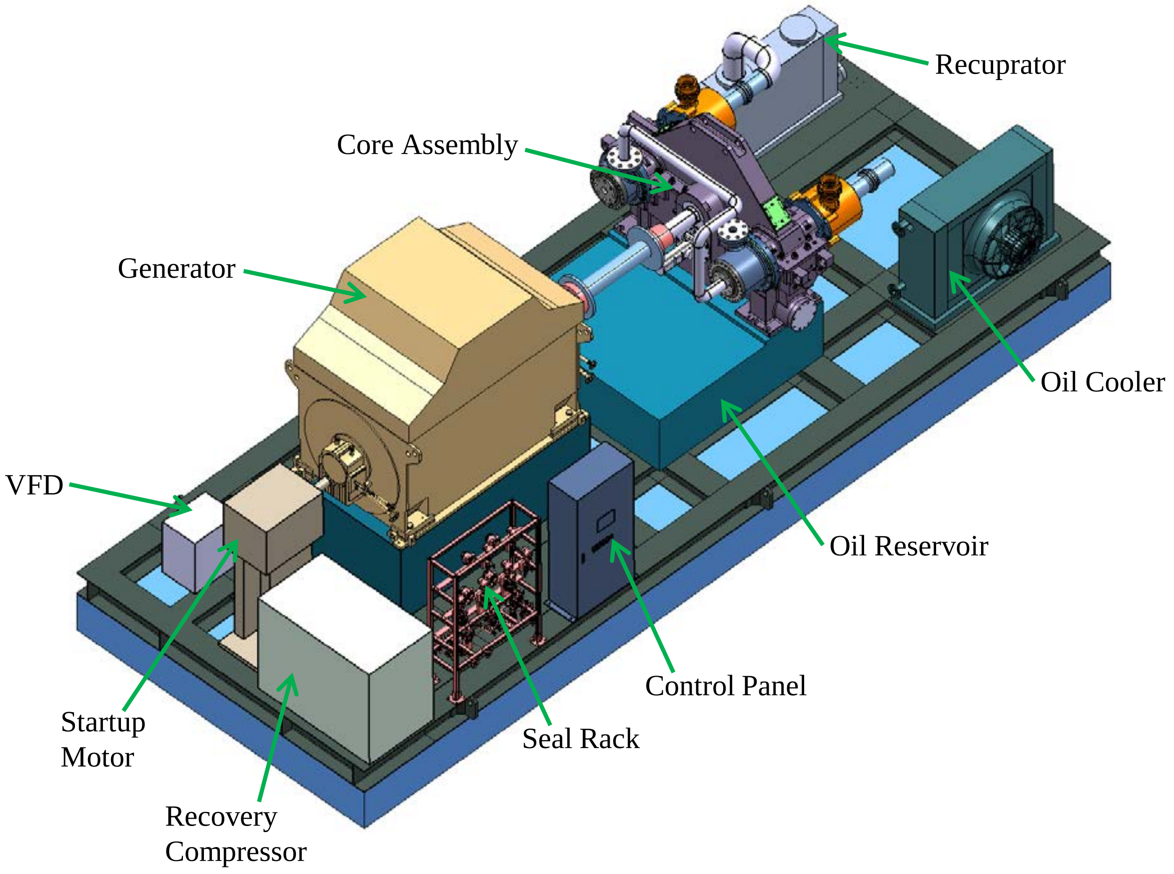
Schematic of a Solar Turbines Titan 130

Powerblock Skid

Conceptual design included considering how the components would fit on a skid as well as conceptual turbomachinery sizing including preliminary aerodynamics and rotordyanmics. Detailed engineering is needed to flesh out the design before manufacturing.

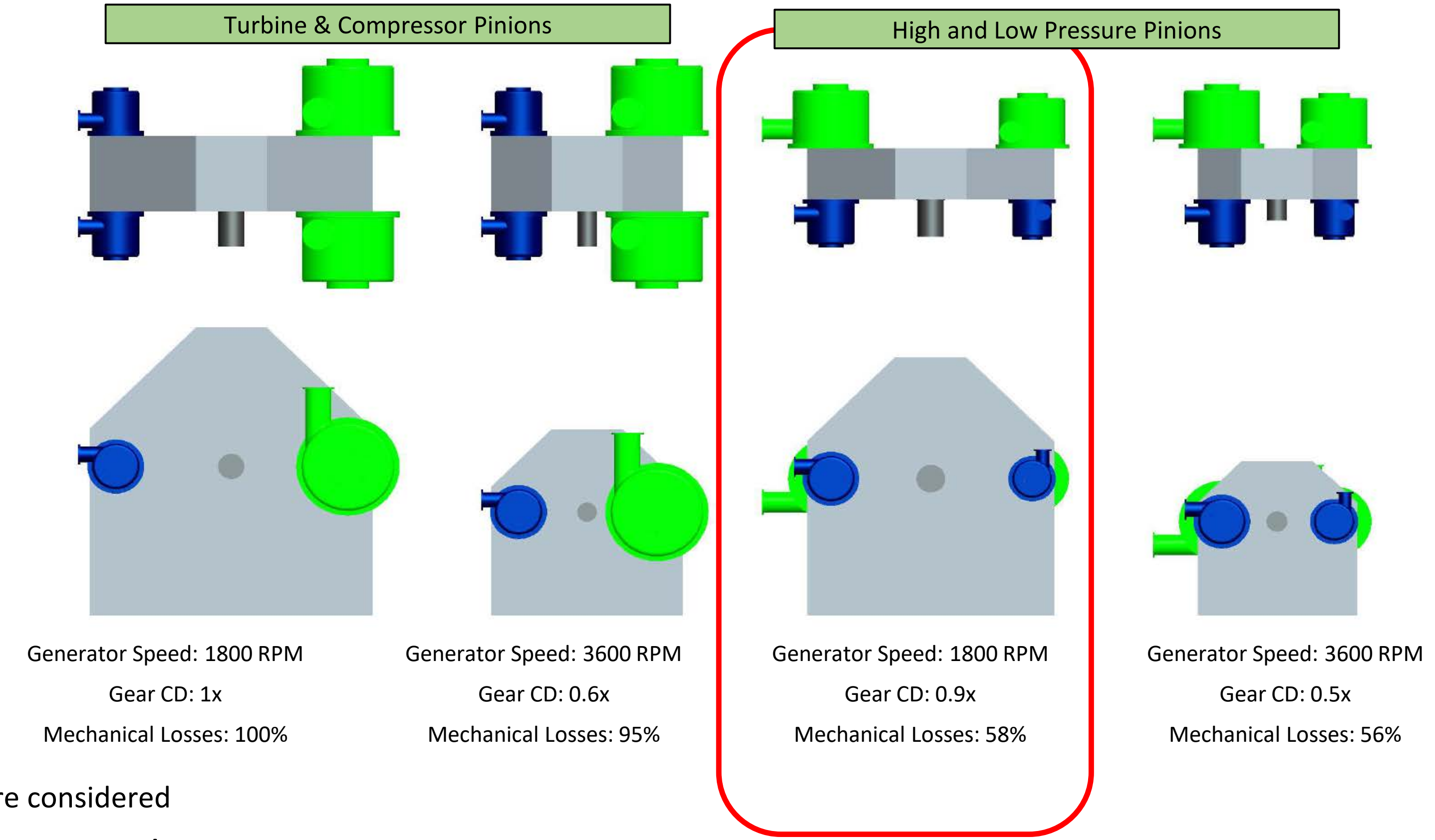


Typical rotor layout



Conceptual skid layout

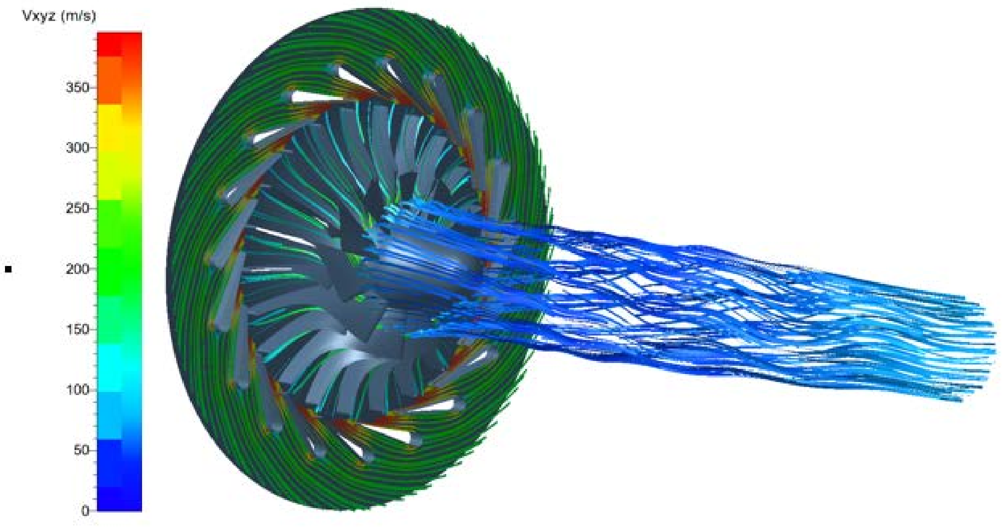
sCO2 Power System – Core Configuration



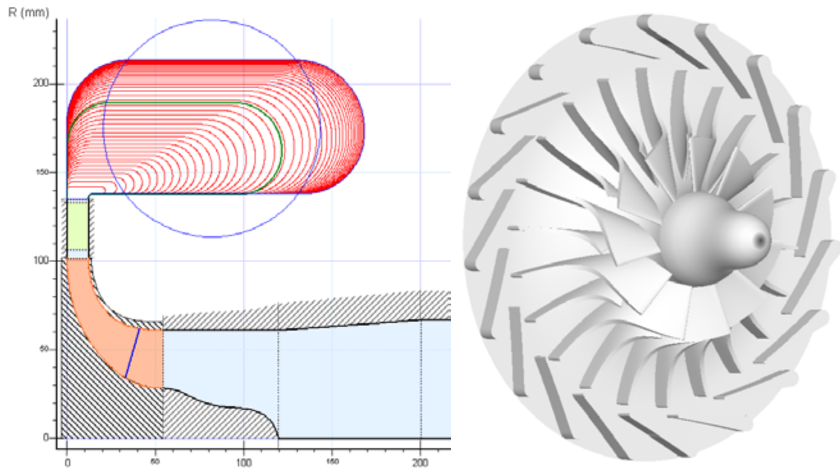
- Two generator options were considered
    1. 1800 rpm generator: Lowest cost
    2. 3600rpm generator: Smallest package
- Two different turbomachinery configurations were evaluated.
    1. Turbine/Comp Pinions: Turbines and compressors on separate pinions
    2. HP/LP Pinions: HP stages (Turbine S1 and Comp. S2) and LP stages (Turbine S2 and comp. S1) on separate pinions
- An HP/LP configuration reduces the size of the gearbox and the mechanical losses
- A 3600rpm generator is not a common offering and is much more expensive at powers below 10MWe

Preliminary Aero/Rotordyanmic Design

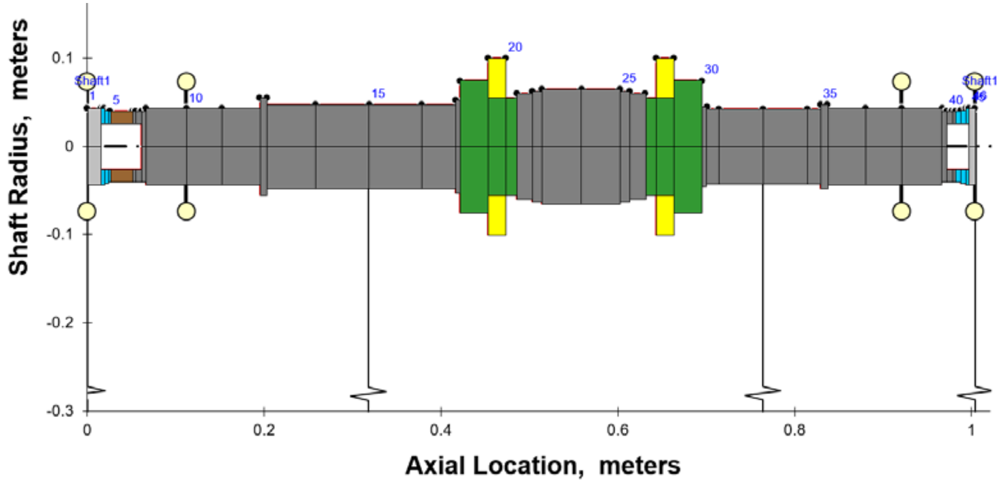
Conceptual and preliminary design work is underway on the turbomachinery block components including aerodynamic and rotordynamic models.



Preliminary Expander CFD



Expander preliminary layout / geometry



Geometry used in the rotordynamic model of LP Pinion

Summary

By utilizing a multi-objective optimization framework, this project has developed a conceptual design for a sCO2 WHR System for a Solar Turbines Titan 130. The chosen conceptual sCO2 cycle increases the thermodynamic efficiency from 35.4% to 47.7%