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

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ABSTRACT

The cycle optimization and conceptual design of an integrally geared Waste Heat Recovery Unit (WHRU) for integration with a Solar Turbines Titan 130 gas turbine to maximize energy output while minimizing capital costs are presented. In applications including natural gas transmission smaller gas turbines, such as those used at natural gas compression stations, are not typically coupled with Waste Heat Recover Systems (WHRS) due to the size, complexity, and initial capital cost of the WHR system. However, these obstacles can be overcome with the use of a supercritical carbon dioxide (sCO_2) power cycle. To design the cycle, the component configuration and cost coupled with the performance throughout a range of off-design conditions are considered. Cycle configurations are down-selected based on achievable efficiencies and constraints including the prevention of acid dew point corrosion in the heaters. Component costs are included from turbomachinery and heat exchangers based on procurement experience, vendor data, and published cost correlations. Off-design performance is evaluated with the use of cycle models built-in numerical propulsion system simulation (NPSS) that incorporate hourly historical weather data for the system location, gas turbine exhaust conditions for varied operational profiles, the conductance ratio method for heat exchanger off-design performance, and turbomachinery maps scaled for design-specific conditions. With a multi-objective optimization process implementing the SMPSO algorithm, a Pareto optimal curve establishes the maximum annual energy output attainable for a range of initial capital cost investments for a given installation location. Supplemented by techno-economic analyses, the optimization results allow for informed decision making towards the cost-effective implementation of the WHRU.

INTRODUCTION

Large combined cycle gas turbine power plants typically rely on steam Rankine bottoming cycles to recover additional energy from the waste heat stream and increase overall plant efficiency. Current state-of-the-art plant efficiencies for large utility-scale plants have reached 62% [1], but further gains are likely to be modest as the current technology nears full maturity. Therefore, a disruptive improvement to the system is needed for continued efficiency improvements, especially for smaller gas turbines whose simple cycle efficiencies are typically much lower than those of larger gas turbines. In the application of Waste Heat Recovery for medium grade heat sources, sCO_2 cycles have advantages over traditional Organic Rankine Cycles (ORC) in areas of chemical stability and installation footprint and cost [2]. The overall goal of the project discussed in this paper is to combine a commercially available gas turbine, Solar Turbines Titan 130, with a compact, skidded, sCO_2-based WHRS to form a combined cycle power system that is highly efficient and modular. This system would apply to new and existing gas turbine installations. This paper discusses the multi-objective thermodynamic cycle optimization process as well as the initial conceptual design for the WHRS.

CYCLE SELECTION AND LAYOUT

Preliminary analysis showed that the preheat cycle is well suited for waste heat recovery applications due to its high level of waste heat stream energy extraction as well as simplicity when compared to other cycles. In the preheat cycle, as the preheater receives flow directly from the compressor, it is susceptible to acid dew point corrosion. Acid dew point corrosion is an issue if the temperature of the flue gas stream from the gas turbine drops below its acid dew point temperature. When this happens, acid droplets can form and damage critical heater and gas turbine components. This is more likely to occur when low compressor inlet temperatures drive down the compressor outlet temperature and thus heater inlet temperature. The compressor inlet temperature is primarily controlled by low ambient temperature. This translates to a system that is unable to take advantage of increased compressor efficiency afforded by lower compressor inlet temperature. Also, a higher acid dew point temperature effectively limits the amount of energy that can be extracted from the waste heat stream, which also limits the combined cycle efficiency. The acid dew point temperature of flue gas is highly dependent on the gas turbine fuel. Pipeline natural gas and hydrogen have relatively low acid dew point temperatures, while unconventional fuels, such as coal-derived syngas, have more sulfur and other impurities and thus higher dew point temperatures.

To address acid dew point corrosion and allow the WHRS to be adaptable to any potential fuel, the project team modified the traditional preheat cycle by adding a stage of recuperation between the compressor and the flow split to increase the temperature of the sCO_2 before the preheater. This is shown schematically in Figure 1.

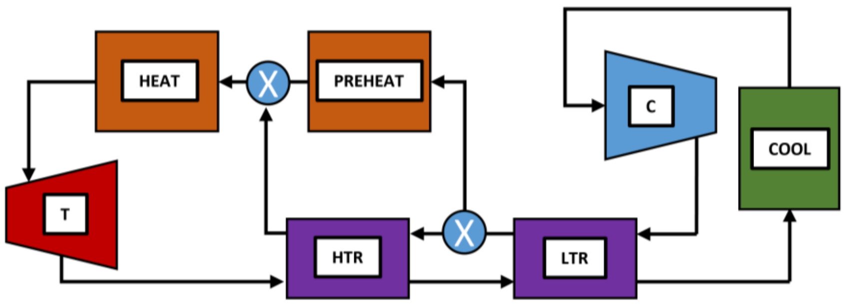

Figure 1: PreheatSR Cycle Layout. The PreheatSR cycle addresses acid dew point corrosion by adding the low temperature recuperator (LTR) to increase the temperature of the flow prior to the preheater

As can be seen in Figure 1, the PreheatSR cycle splits the recuperator into two sections, the Low-temperature Recuperator (LTR) and High-temperature Recuperator (HTR). By tuning the amount of recuperation in the LTR, the preheater inlet temperature can be adjusted to ensure that no acid dew point corrosion will occur. This is a unique aspect of the PreheatSR cycle that allows it to take full advantage of lower compressor inlet temperatures while limiting the negative performance impact of using high sulfur content fuels like coal-derived syngas. Figure 2 shows the effect of various heater inlet temperature (HIT) limits on cycle performance for both the Preheat and PreheatSR cycles at various compressor inlet temperatures.

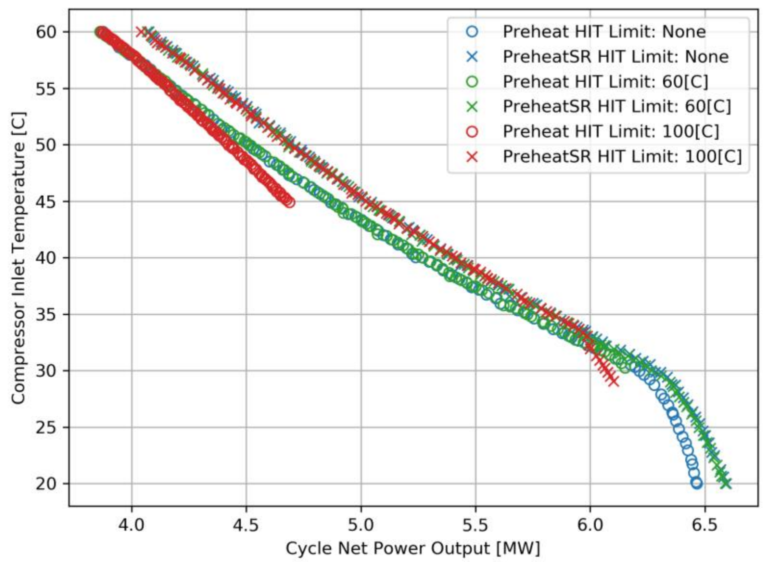

Figure 2: Effect of Heater Inlet Temperature (HIT) Limit on Cycle Performance at Various Ambient Temperatures

Several insights are apparent from the results shown in Figure 2. First, the PreheatSR cycle provides increased performance when compared to the Preheat cycle even without a heater inlet temperature limit. This is due to the extra full flow recuperation afforded by the PreheatSR cycle. Second, the PreheatSR cycle provides much better performance with an imposed HIT limit when compared to the Preheat cycle. For a HIT limit of 60°[C], which is typical of clean pipeline natural gas, the Preheat cycle is effectively limited to a compressor inlet temperature of 30°[C]. This means that for low ambient temperature conditions, the Preheat cycle cannot take advantage of the lower compression power afforded by lower compressor inlet temperatures. In this situation, the Preheat cycle would be required to reduce heat rejection to ensure that the compressor outlet temperature, and thus heater inlet temperature, is below the HIT limit. As the PreheatSR cycle has an extra stage of recuperation, it can heat the compressor outlet flow to above the HIT limit even with a low compressor inlet temperature. As shown in the figure, with a HIT limit of 60°[C] and assuming that heat rejection to a 20°[C] compressor inlet temperature is possible, the PreheatSR cycle provides a cycle performance increase of 7% over the Preheat cycle. The required HIT limit will increase with alternative gas turbine fuels such as coal-derived syngas. The high performance of the PreheatSR cycle at high HIT limits makes the PreheatSR cycle a highly capable and adaptable cycle for use with these alternative fuels.

The majority of the core components of the PreheatSR are packaged on a single skid and include gearbox and turbomachinery core assembly, lube oil reservoir, generator, control panel, seal rack, oil cooler, recuperator, recovery compressor, startup motor, and VFD. A graphic of the skid layout is shown in Figure 3. The size of the skid is constrained in order to allow for shipment by truck.

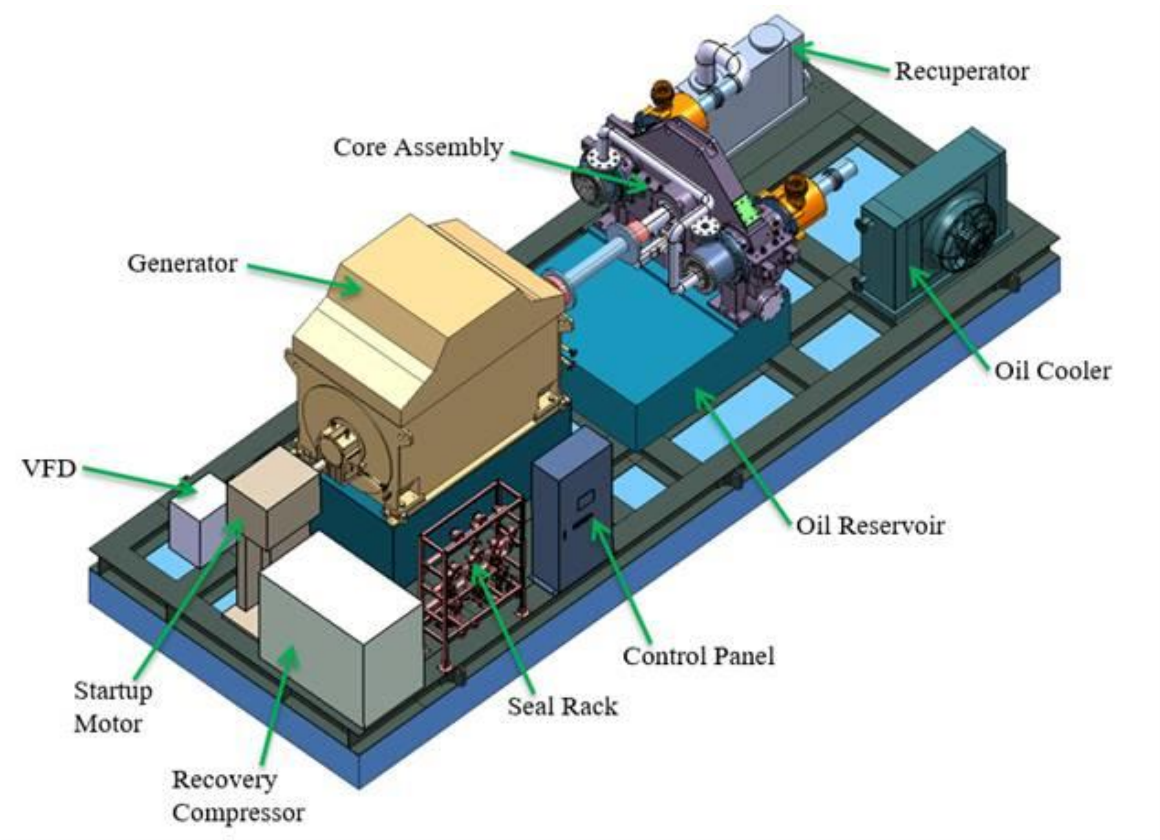

Figure 3: Skid Layout

While prior development for the Department of Energy (DOE) Apollo program featured the integrally geared machine having separate compressor and expander pinions, the comparatively lower turbine inlet temperature of the WHR machine allows for separate high- and low-pressure pinions that have the advantage of only needing to transmit the net power (turbine – compressor) rather than the combined power. The core assembly also features numerous design features that incorporate lessons learned from the development of similar equipment for CSP applications, including usage of a stainless steel casing instead of more expensive nickel alloys and additional support members on the gearbox.

Cycle components not positioned on the skid include standalone units of the heater and cooler assembly. With cooling water infrastructure rarely being available at locations including natural gas compression stations where a WHRS might be applied, commercially available air coolers are implemented. The air cooler assembly will have multiple bays employing forced convection through a series of fans that include VFD controllers. The VFD controllers allow for providing optimal net energy output for the cycle by reducing fan power consumption when cooler ambient temperatures lead to reduced airflow rates being required. The heater assembly includes a main section with the full-cycle mass flow and a preheating section that has a fraction of the total cycle mass flow. The configuration of the heater assembly is similar to that of a heat recovery steam generator (HRSG), employing ducting from the gas turbine exit to a stack that transfers heat through GT exhaust flowing over coils containing the CO_2 cycle flow.

CYCLE OPTIMIZATION

Thermodynamic cycle analysis of the WHRS was conducted using a multi-objective optimization algorithm that seeks to maximize the annual energy output of the cycle while minimizing the capital cost of the WHRS. The optimization algorithm uses two processes to identify the best cycle design: an outer process that defines the design point of the cycle and machinery specifications, and an inner process that optimizes the off-design operation of the chosen design point cycle for a range of ambient conditions.

The outer optimization process uses the SMPSO algorithm [3] to evaluate a large swarm of candidate designs over numerous generations, arriving at a Pareto front that defines the maximum annual average cycle net power output at different capital costs. The swarm candidate designs, and thus a member of the final Pareto front, have a unique combination of 12 variables; these variables include the design ambient temperature, heat exchanger effectiveness, design cycle mass flow, and rotor speed among others. To address the acid dew point corrosion issue for pipeline grade natural gas, the optimization constrains the preheater inlet temperature to be greater than 60° [C]. The use of the multi-objective optimization routine allows for the navigation of the complicated interplay between LTR design point effectiveness, cooler design point effectiveness, and off-design cooler fan power subject to the preheater temperature limit during all off-design points.

The inner optimization process takes the candidate design and evaluates its design and off-design performance. The evaluations are carried out within Numerical Propulsion System Software (NPSS) [4], an engineering design tool used for aero-thermal systems. Custom elements were designed in NPSS, including heat exchangers that use the conductance ratio method [5] to predict off-design performance and turbomachinery that reflects HPSA sizing and performance methods. The design run in NPSS sets the necessary conditions for the heat exchangers and compressor and expander performance maps necessary for off-design cycle evaluation. The off-design evaluations are completed over a range of six different ambient temperatures with Titan 130 gas turbine exhaust conditions reflecting the changes in gas turbine operation for each specific ambient condition. Input variables of cycle mass flow rate, preheater flow split, and air cooler airflow rate are used for off-design valuation. The combinations of variable values evaluated are derived from a Python implementation of a unit hypercube sampling method [6].

The cycle point for each ambient condition is chosen based on its net power output, a value that considers the turbomachinery mechanical losses and generator efficiency as well as the power consumption of the air cooler fans.

The outer optimization receives the design conditions as well as the off-design performance for an array of ambient temperatures and the total cost of all the cycle components. To calculate the average yearly net power output, average hourly temperature data for a calendar year for the site of interest is used. A weather station nearest the Williams Company gas processing plant located in Oak Grove, West Virginia was chosen as a representative site for the optimization study. The power output at each hour is interpolated from the off-design performance points and the average yearly power output value is calculated with Simpson's rule integration method. A typical series of off-design performance points along with the ambient temperature series used can be seen in Figure 4.

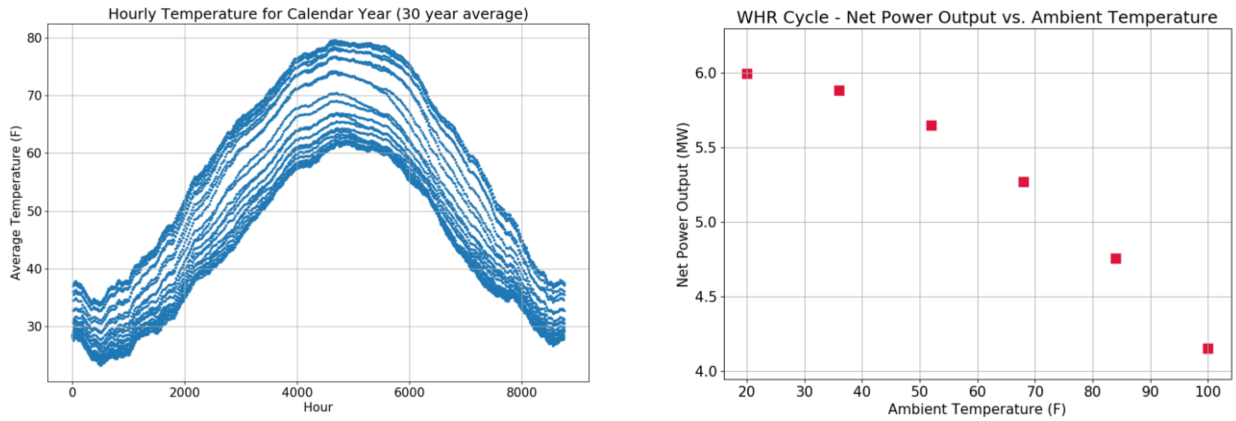

Figure 4: 30-year Average Temperature for Oak Grove, West Virginia (left) and Cycle Off-Design Performance for Different Ambient Points (right)

For the outer optimization to evaluate the other objective, WHRS capital cost, cost functions for each component of the cycle are required. For turbomachinery components, HPSA experience in the production of integrally geared turbomachinery informed the creation of a model that uses compressor and turbine operating temperature and pressure, mass flow, stage count and other parameters to compute the total turbomachinery package cost (including dry gas seal and seal rack, gearbox, generator, skid, lube system, and instrumentation). The heat exchanger cost correlations were based on vendor data and published correlations, with each expressing cost as a function of the thermal conductance (UA) value. For the cooler and recuperator, correlations compiled by Weiland based on numerous quotes for sCO_2 power cycles application were used [7]. For the heater, quotes received from vendors for WHRS cycle conditions of varying heater approach temperatures were implemented for the heater and preheater cost relationship.

The final Pareto front generated defines 160 candidate designs (defined by the swarm size) along with the distribution of component costs throughout the Pareto front is shown in Figure 5.

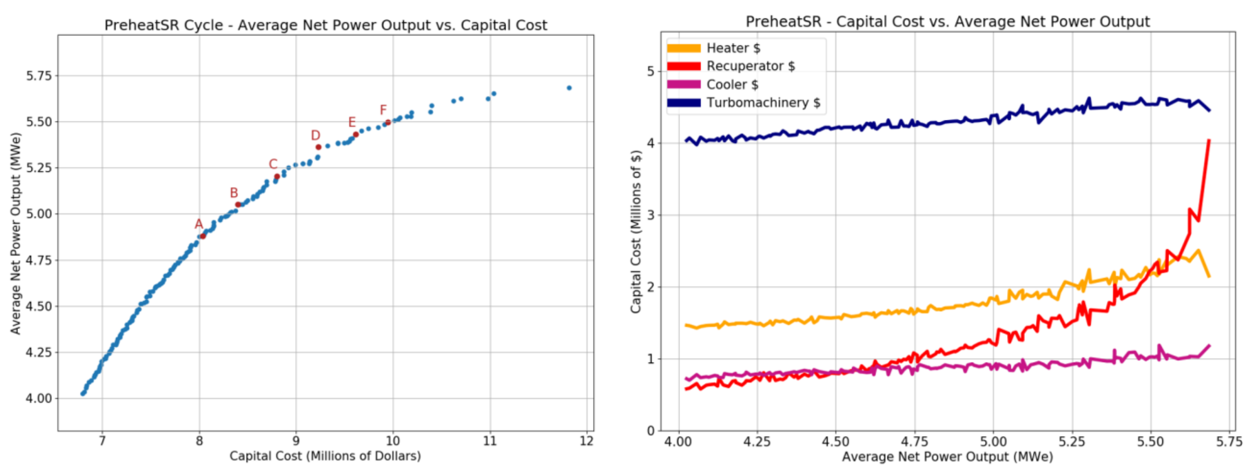

Figure 5: Final Pareto Front of PreheatSR for WHR Application (left)
and Breakout of Component Costs (right)

As shown in Figure 5, higher average yearly performance is only possible with an increased capital cost. The Pareto front shown in Figure 5 effectively shows the maximum possible performance given a certain capital cost. Figure 5 also shows the distribution of component capital cost along the Pareto front. From the figure, it is clear that the main cost driver is the recuperator.

To narrow the front down to design with which to continue forward, a techno-economic analysis was used that considered the net present value (NPV) to assess the profitability of investment in a WHRU. To calculate an estimate for the revenue provided each year, the following assumptions were used:

- 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

Figure 6 displays the NPV for a range of discount rates, with letters A-F used to inspect specific designs along with a range of possible selections. With design D having the greatest NPV for almost all of the discount rates assessed, it was chosen as the design to go forward with detailed design.

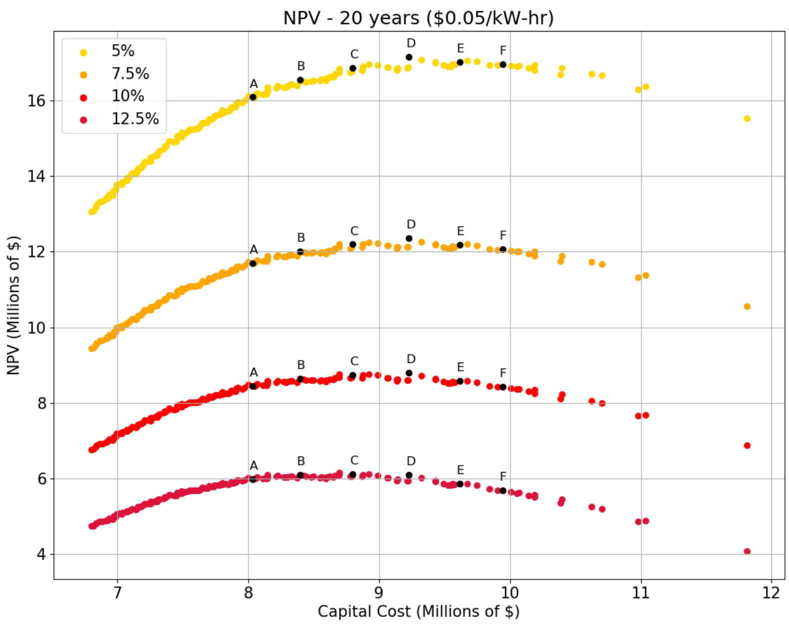

Figure 6: Net Present Value of Various Design

Table 1 lists selected cycle design parameters for point D from Figure 5 and Figure 6.

Table 1: Selected Cycle Design Parameters

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

CONCLUSIONS

This paper has presented the cycle design and optimization details for a sCO_2-based WHRS targeting the Solar Turbines Titan 130. The PreheatSR cycle layout was chosen to effectively address the issue of acid dew point corrosion and ensure high system performance is not significantly impacted by use of alternative fuels. The optimization process discussed uses a multi-objective optimization to discover a series of optimal cycle configurations given ambient temperature variability for a chosen site location while considering the initial capital cost of the cycle components. Cycle models built that incorporated off-design methods for the heat exchangers and turbomachinery allowed for the investigation of cycle operation that maximizes power output for individual cycle conditions. The resulting Pareto front serves as a guide for how to configure the WHRS cycle for the highest yearly energy extracted for a given investment.

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DISCLAIMER

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