Thermo-Economic Analysis of Four sCO2 Waste Heat Recovery Power Systems

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Introduction

- **Goal: Provide A System Performance and Economic Analysis of Four Waste Heat Recovery sCO2 power system**
- **Four WHR sCO2 power systems:**
  - Simple Recuperated Brayton Cycle (SRBC)
  - Cascaded Cycle : Patented & WHR
  - Dual Recuperated Cycle: Patented & WHR
  - Preheating Cycle: Public & WHR
- **Assumptions**
  - Gas Turbine, M2500 extending EPRI Study by Kimzey
  - sCO2 Bottoming Cycle Power Systems
  - Economic, Component Costs and Operating Conditions
- **Comparison of System Performance**
  - Focus: on Maximizing Annual Revenue = Electric Power Produced
  - Answers these questions:
  - Does It make economic sense to use HX's of High Effectiveness?
  - How do the publically available cycles compare to the commercially patented cycles?
- **Economic Summary**
  - (System Costs, Annual Revenue, LCOE, Rates of Return)
- **Conclusions**
  - All WHR have Higher Revenue, Lower LCOE, Produce Substantially Greater Elect Power
    - But at greater cost
  - As a group the WHR Perform Similarly in terms of Electrical Power and Economics
  - Recuperators with High Effectiveness are Generally Favored

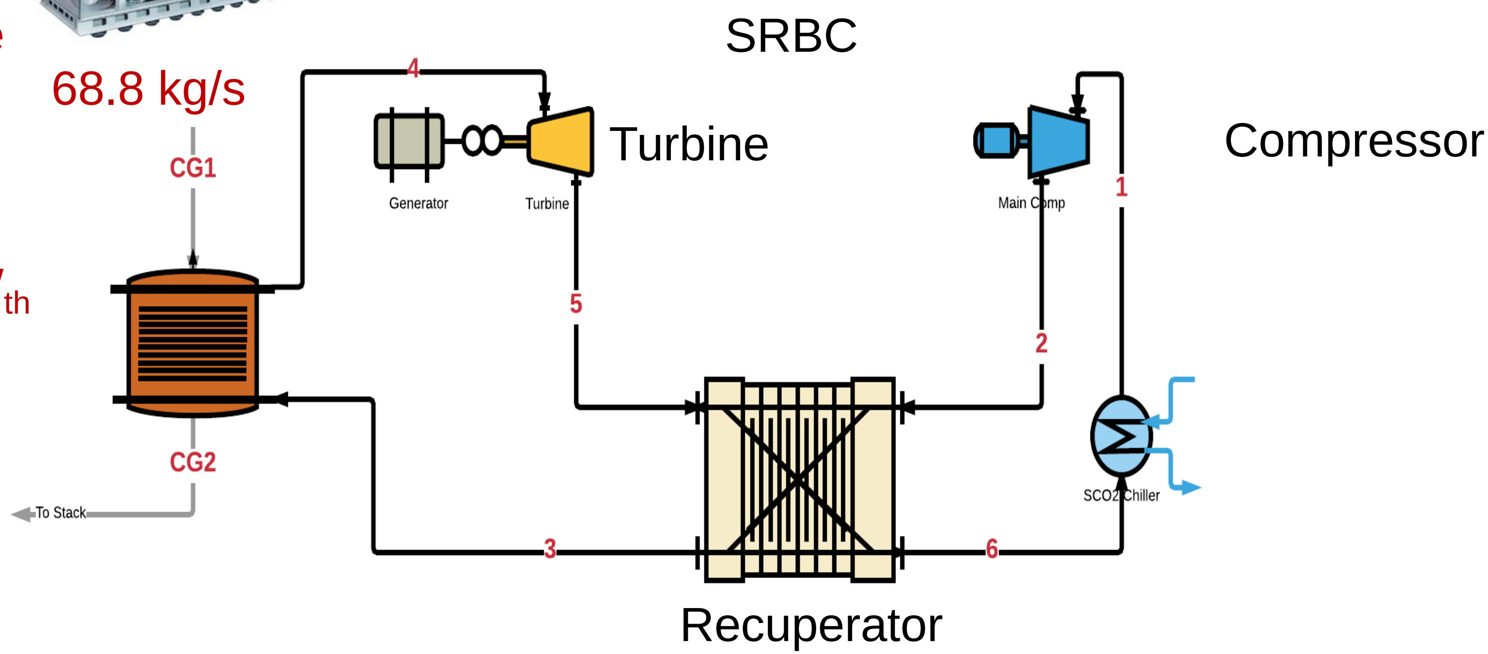
Gas Turbine Assumptions

Primary Gas Turbine	LM-2500PE
Mass Flow Rate Gas Turbine	68.8 kg/s
Temp of Gas Turbine Exhaust	822.1 K
Efficiency (at Gen Terminals at 15 C ambient)	35.5%
Thermal Combustion Power (@ 10146 kW/ BTU/hr)	63,131 kW_{th}
Thermal Exhaust (Waste Heat) Power kW (@ 15 C)	40,731 kW_{th}

LM2500PE
Gas Turbine

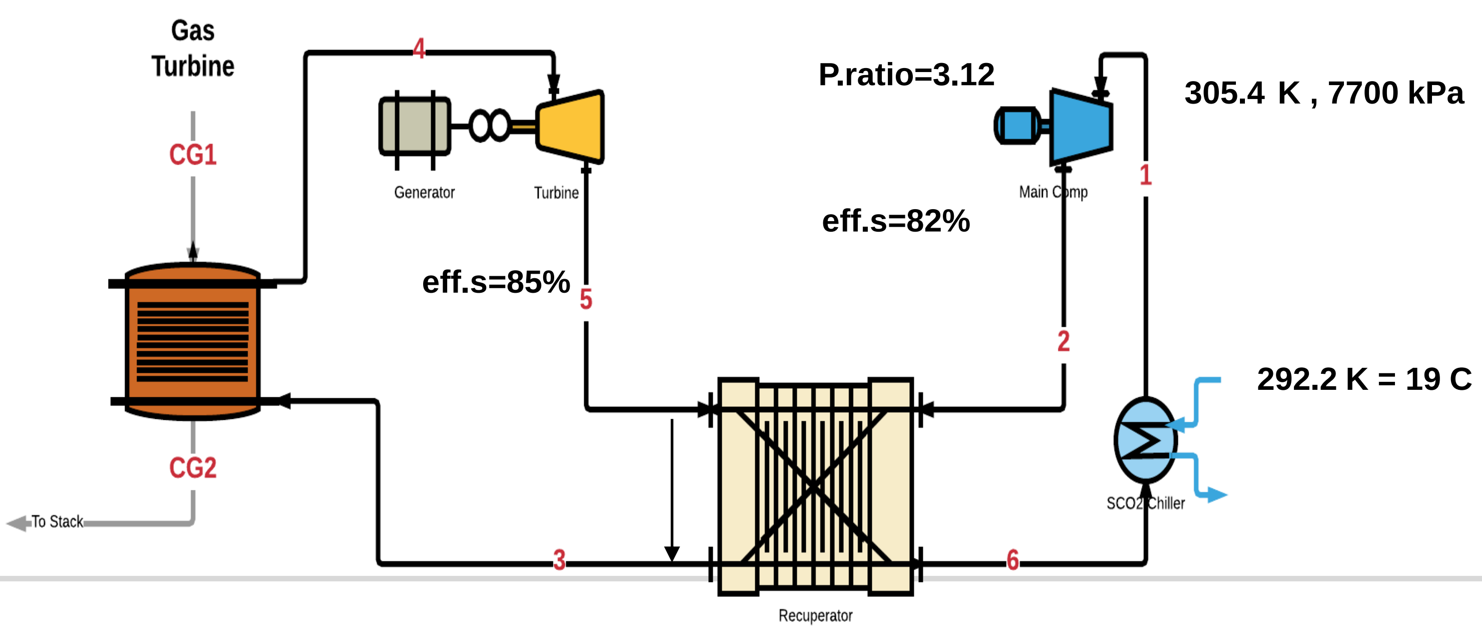
822.1 K
(538 C)

40.7 MW_{th}



sCO2 Power Cycle Assumptions

sCO2 Assumptions	Value
Turbine Isentropic Efficiency	85%
Compressor Isentropic Efficiency	82%
Losses Shaft to Electrical (Bearings, Gears, Generator, etc.)	7%
Water Inlet Temp	292.2 K = 19 C
Compressor Inlet Pressure	7700 kPa
Compressor Inlet Temp	305.4 K
Compressor Pressure Ratio	3.12
Operating Conditions Varied to Optimize Net Annual Revenue *Variables were: Turbine Inlet T + All Heat Exchanger Approach Temperatures, Split Flow Fraction and Compressor Mass Flow Rate*	-



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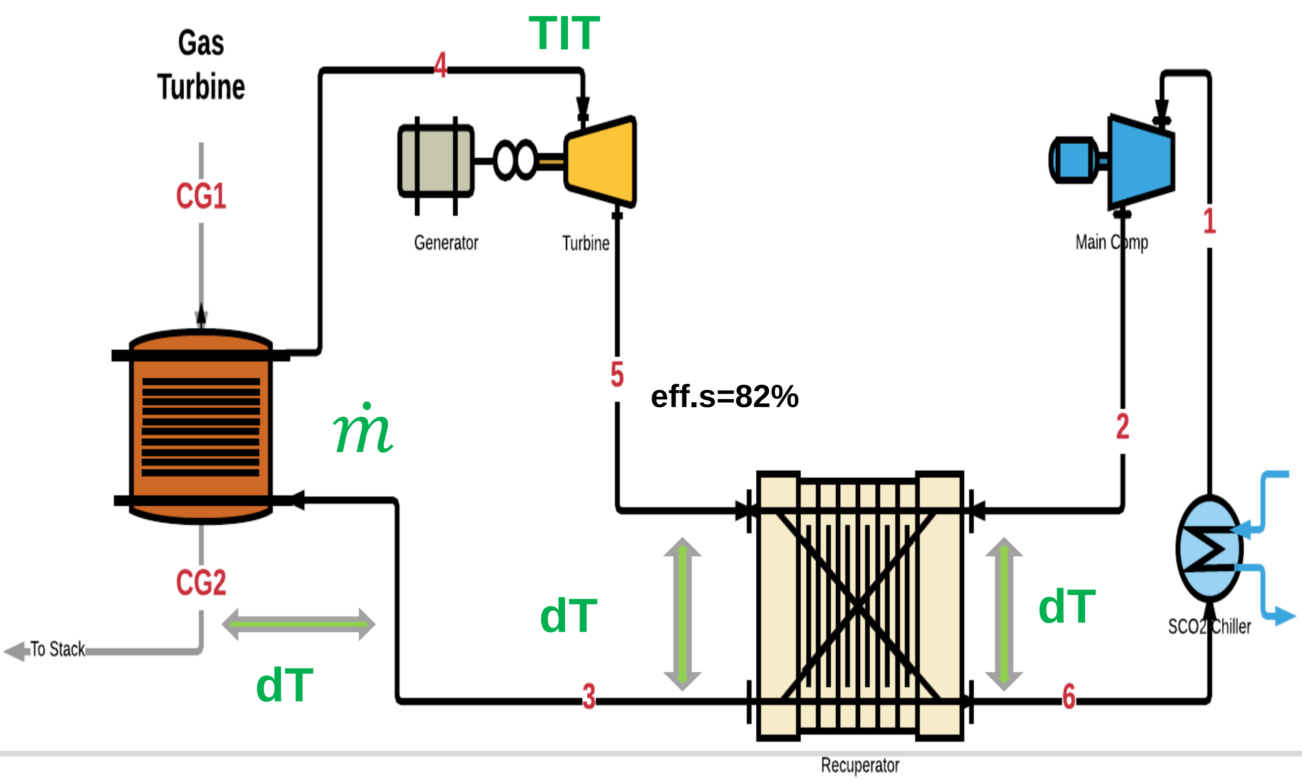
Performance Optimization

Optimization Parameters

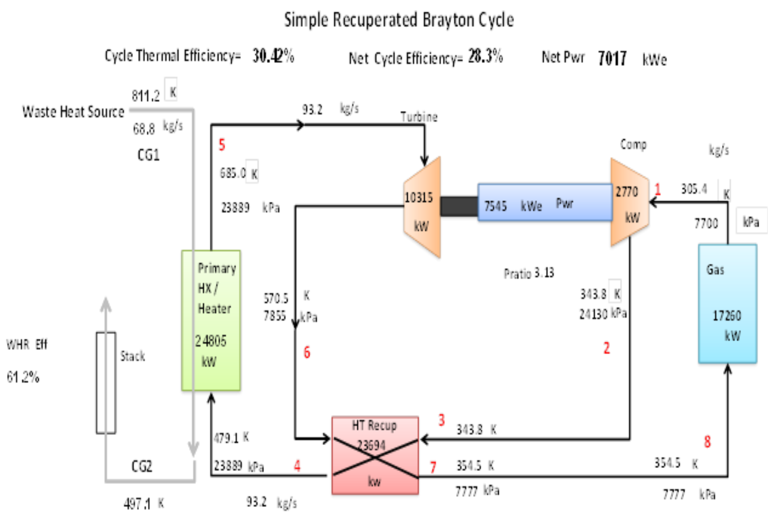
- Mass Flow Rate
- Turbine Inlet Temp
- $dT_{approach}$ Recuperator Cold side
- $dT_{approach}$ Recuperator Hot side
- $dT_{approach}$ Prim HX
- Split Flow (if used)



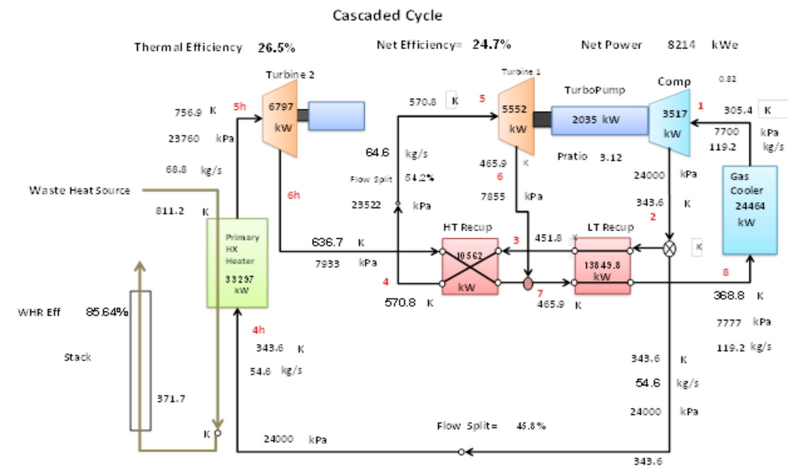
+ Flow Split

Four sCO2 Power Cycles

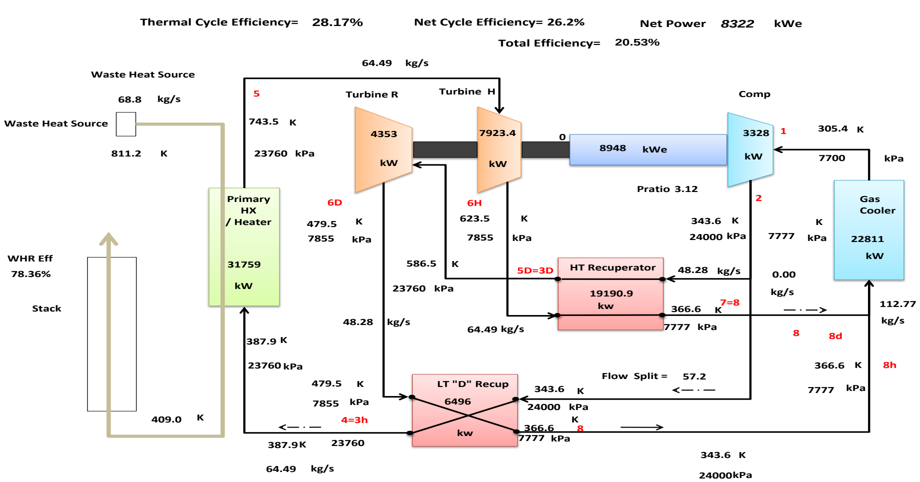
Simple Recuperated Brayton Cycle



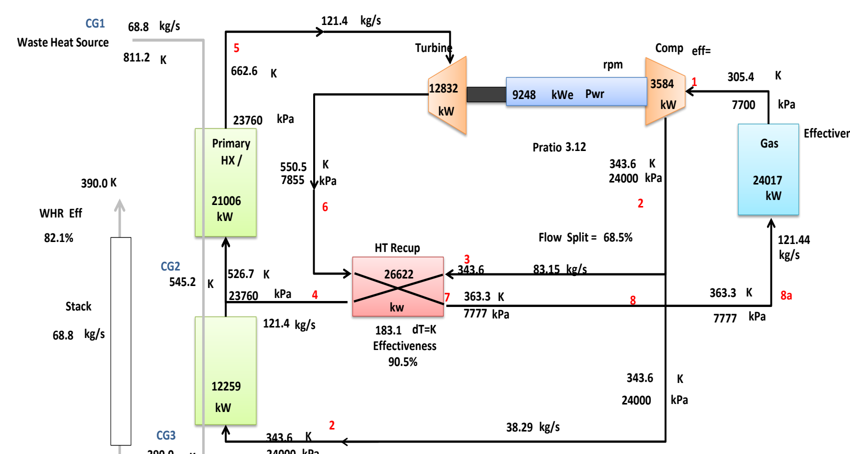
Cascaded Cycle



Dual Recuperated Cycle



Preheating Cycle



All WHR sCO2 Cycles Use Split Flow

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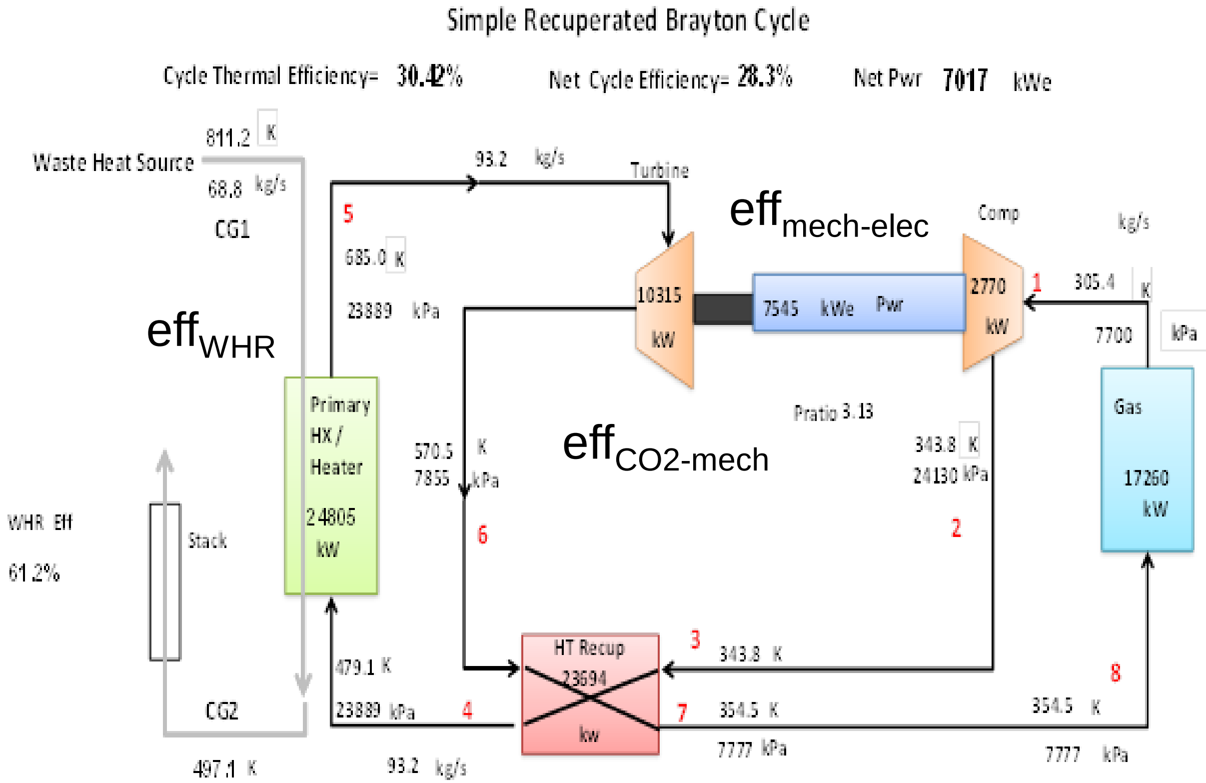
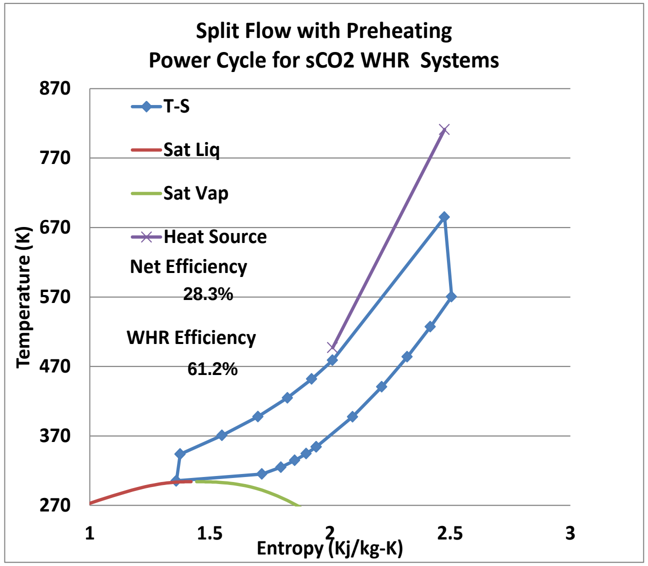
Simple Recuperated Brayton Cycle



glide curve



Net Efficiency is $eff_{NET} = eff_{WHR} * eff_{co2\text{-}mech} * eff_{mech\text{-}elec}$ (93%)

CG Exit Temp is Limited by Recup High Pressure Exit Temp: This is high (see glide curve)

This lowers Waste Heat Recovery Efficiency $eff_{WHR}=(Q_{CO2}/Q_{WH}) = 61.2\%$

Power Optimization Increases $eff_{CO2} = 30.4\%$

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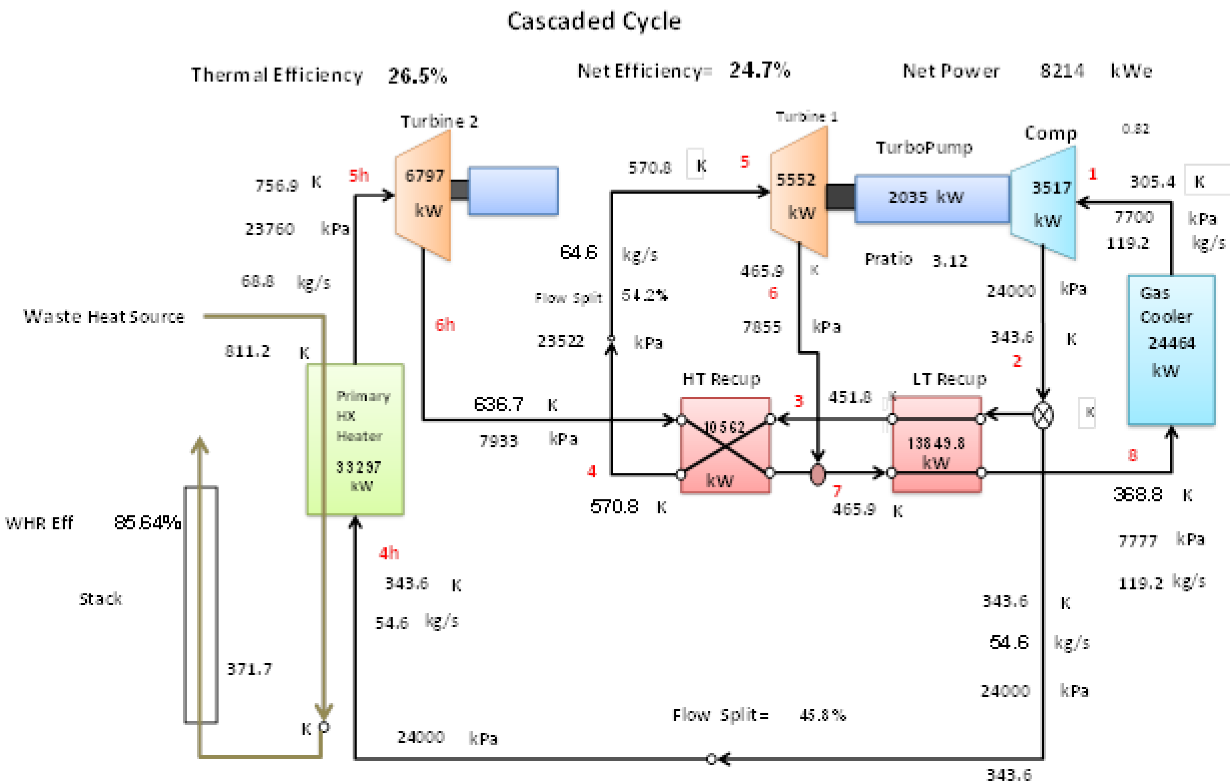
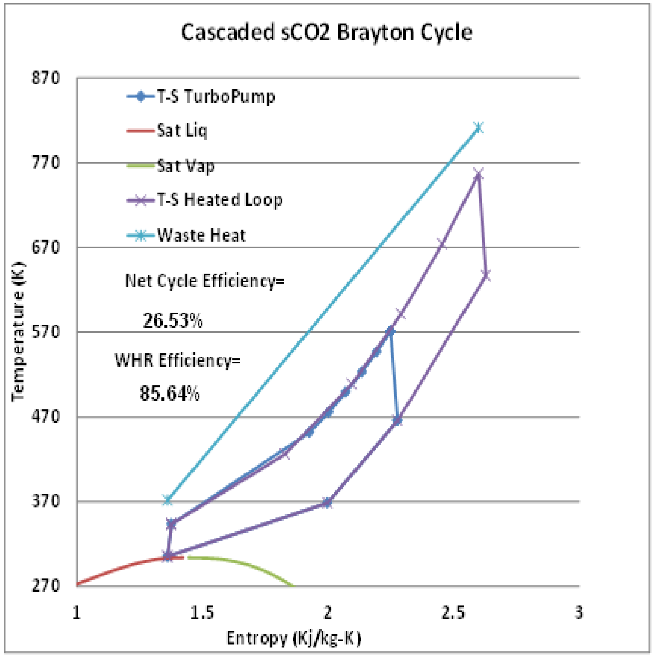
Cascade Cycle



glide curve



CG Exit Temp is now limited by Compressor Exit Temp: This is low (see glide curve)

This Increases Waste Heat Recovery Efficiency $eff_{WHR}=(Q_{CO2}/Q_{WH})$ 85.6%

Power Optimization with 2 Turbines and 2 Recup Increases eff $_{CO2}$= 26.5%

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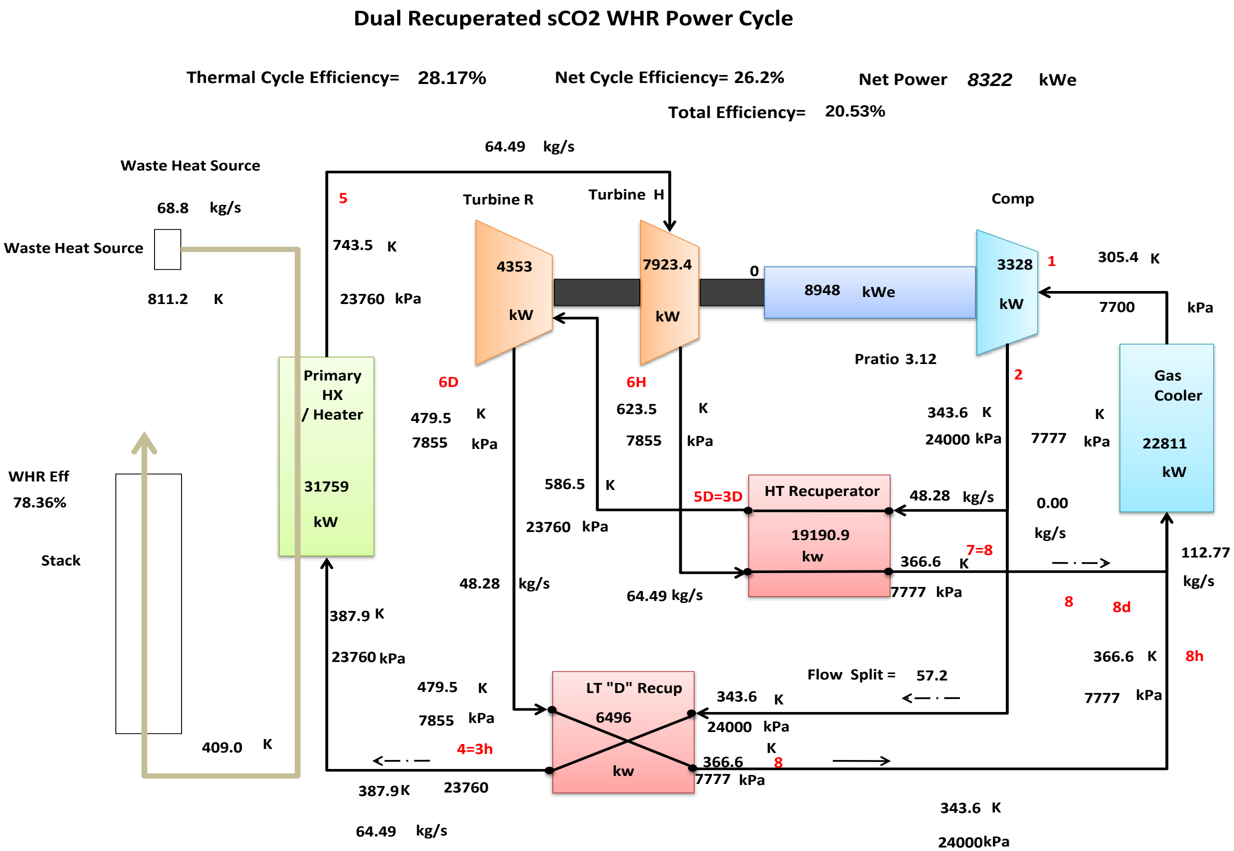
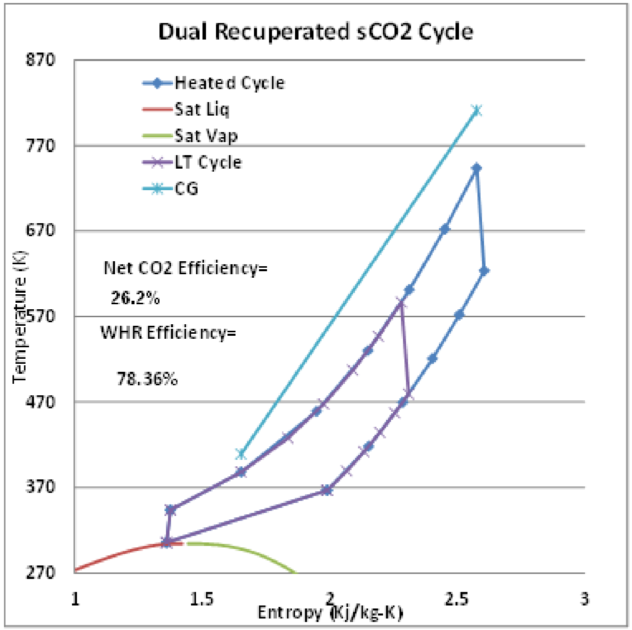
Duel Recuperated Cycle

glide curve





CG Exit Temp is now limited by LT Recup Exit Temp This is intermediate (see glide curve)

This Increases Waste Heat Recovery Efficiency $eff_{WHR}=(Q_{CO2}/Q_{WH})$ 78.4%

Power Optimization with 2 Turbines and 2 Recup Increases eff $_{CO2}$= 28.2%

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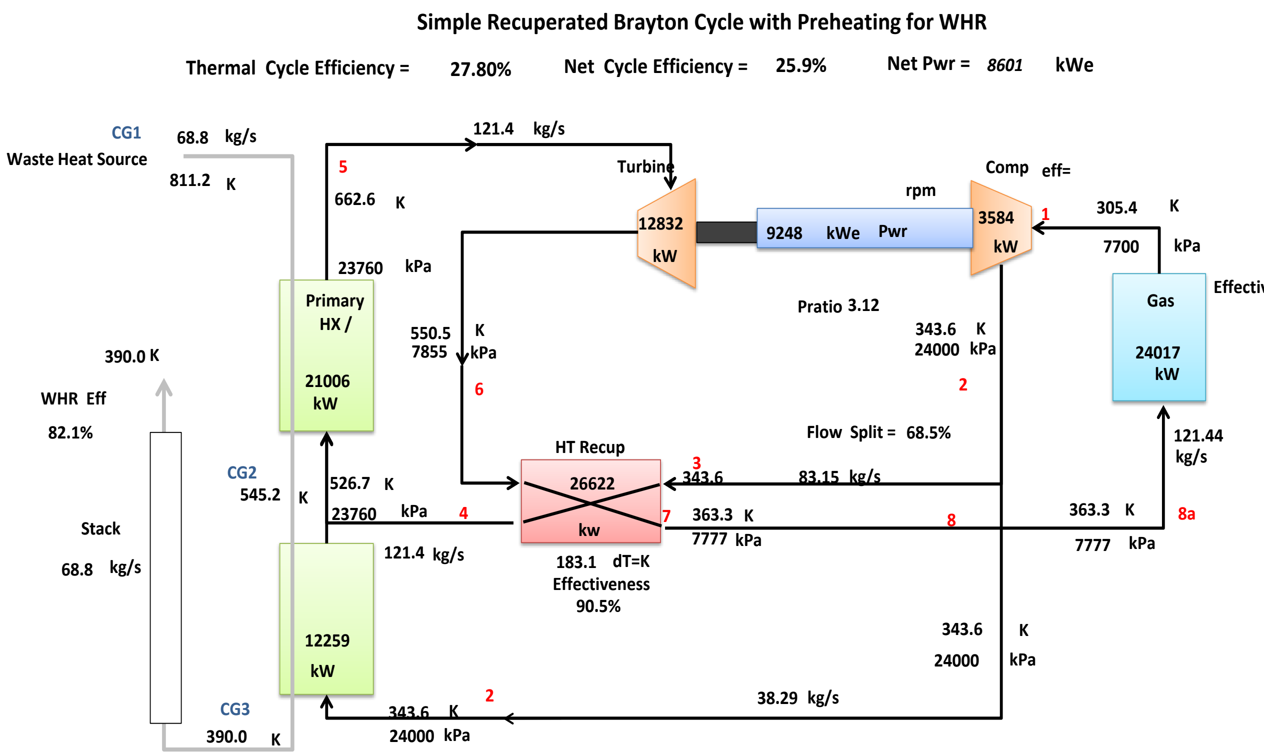
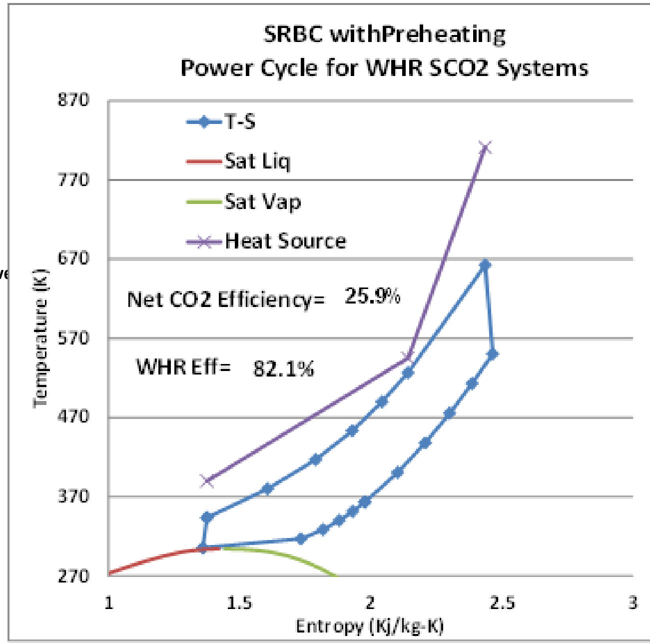
sCO2 Preheating Cycle

glide curve





CG Exit Temp is now limited by Compressor Exit Temp This is low (see glide curve)

This Increases Waste Heat Recovery Efficiency $eff_{WHR}=(Q_{CO2}/Q_{WH})$ 82.1%

Thermal Cycle Efficiency: eff_{CO2}= 27.8%

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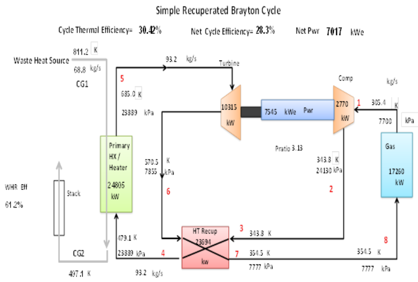
Four sCO2 Power Cycles

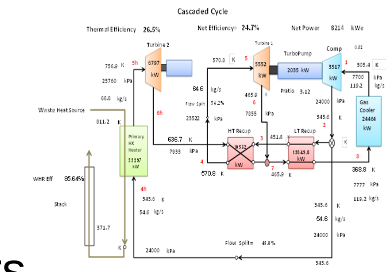
Simple Recuperated Brayton Cycle

1Turbine
1 Compressor
1 Recuperator
1 CO2 Chiller
1 Prim Hx
5 Components : No Split Flow



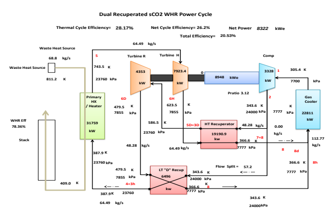
Cascaded Cycle

2 Turbines
1 Compressor
2 Recuperators
1 CO2 Chiller
1 Prim Hx
7 Components + Split Flow



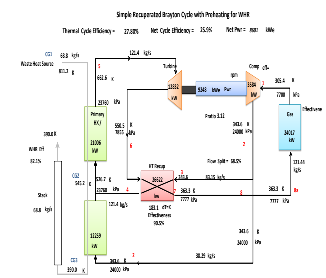
Dual Recuperated Cycle

2 Turbines
1 Compressor
2 Recuperators
1 CO2 Chiller
1 Prim Hx
7 Components + Split Flow



Preheating Cycle

1 Turbines
1 Compressor
1 Recuperators
1 CO2 Chiller
2 Prim Hx
6 Components + Split Flow



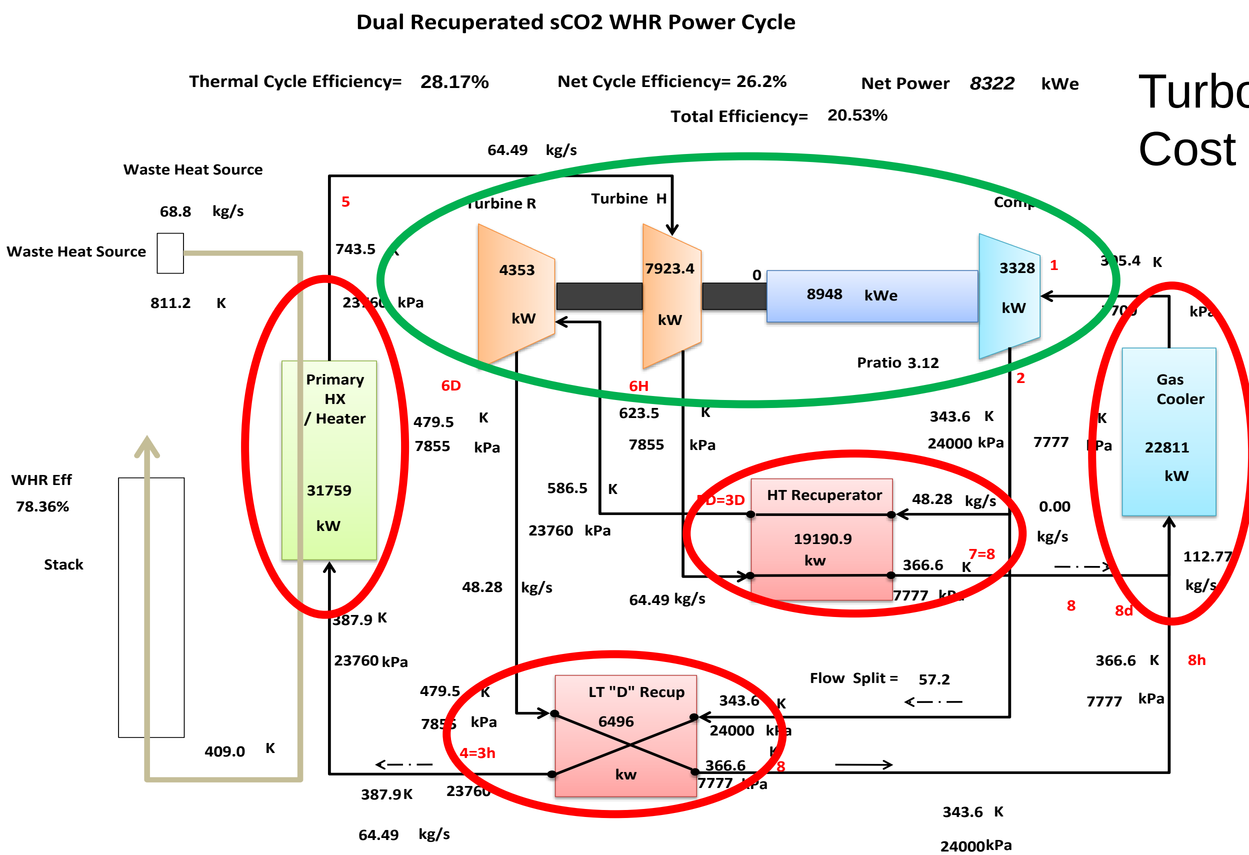
Economic Assumptions

Economic Assumptions	Value
Plant Lifetime	20 yr
Plant Utilization Factor	85%
Discount Rate	5%
Sale Price of Electricity	$\$0.06/kWh_e$
Thermal Exhaust (Waste Heat) Power kW (@ 15 C)	$40{,}731\ kW_{th}$

+

Component Specific Costs

Component Costs



Turbo Machinery + Aux

$\text{Cost} = \text{SpecCost}_{Turb+Aux} * \text{Pwr}_e$

Primary Heater Recuperators CO2 Chillers

$Q = U * A * LMDT$ $\text{Cost} = \text{SpecificCost}_{HX} * Q/LMDT = U * A$

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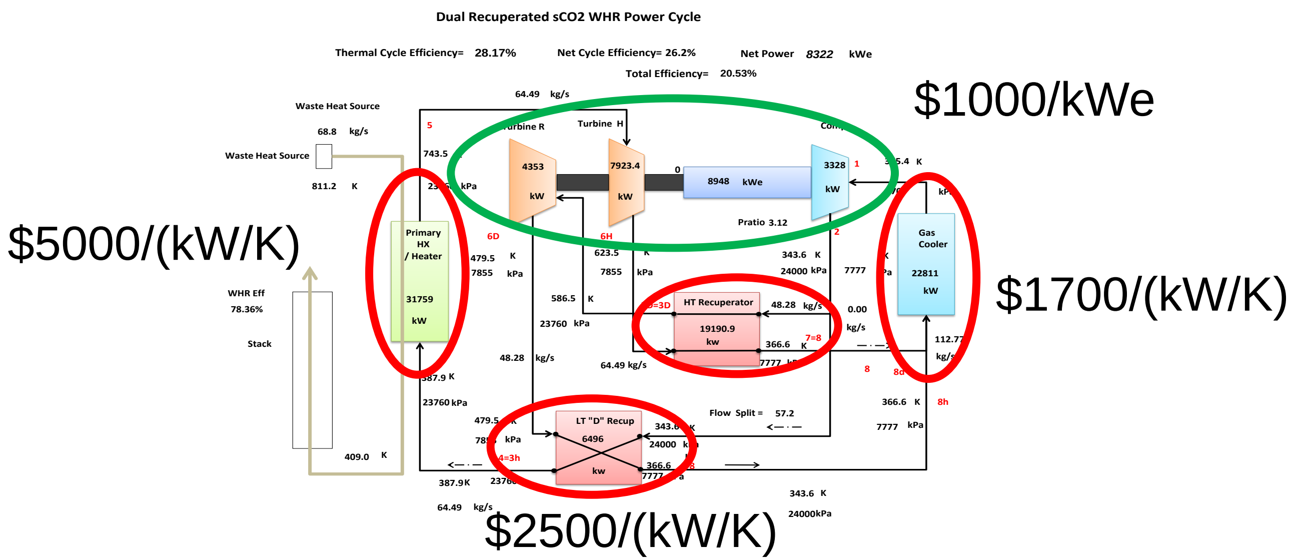
Component Specific Costs



Component Description	Cost Units	Component Specific Costs
Recuperators (cost/UA)	\$/(kW.th/K)	2500
Fin Tube Primary Heater (cost/UA)	\$/(kW.th/K)	5000
Tube and Shell CO2-Chiller (cost/UA)	\$/(kW.th/K)	1700
Turbomachinery+Gen+Mtr+Gear+Piping+Skid+I&C+Aux.BOP	\$/kWe	1000

Summary of Results

		SRBC	Cascaded	Dual Recup	Preheating
LM-2500PE	**Units**				
Waste Heat (Brochure) LM2500	kW.th	40,731	40,731	40,731	40,731
Waste Heat Combustion Model	kW.th	40530	40530	40530	40530
Mass flow rate thru Comp	kg/s	93.2	124.6	112.8	121.4
Max flow rate in Heater	kg/s	93.18	56	64.49	121.4
Efficiency of WHR		**61.2%**	**85.6%**	**78.4%**	**82.1%**
Net SCO2 Cycle Efficiency		**28.3%**	**24.7%**	**26.2%**	**25.9%**
Total Efficiency		**17.31%**	**21.13%**	**20.53%**	**21.22%**
Max Turbine Inlet T	K	685.0	756.9	743.5	662.6
Max Turbine Inlet T (C)	**C**	**411.8**	**483.8**	**470.3**	**389.5**
Stack Exit Temp (K)	K	497.1	372	409.0	390.0
Stack Exit Temp (C)	**C**	**223.9**	**99**	**135.9**	**116.8**
Total UA	**kW/K**	**1795**	**2807.98**	**2447**	**2966**
Recup UA	kW/K	630.5	1036.96	782.8	1226.76
Heater UA	kW/K	446.6	837.58	794.1	740.71
Chiller UA	kW/K	718.2	933.45	870.4	998.97
Recup Costs	$	1,576,314	2,592,403	1,957,006	3,066,890
Heater Costs	$	2,232,836	4,187,885	3,970,675	3,703,565
Chiller Costs	$	1,221,021	1,586,858	1,479,629	1,698,246
Total HX Costs		**5,030,171**	**8,367,146**	**7,407,310**	**8,468,702**
HEAT EXCHANGER EFFECTIVENESS					
Prim HT HX	%	94.6%	94.0%	95.0%	93.5%
Preheater HX	%				90.8%
HT Recup	%	94.0%	92.3%	83.1%	90.5%
LT Recup	%		88.4%	91.8%	-
CO2 Chiller	%	73.8%	82.3%	81.8%	81.2%
Closest Approach Temperature (K)	**(K)**	**10.7**	**18.0**	**21.1**	**18.0**
CC Heat Rate (GT only=9611 BTU/kWh)	**BTU/kWh**	**7323**	**7037**	**7012**	**6949**
Effective Revenue from Elect Sales	**$M/year**	**2.168**	**2.339**	**2.456**	**2.473**
Approx $/kWe Net	**$/kWe**	**1717**	**2019**	**1890**	**1985**
Net Elect. Power	**kWe**	**7017**	**8214**	**8322**	**8601**
Combined Cycle Total Efficiency	**%**	**46.6%**	**48.5%**	**48.7%**	**49.1%**
Total Capital Costs (FOAK)	**M$**	**12.047**	**16.581**	**15.729**	**17.070**
Rate of Return	**%**	**18.0%**	**14.1%**	**15.6%**	**14.5%**

WHR are Grouped Together

Max TIT Higher for Pat. Cycles

High Effectiveness for HXs

Approach Temps 10 C – 21 C

CC Heat Rate Near 7000 BTU/kWh

See Bar Charts (Next)

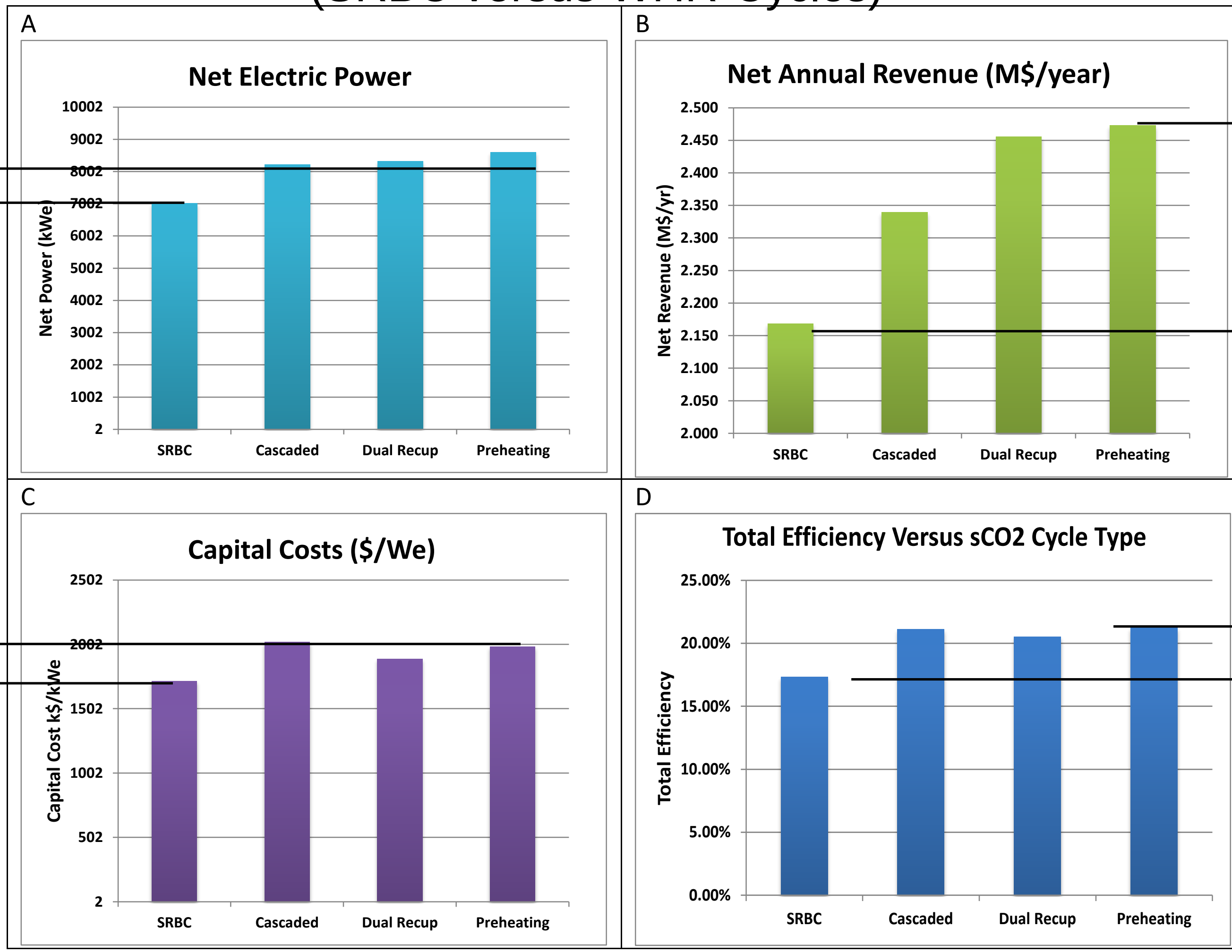
Economic Performance Summary Chart for sCO2 Bottoming Cycle

(SRBC versus WHR-Cycles)

~1 MWe Additonal Power

300 k$/KWe Additional Capital Costs

CapX ~ 2 $/We



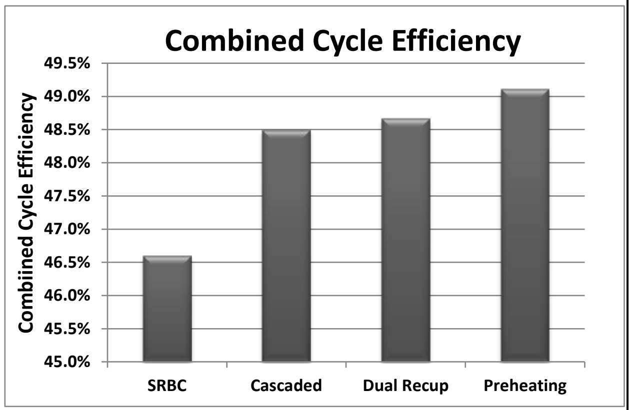
300 k$/yr Additional Revenue

3% points Additional Net Efficiency for sCO2 Bottom Cycle

Combined Cycle Economic Comparisons

	SRBC	Cascaded	Dual Recup	Preheating	Gas Turbine Only
LCOE at Fuel Costs of 3$/MMBTU	$0.0294	$0.0291	$0.0289	$0.0289	$0.0342
LCOE at Fuel 5$/MMBTU	$0.0416	$0.0409	$0.0406	$0.0405	$0.0502

A



CC Eff 35.5% to 46-49%

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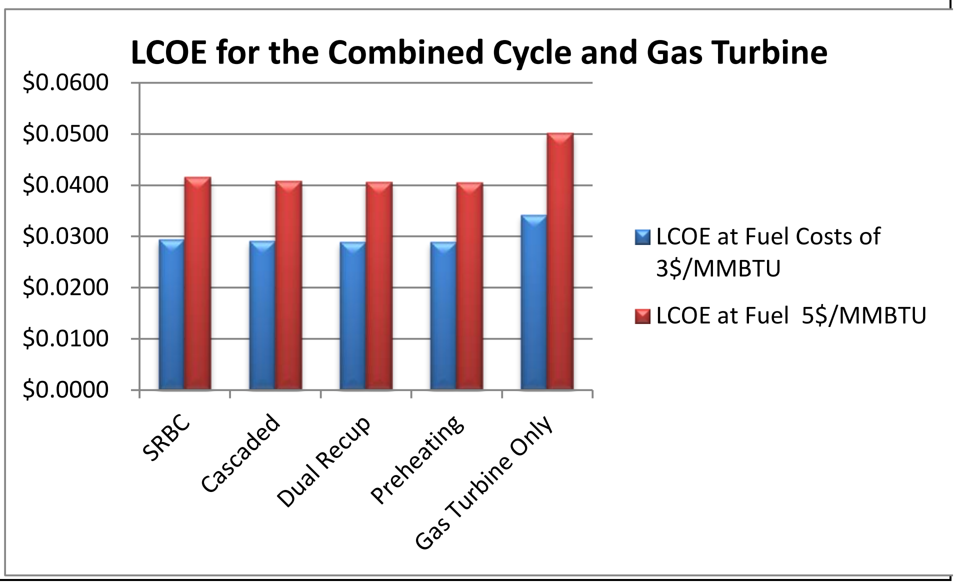

Combined Cycle Capital Costs ($0.750/We for Gas Turbine and $2/We for sCO2) = $1.05/We
Combined Cycle Efficiency Increases from 35.5% to 46-49%)
LCOE Decreases from $0.05/kWh to $.04/kWh (Well below Grid Price of Elect) (5$/MM BTU of Nat Gas)

Conclusions

- **Conclusions for Combined Cycle**
  - Combined Cycle Efficiency Increases from 35.5% to 46-49%
  - With LCOE reduction of 1cent/kWh at $5/MMBTU Natural Gas
  - LCOE is well below market price of electricity in most markets
  - Reduction of Heat Rating from 9611 BTU/kWh to ~7000 BTU/kWh
- **Conclusions for sCO2 WHR Power Systems**
  - All WHR systems perform about the same (both power and economics)
  - All WHR cycles produce 1.2-1.6 MWe more compared to SRBC
  - Annual Revenue for WHR sCO2 increases $200-300 k/yr (12-15% above SRBC)
  - Capital costs increase from 12 M$ to 16-17 M$ (from 1.7 to ~ 2$/We)
  - HXs represent about 40-50% of total system cost
  - Economic benefit to increasing HX Effectiveness to 93-95% range
  - WHR Efficiency is 61% for SRBC and 75-85% for WHR systems

sCO2 WHR Performance and Economic Benefits are Substantial

Key: A Business Model that Meets Customer's Needs

Expanding Markets, New Markets, Modularity, Power Independence, Grid Independence, Grid Reliability, High Reliability, More Competitive Products