

Advanced Gas Turbine and sCO₂ Combined Cycle Power System

UTSR Meeting

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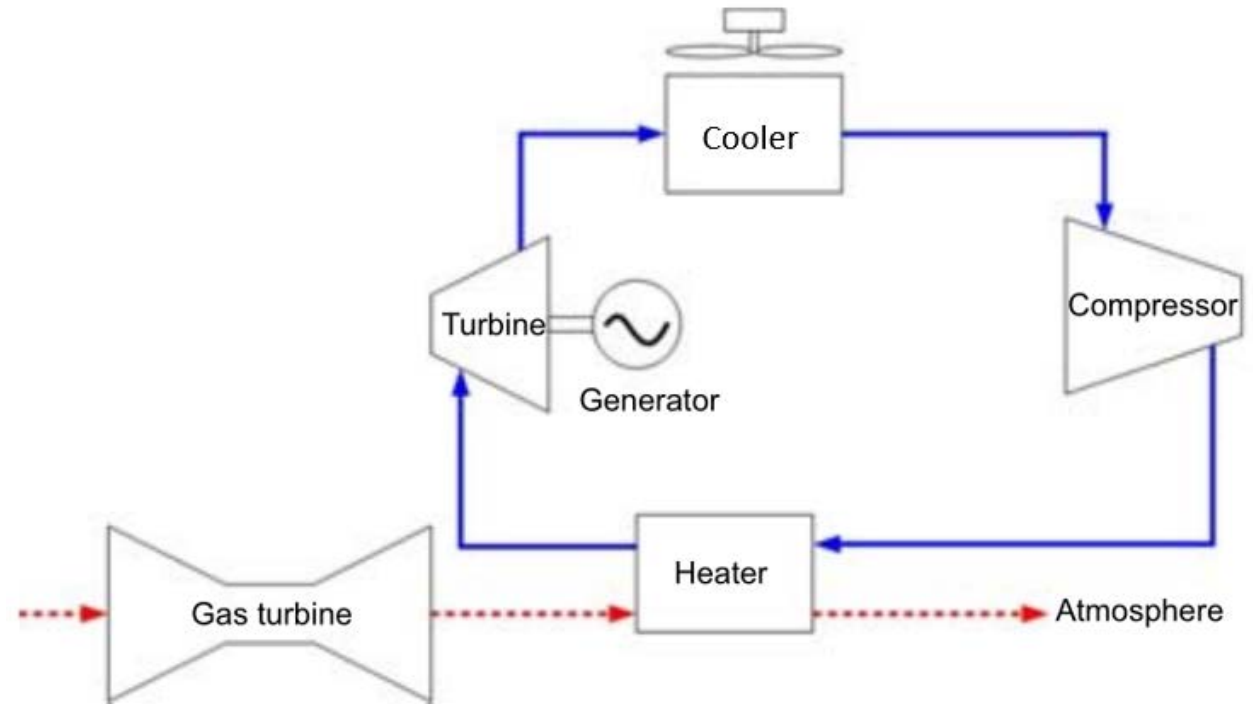
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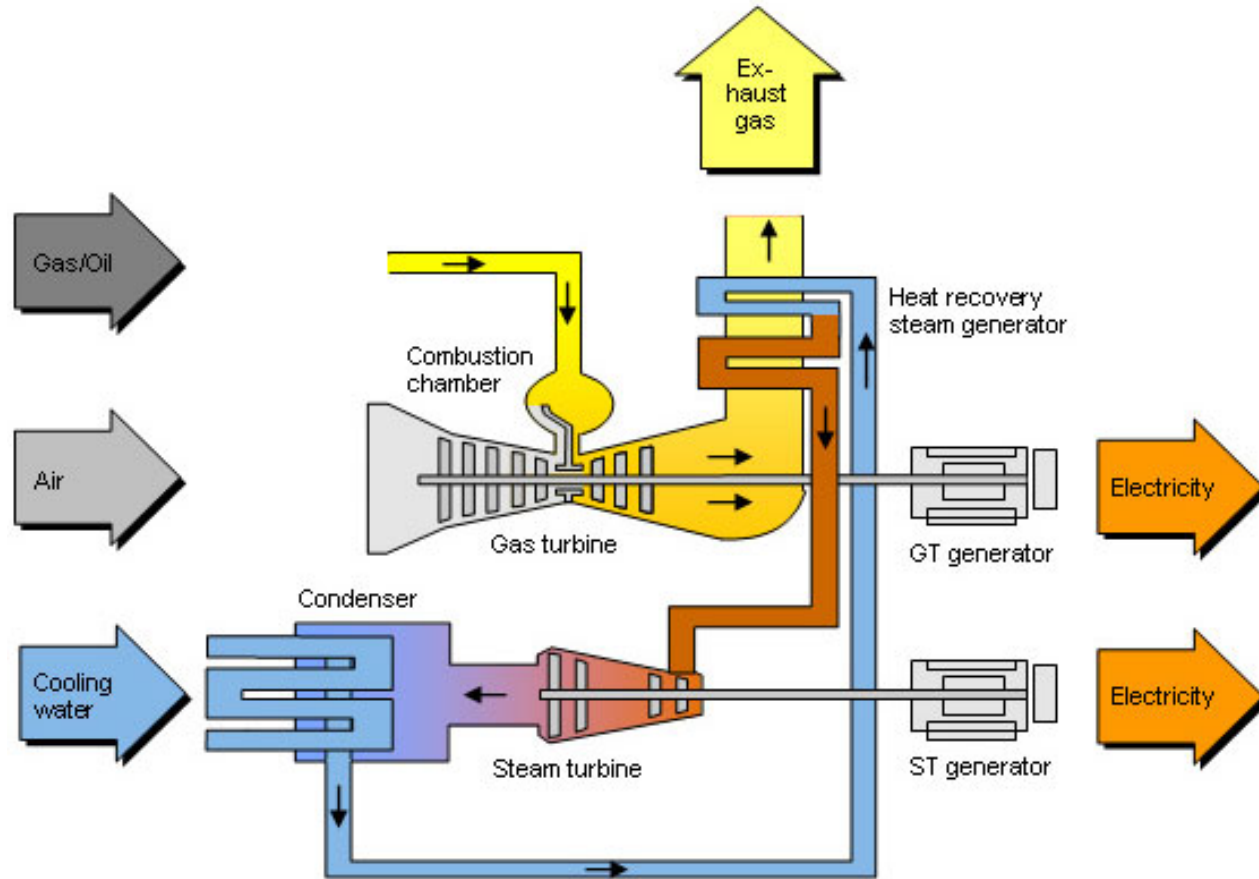
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Project background and motivation: Large scale combined cycles



*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 traditionally 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: sCO₂ small scale combined cycle



Solar Titan 250 and gas compressor at a Spectra Energy gas compression station.

WHR systems are not typically added to smaller gas turbines of the type used at natural gas compression stations due to:

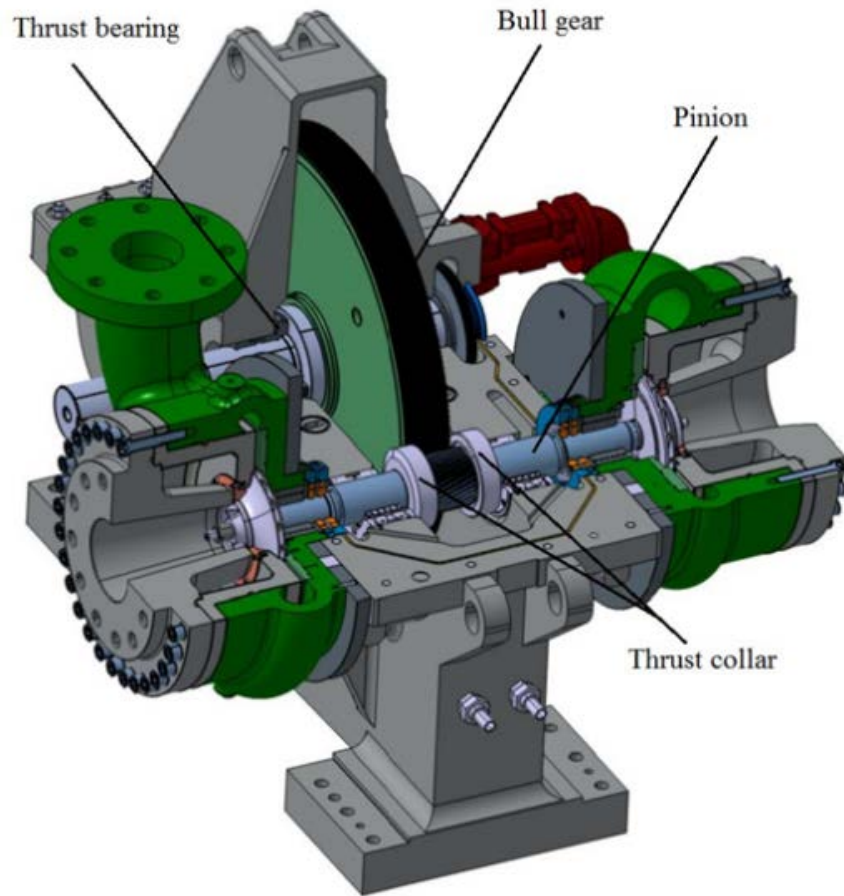
- Size
- Complexity
- Initial capital cost
- On site water requirements

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

Project background and motivation: 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.

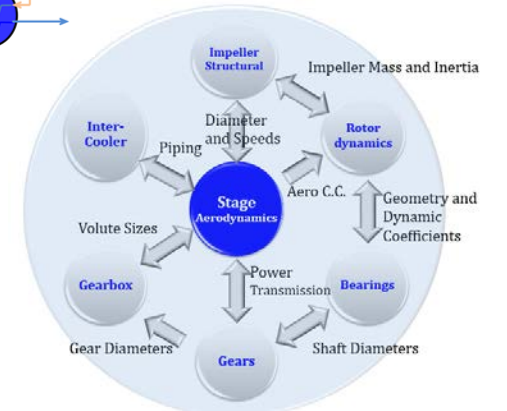
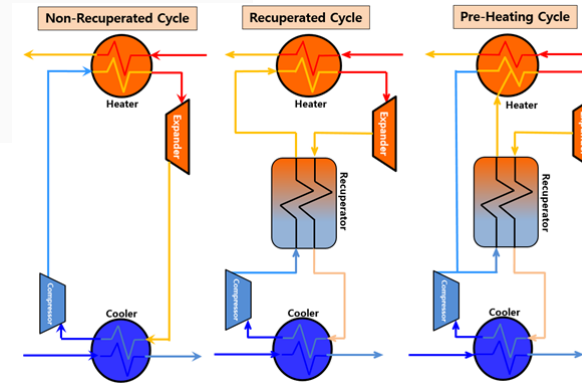
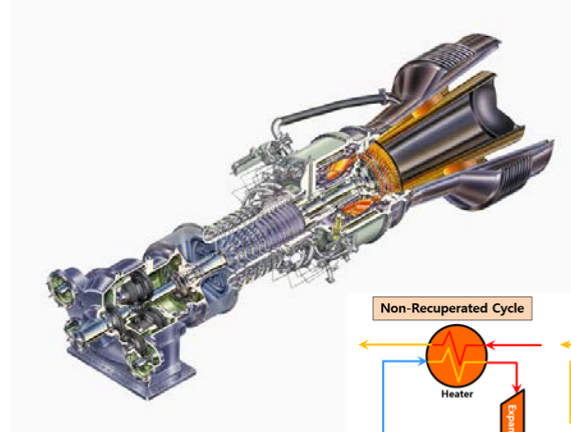
Integrally-geared machines have the following benefits:

- Independent pinion speeds increase overall machine efficiency
- Easy access between stages for intercooling and or reheating
- Stage access allows for each stage to have IGVs for better control
- Compactness
- Extra process compression pinions can be added to use energy recovered by WHRS directly

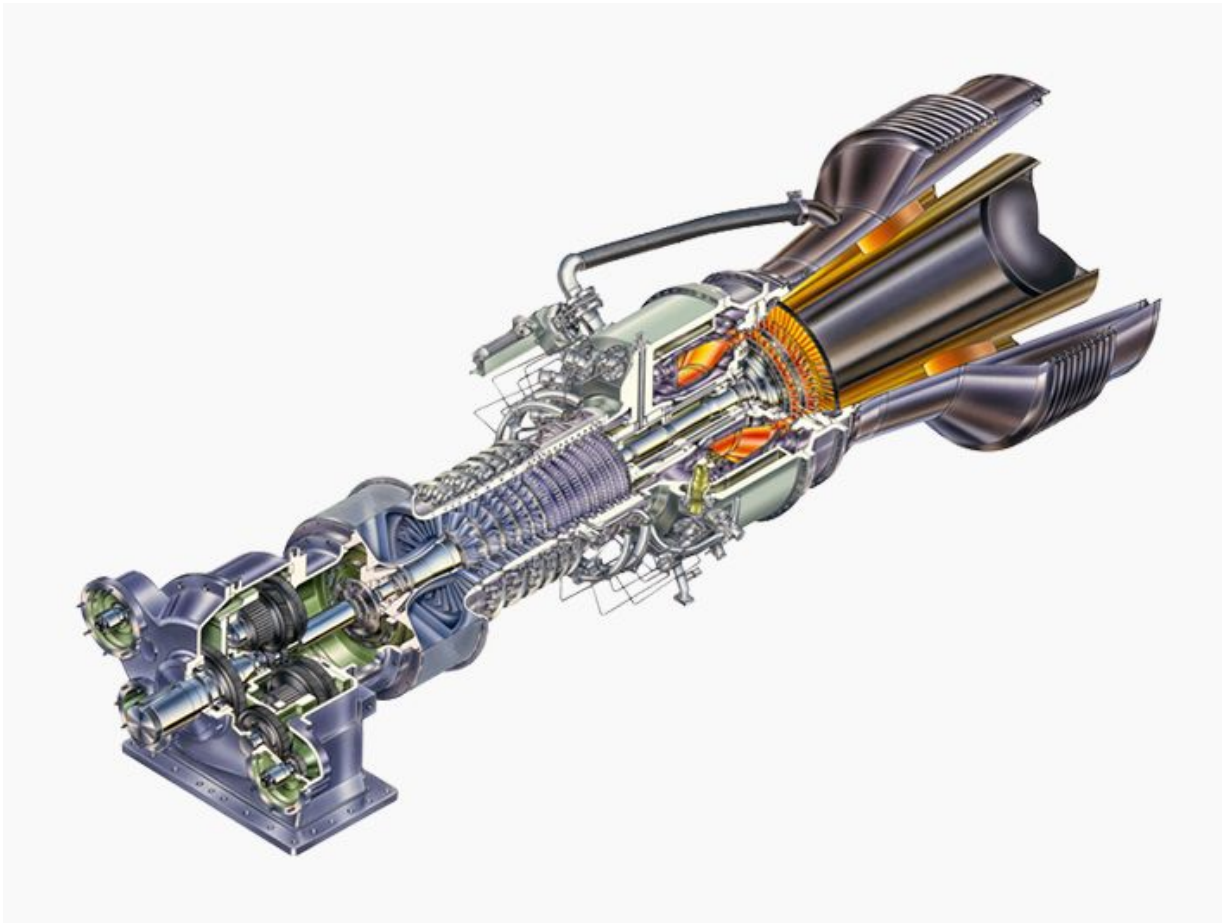
Technical Approach

Overall technical approach:

1. Define cycle boundary conditions
2. Cycle selection, design, and optimization
3. Conceptual design/sizing



Technical Approach: Define turbine outlet stream boundary conditions



Schematic of a Solar Turbines Titan 130 which is often used at natural gas compression stations. A Titan 130 produces 16.5 MWe

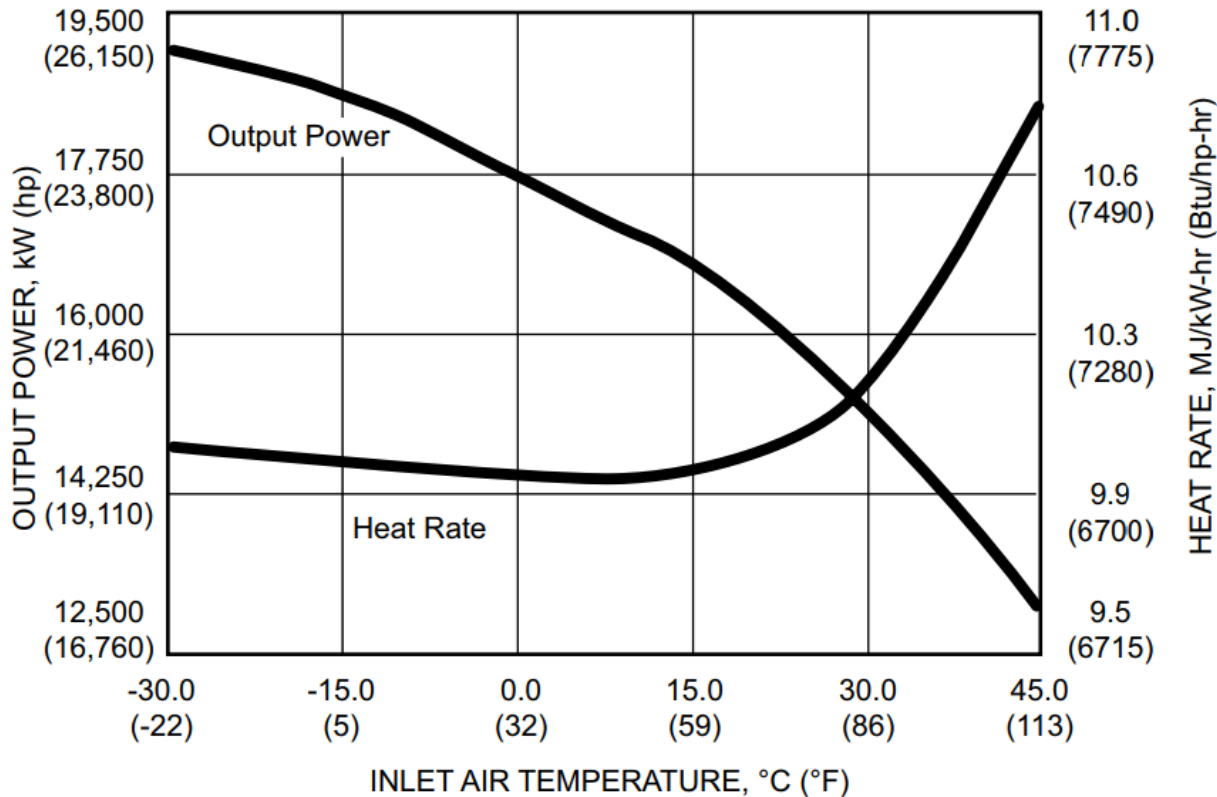
Market research will be conducted to determine which existing gas turbine to target for WHRS development. Presently, the Solar Turbines Titan 130 looks very promising.

Apart from turbine operating conditions at a series of loads and ambient conditions we also need to answer questions such as:

- How often does a gas turbine typically run?
- How often are starts/stops?
- What are ramp rates?
- What gas turbine load is typical?
- What are typical ambient air conditions?
- Is electrical power needed or would direct mechanical coupling be more appropriate?
- What size/weight/portability requirements are there for easy WHRS installation in existing compression stations?

All of these factors will influence the WHRS cycle and machinery design.

Technical Approach: Define turbine outlet stream boundary conditions

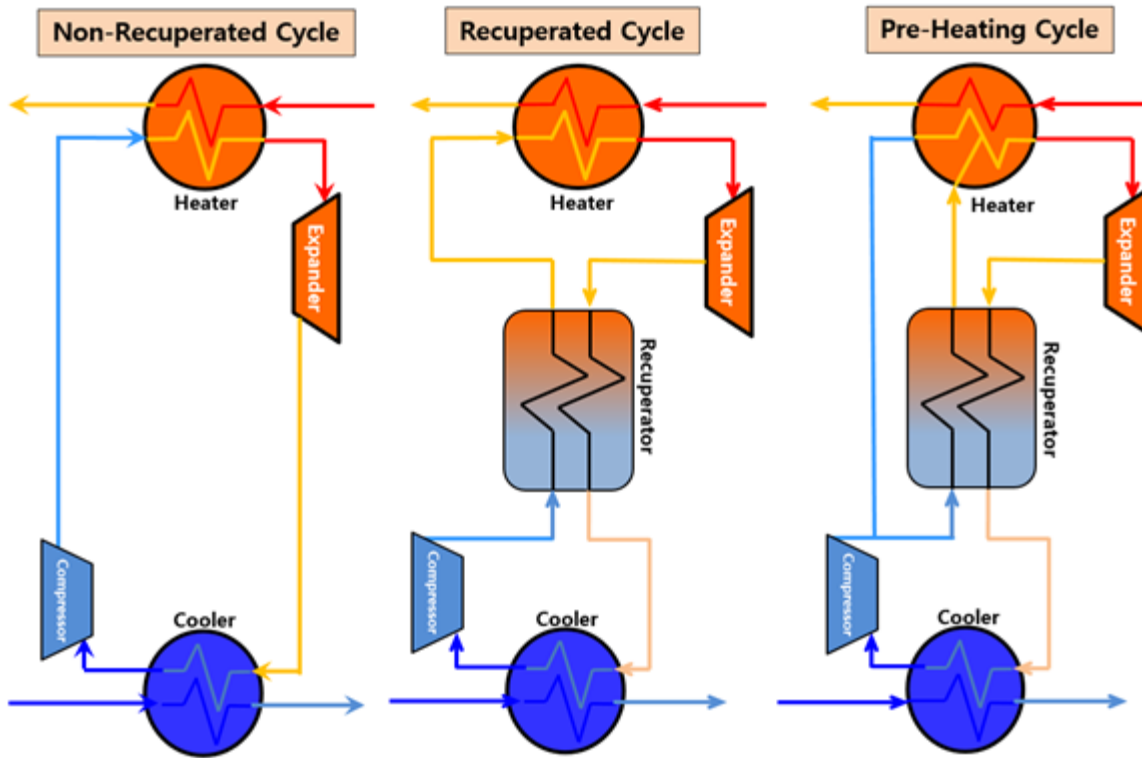


As an example, this chart shows the heat rate and output power as a function of ambient air temperature. The ambient air temperature will change depending on site location, season, and even time of day and can have a large impact on cycle performance.

Similar performance curves are available for elevation, turbine load, etc.

Solar Turbines Titan 130 performance as a function of inlet temperature

Technical Approach: WHRS Conceptual Design (cycle)



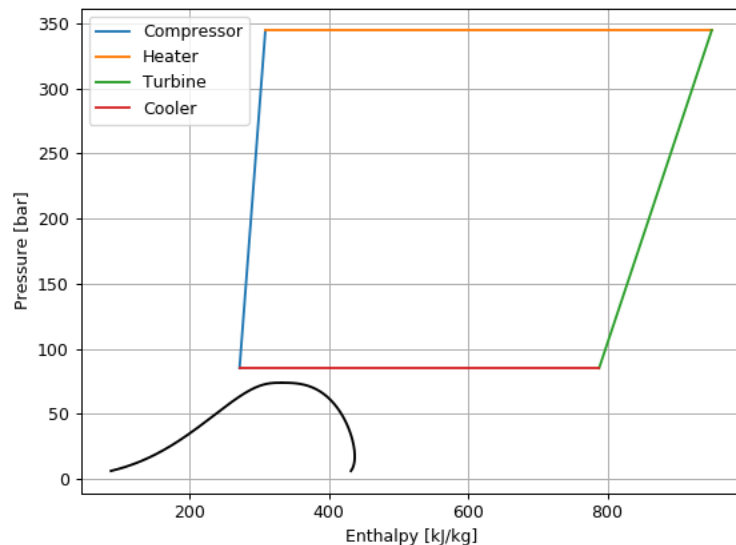
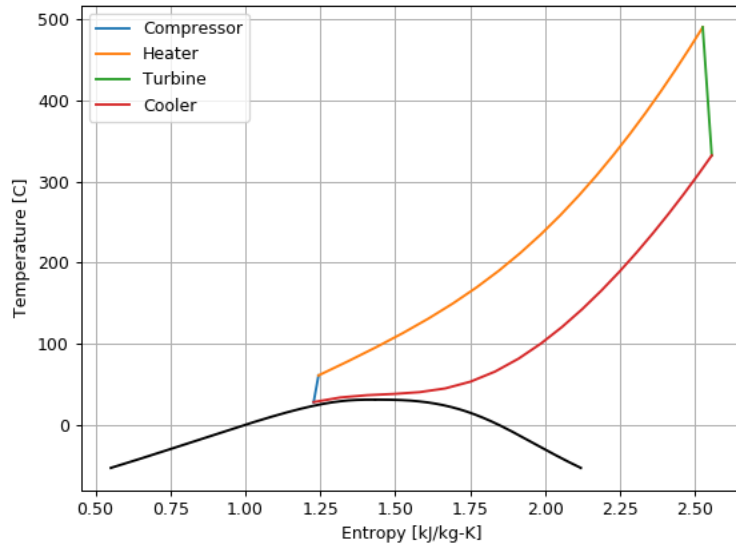
Examples of potential WHRS cycles.

The first step to designing the WHRS is defining the thermodynamic cycle. Many cycle configurations are possible.

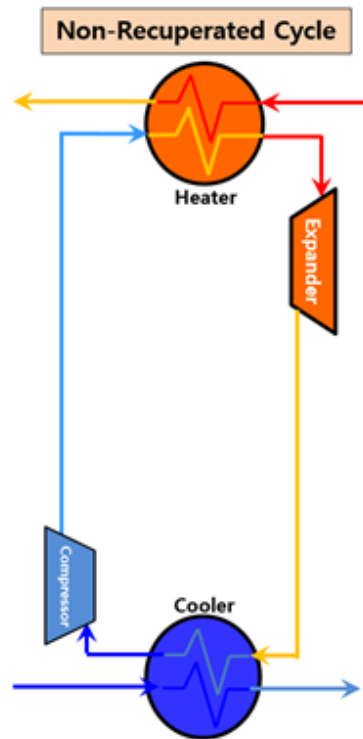
Cycle design and optimization will be done to optimize the cycle for the given boundary conditions and operating profile taking into account capital expense and machine complexity.

The cycle chosen will underpin the entire machine and effect every aspect of its operation.

Technical Approach: WHRS Conceptual Design (cycle)



Simple, or non recuperated, cycle.



Many cycle configurations are possible. The simplest is called a simple, or non-recuperated, cycle.

In this cycle, the flow goes through the compressor, is heated, goes through a turbine, is cooled and then goes back through the compressor.

The turbine produces more work than the compressor requires and power is generated.

This is a closed loop Brayton cycle.

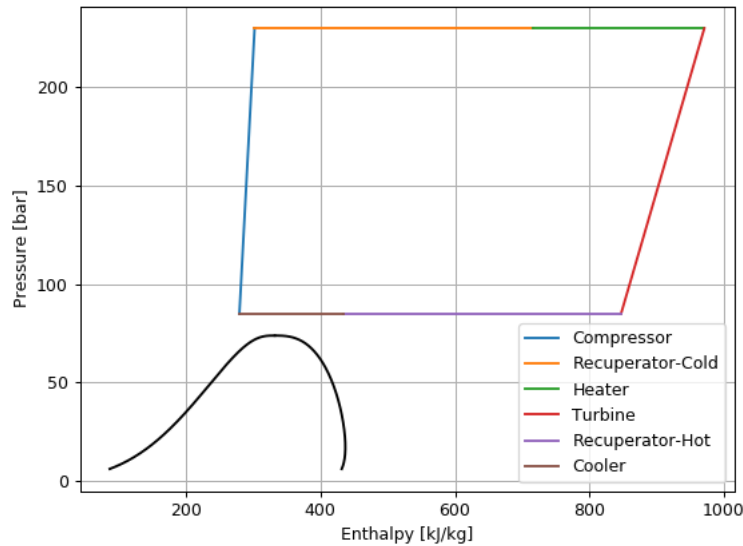
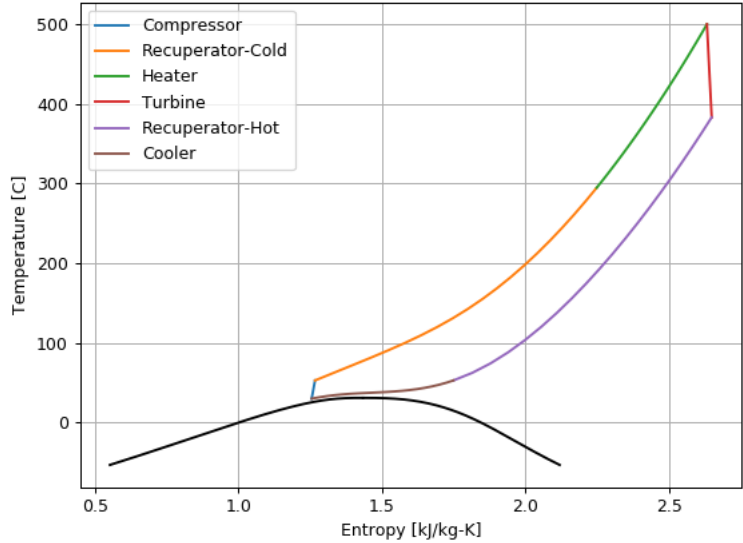
The cycle thermal efficiency is determined by

Thermal efficiency = Net power out / Heat in

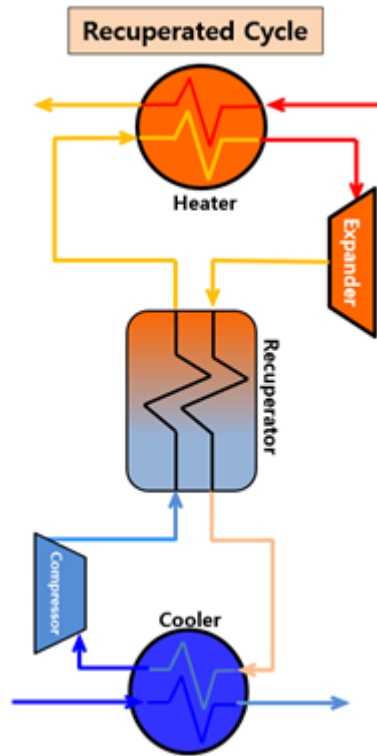
How can we increase thermal efficiency?

- Change temperatures and pressures
- Machine efficiencies
- Reduce heat in

Technical Approach: WHRS Conceptual Design (cycle)



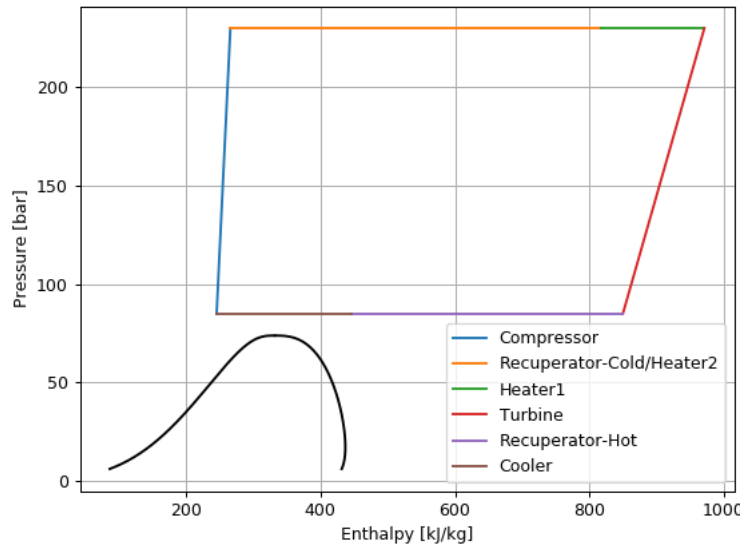
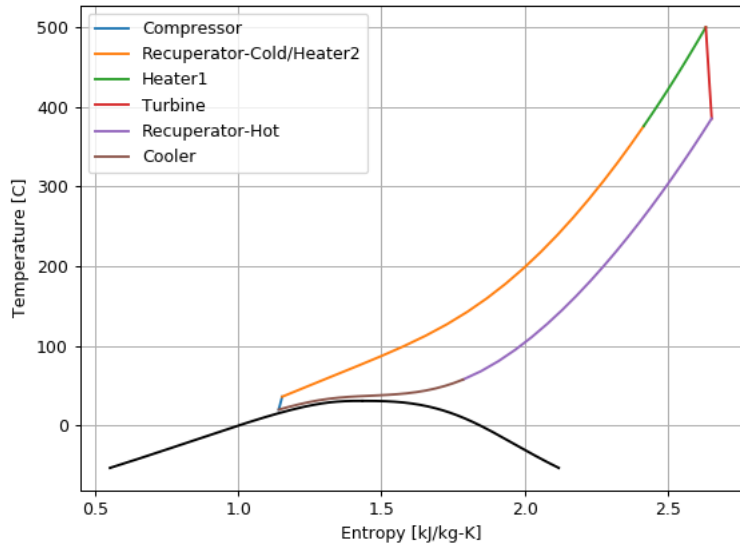
Recuperated Cycle



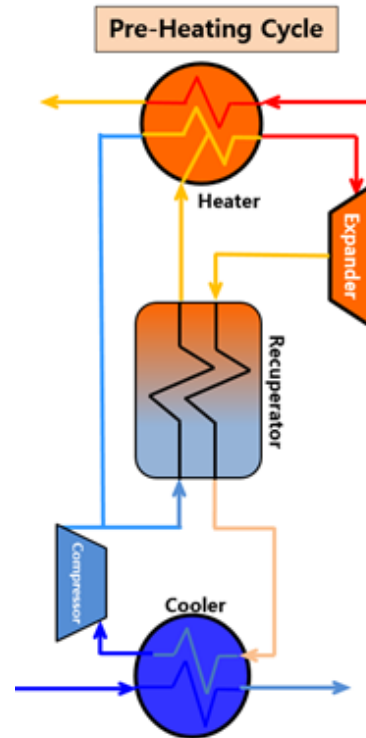
The efficiency of the simple cycle can be improved by reducing net heat input by adding recuperation. This adds a heat exchanger to the exhaust of the turbine to preheat the CO₂ before it enters the heater by transferring heat from the turbine exhaust to the compressor exhaust. Recuperation also reduces required cooling.

Is high thermal efficiency really what we want in a WHRS or is there a better metric?

Technical Approach: WHRS Conceptual Design (cycle)



Pre-heating Cycle



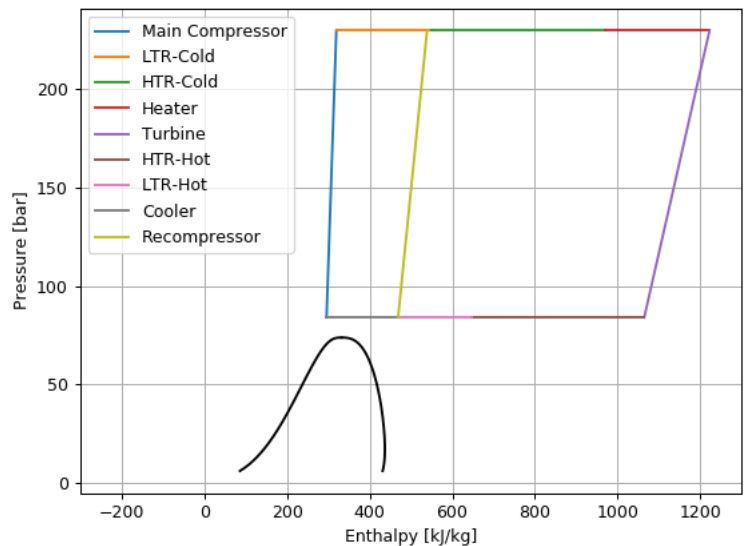
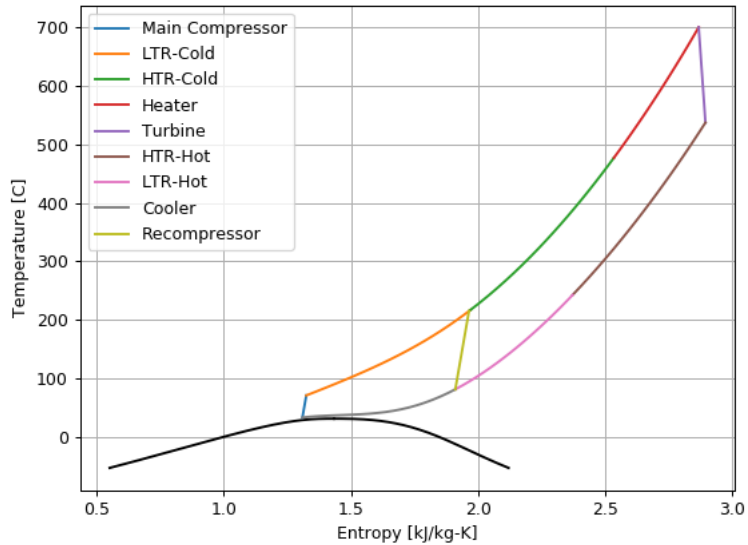
The preheating cycle is a variation on the recuperated cycle which allows for more heat to be extracted from the gas turbine exhaust.

In this cycle, the flow is split, with some of the flow going to the recuperator and the rest going into a secondary heater.

This secondary heater allows for full recuperation and also allows you to pre-heat extra massflow prior to primary heating.

This cycle configuration does not have the highest thermal efficiency but it has high net power produced and is relatively simple compared to other advanced cycles.

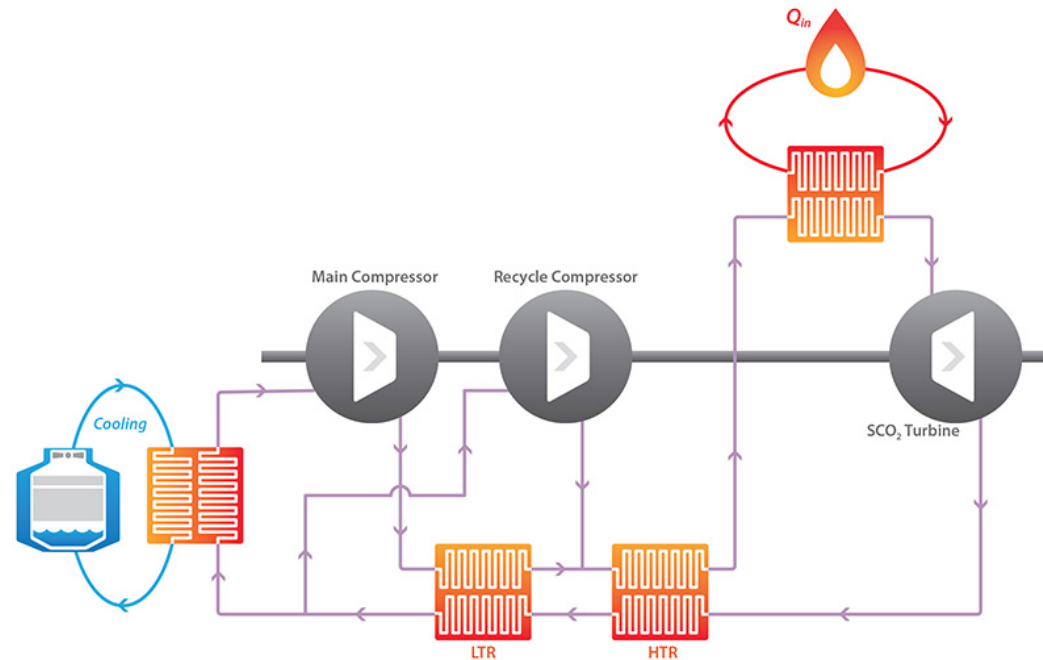
Technical Approach: WHRS Conceptual Design (cycle)



Recompression Cycle

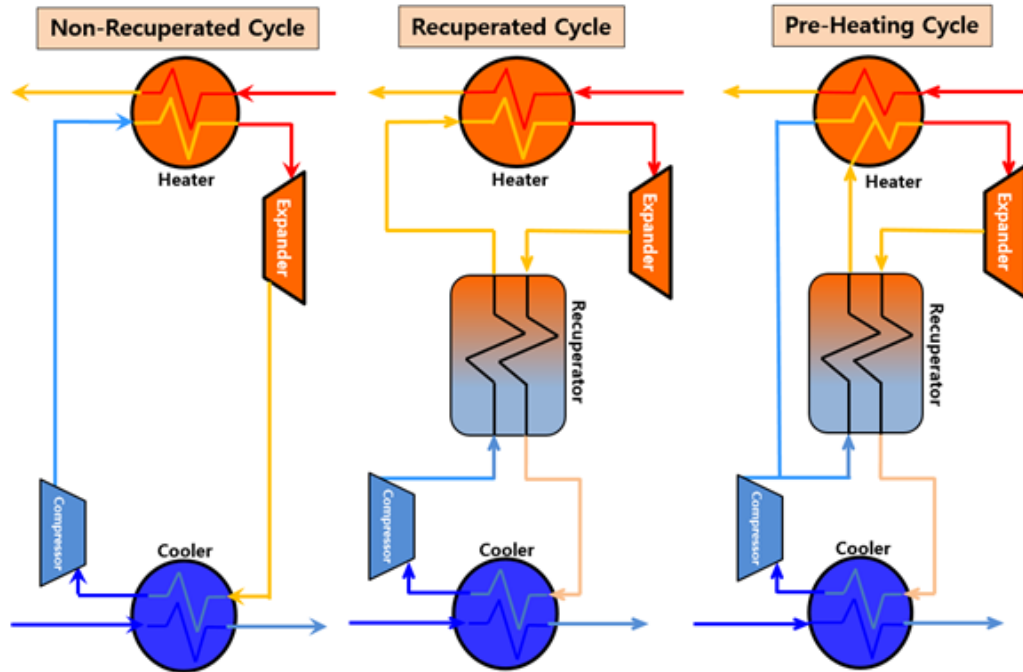
Much more advanced cycles, such as the recompression cycle, are possible and popular for sCO₂ power generation.

As the cycle becomes more complicated, overall cost and size go up.



Recompression Cycle layout, [DOE NETL]

Technical Approach: WHRS Conceptual Design (cycle)

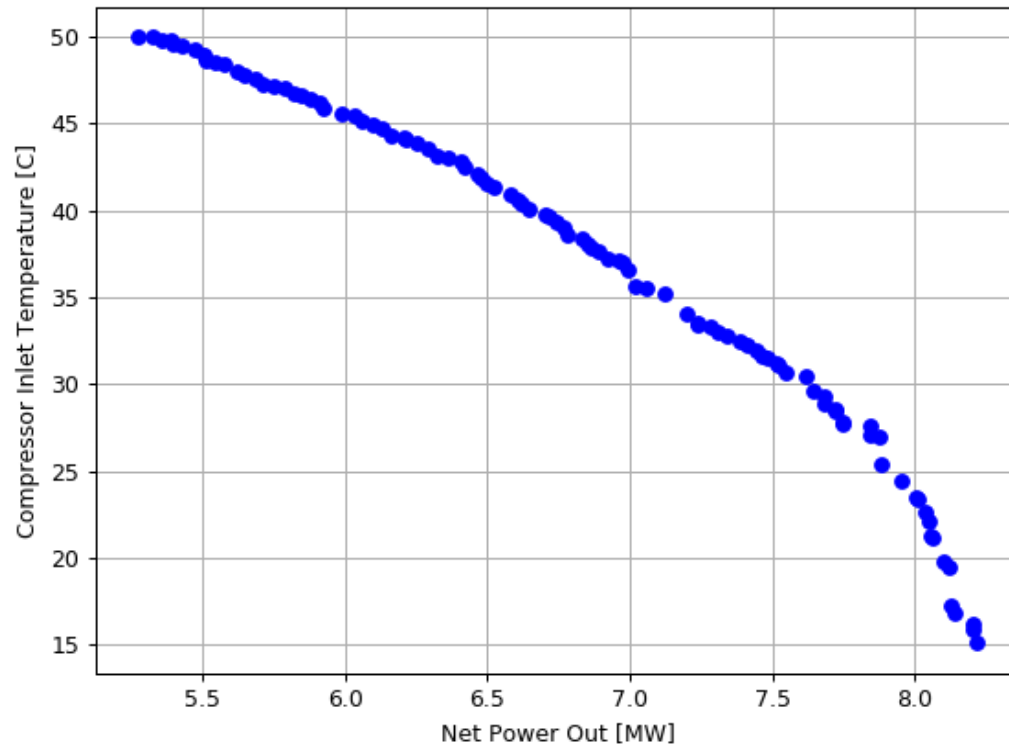


Examples of potential WHRS cycles.

Preliminary cycle analysis shows that the pre-heating cycle is able to recover the most power from the Titan 130 (16.5 MW). It does so even at a lower turbine inlet pressure and temperature.

	Non-recuperated	Recuperated	Pre-heating
Turbine inlet T [C]	493	396	330
Turbine inlet P [bar]	300	300	220
Thermal Efficiency [%]	19.0	32.3	28.4
Heat Recovery [MW]	4.4	5.6	6.7
Heat Recovery eff. [%]	17.7	22.3	27.0

Cycle Modeling Future work: Tradeoffs and optimization



NSAGA-II generated plot of compressor inlet temperature vs net power out.

When an overall cycle is chosen we still have a lot of trade-offs to do.

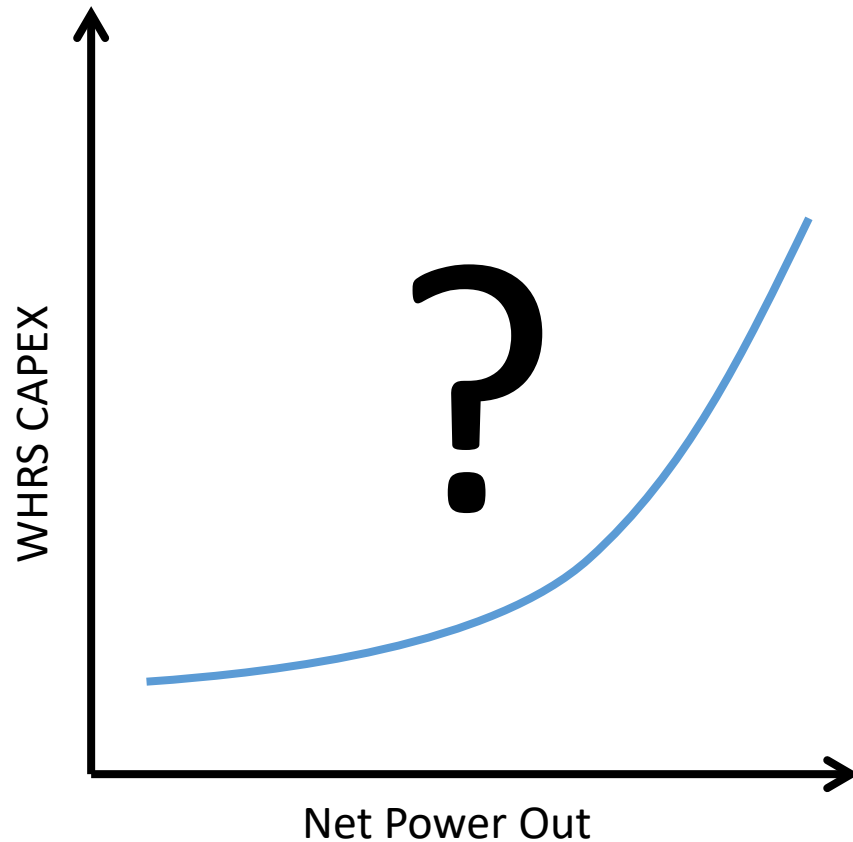
Using modern optimization tools, we can create Pareto fronts to allow for insight into these trade-offs.

For example, NSGAI was used to create this plot showing the Pareto front with two objectives, maximize net power and maximize compressor inlet temperature.

Similar plots can be created for:

- **Recuperator effectiveness** (more effective recuperators will allow for better cycle performance, but are bigger and cost more)
- **Turbine inlet temperature** (turbine inlet temperature will affect turbine performance as well as mechanical robustness)
- **Cycle high pressure** (higher pressures are better, but lead to larger more expensive casings)
- **Cycle low pressure** (lower pressures, near the critical point, are better but operating near the critical point is challenging)
- Many more off design scenarios

Cycle Modeling Future work: WHRS Cost Function and MO Optimization



An alternative approach to looking at each component individually would be to look at the overall cycle as a whole and develop a cost model for each component

Cost of turbomachinery as a function of

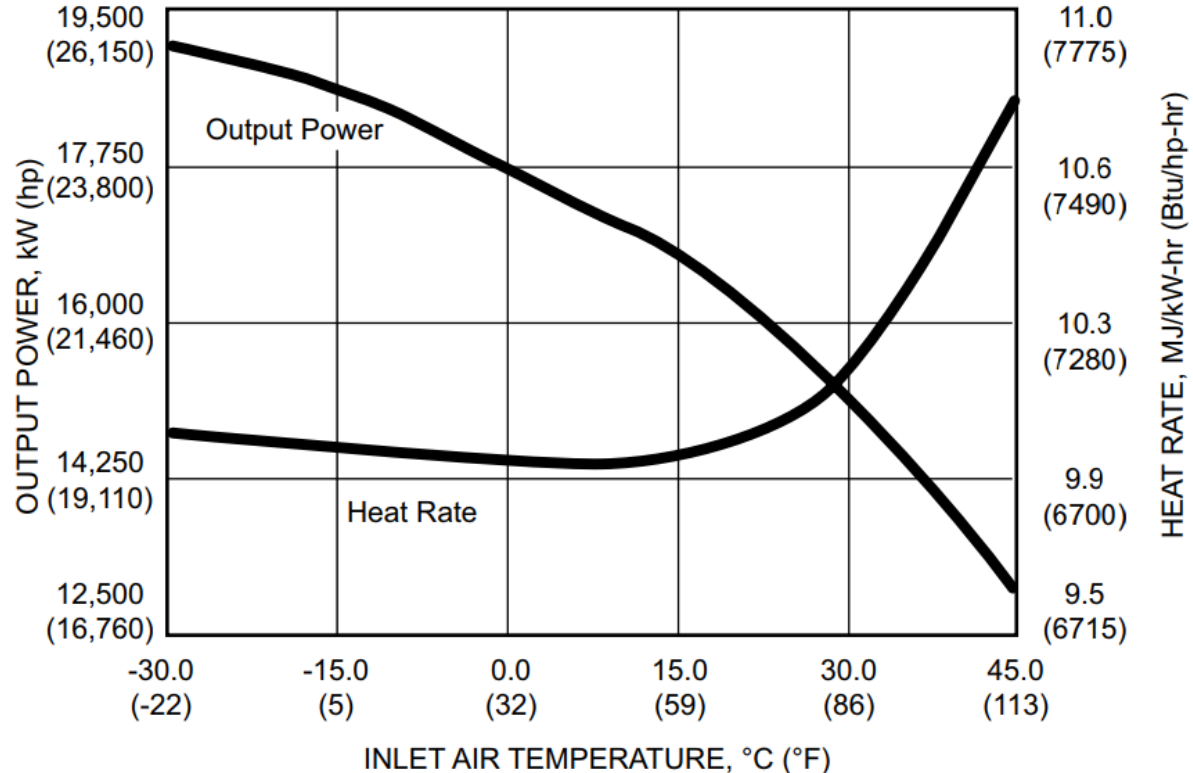
- Design pressure
- Design temperature
- Number of stages
- Number of pinions
- Power
- IGVs?
- Standardness of turbomachinery

Cost of heat exchangers as a function of

- Design pressure
- Design temperature
- Pressure drop
- Overall UA

With a system level cost function, we can use optimization to maximize power while minimizing CAPEX.

Cycle Modeling Future work: Off-design Optimization

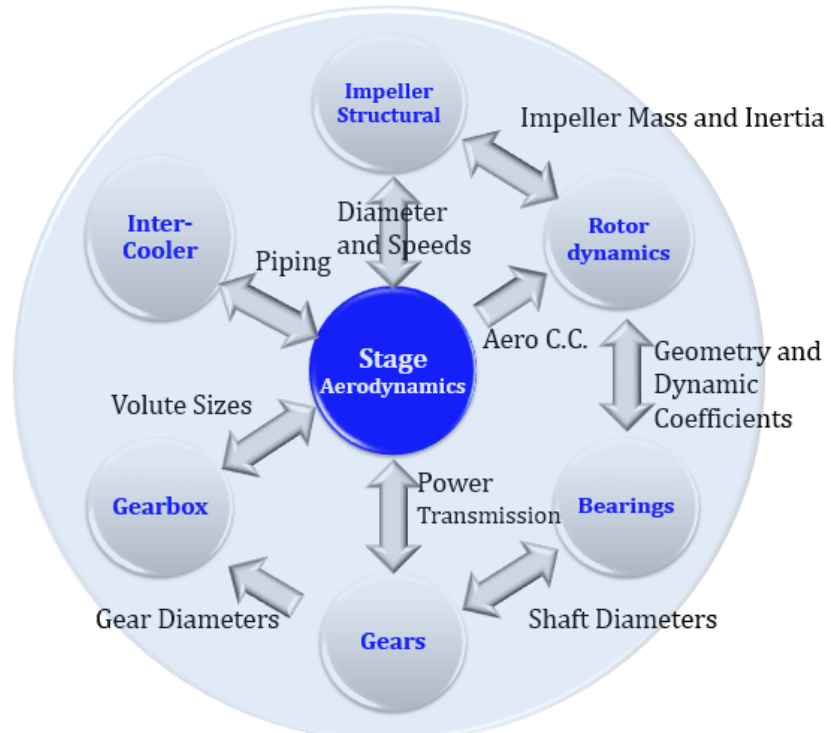


We can also take the definition of net power one step further and optimize for the best overall performance during over a series of off-design scenarios.

For example, A WHRS whose performance is very sensitive to ambient air temperature should score lower than one which is more robust to changes in ambient air temperature.

1D turbomachinery codes can readily produce off-design performance characteristics. SwRI has also developed a tool that allows for off-design heat exchanger performance without detailed specification of heat exchanger geometry.

Technical Approach: Aerodynamic/Mechanical/Rotordynamic design



Once the cycle has been defined and optimized, conceptual aerodynamic, mechanical, and rotordynamic design can begin. These three design phases will be highly iterative and build on each other.

Aerodynamic

Advanced meanline codes and correlations as well as Hanwha design experience will be used to define the impellers.

Mechanical

Mechanical design of the rotating and stationary components will be carried out using reduced order models and correlations. The design task will include gear design to maximize life, structural assessment to ensure maximum strength, and that the resulting design is serviceable.

Rotordynamic

Rotordynamic design will determine the optimal bearing and seal arrangements for the WHRS. The design will minimize shaft motions at critical clearances, such as impeller tips and seal locations.

Summary

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

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

